U.S. Department of Energy
Office of Electricity Delivery & Energy Reliability

Smart Grid Research & Development

Multi-Year Program Plan (MYPP)

2010-2014

DRAFT

Second Draft: March 2010

Acknowledgment

To create this Multi-Year Program Plan (MYPP) for the Smart Grid Research & Development Program within the U.S. Department of Energy (DOE), Office of Electricity Delivery & Energy Reliability, DOE has relied upon significant original input, continuing contributions, and review comments from the following individuals and organizations. DOE is grateful to the various stakeholders who attended the Smart Grid R&D Roundtable Meeting on December 9-10, 2009 (see Appendix 2) and the MYPP Working Groups, listed below, for their critically important contributions. DOE also acknowledges the efforts of Energetics Incorporated in facilitating several of the workshops and Energy & Environmental Resources Group, LLC (E2RG) in assembling and assimilating these contributions that serve as the basis of this MYPP.

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Executive Summary

The Smart Grid Research and Development (R&D) Program within the Research and Development Office of the DOE Office of Electricity Delivery & Energy Reliability (OE), in accordance with Title XIII of the Energy Independence and Security Act of 2007 (EISA), is tasked with accelerating the deployment and integration of advanced communication and control systems that are needed to modernize the nation's electric delivery network. The comprehensive and rigorous R&D effort proposed in this Multi-Year Program Plan (MYPP) is foundational in advancing both the underlying science and the technology required to realize smart grid capabilities and benefits.

The vision of the Smart Grid R&D Program is that:
By 2030, the power grid has evolved into an intelligent energy delivery system that supports plug-and-play integration of dispatchable and intermittent low-carbon energy sources, and provides a platform for consumer engagement in load management, national energy independence, innovation, entrepreneurship, and economic security. This smart grid supports the best and most secure electric services available in the world and connects everyone to abundant, affordable, high quality, environmentally conscious, efficient, and reliable electric power.

The OE defines the smart grid by seven performance-based functionalities: 1) customer participation, 2) integration of all generation and storage options, 3) new markets and operations, 4) power quality for the 21st Century, 5) asset optimization and operational efficiency, 6) self healing from disturbances, and 7) resiliency against attacks and disasters. These functionalities will lead to achieving the Smart Grid R&D Program's four primary outcomes of reduced peak demand, improved operational and system efficiency, higher grid reliability and resilience, and lower carbon emissions and higher economic productivity from integration of more distributed and renewable generation. While the smart grid transformation is a continuing process, the Smart Grid R&D Program has defined a target goal for each outcome to support the OE's 2030 vision for grid modernization. The Smart Grid 2030 Targets and associated key milestones are:

- 20% reduction in the nation's peak energy demand
    - Demonstrate 10% peak load reduction or improvement in asset utilization on two prototypical feeder systems by 2010
- 100% availability to serve all critical loads at all times and a range of reliability services for other loads
    - Develop integrated distribution management systems (DMS) for distribution automation by 2014; demonstrate DMS under real-use conditions by 2015
- 40% improvement in system efficiency and asset utilization to achieve a load factor of 70%
    - Demonstrate prognostic health management technologies and distributed sensors for critical distribution system assets by 2014
- 20% of electricity capacity from distributed and renewable energy sources (200 GW)

- Demonstrate fast voltage regulation and overvoltage protection solutions under high penetration of renewable energy by 2014

These 2030 Targets support the 2010 OE Strategic Goals under the Secretarial Objectives of science, discovery and innovation; clean secure energy; economic prosperity; and lower greenhouse gas emissions.

The portfolio of Smart Grid R&D Program activities will primarily focus on distribution systems and consumer devices, including interfaces and integration with transmission and generation systems. The R&D areas are organized into the following five topics:

1. Standards & Best Practices
2. Technology Development
3. Modeling
4. Analysis
5. Evaluation & Demonstrations

Each R&D topical area is summarized below, with more detailed descriptions in Chapter 3 of this MYPP.

Standards & Best Practices

Standards & best practices are needed for electrical and communications interconnection, integration, interoperability, conformance test procedures, and operating practices. R&D activities will focus on:

- Developing, maintaining, and harmonizing national and international standards on interconnection, integration, interoperability, and cyber security requirements and conformance test procedures for distributed energy resources.
- Developing and maintaining legacy and advanced distribution system protection, operations, and automation best practices.
- Developing best practices to allow for improved markets by defining reliability and ancillary service requirements and clarifying roles of entities within the smart grid, such as load serving entities, aggregators, energy management systems, and independent system operators.
- Developing best practices to manage plug-in electric vehicle (PEV) charging and "roaming" from one location to another.

Technology Development

Technology development encompasses advanced sensing and measurement, integrated communications and security, advanced components and subsystems, advanced control methods and system topologies, and decision and operations support. R&D activities will focus on:

- Concepts in home-area and distribution-level, low-power, secure communications.
- Distribution system and customer-side sensing, e.g., advanced ubiquitous voltage, current, and phasor measurements in distribution.

- Grid-to-vehicle and vehicle-to-grid technologies, e.g., intelligent control of PEV charging.
- Protection and control technologies that work safely, efficiently, and reliably in the presence of high-penetration distributed energy resources and changing network conditions.
- Operations support tools, e.g., data reduction and visualization for utility operator assimilation.

Modeling

This topic area includes accurately modeling the behavior, performance, and cost of distribution-level smart grid assets and their impacts at all levels of grid operations from generation to transmission and distribution. R&D activities will focus on:

- Making comprehensive smart grid components and operations modeling capabilities available in distribution engineering tools so that smart grid options can be considered on an equal footing with today's strategies during the system design process. Creating a public library of smart grid component models, controls, operating strategies, and test cases for the vendor community and utilities to draw upon when upgrading their tools.
- Establishing benchmark test cases to validate smart grid models and software tools. Expanding Institute of Electrical and Electronics Engineers (IEEE) distribution test cases (now focused primarily on power flow) to include smart grid assets and operations.
- Developing fast computational algorithms and parallel computing capabilities to increase the speed of smart grid models so that they can be embedded in real-time controls and decision support tools.
- Developing the capability to model impacts of smart grid operations on the entire grid. Developing reduced-order models of quasi-steady and dynamic response of a smart grid on the transmission and generation system.
- Providing for continuous updates of the distribution system model in distribution engineering tools so that they accurately reflect the current configuration, which will be increasingly dynamic as smart grid technology is deployed. Linking distribution engineering models with the work order, outage management, and automated mapping/facilities management/geographic information systems.
- Developing and demonstrating techniques for integrating communication network models, wholesale market models, and renewable resource models to form more comprehensive smart grid modeling environments.
- Supporting development of open standards for describing distribution systems, customer loads, and smart grid components.

Analysis

Analysis of measured data and simulations is needed to better understand the impacts and benefits concerning capacity usage, power quality and reliability, energy efficiency, operational efficiency, and clean technology, as well as economic/business environment and crosscutting goals. R&D activities will focus on:

- Assessing the progress of smart grid deployments and investments. Investigating issues and proposing mechanisms to ensure sufficient data are collected to support analyses, and ensuring effective access and use of measurement data collected. Researching appropriate mechanisms to manage and coordinate such large datasets with existing and emerging datasets related to smart grid, such as those gathered through international efforts and the Smart Grid Information Clearinghouse project. Common standards and formats for data are required.
- Understanding the issues and potential remedies to support effective cyber security, information privacy, and interoperability practices and their acceptance by industry.
- Providing an analytic basis for the delivery of appropriate levels of power quality and reliability at the various levels of "smart" distribution infrastructure and end-use systems, recognizing the differentiated costs and benefits.
- Assessing the impact of a smart grid on the number, duration, and extent of electricity outages, including cascading events.
- Evaluating the energy efficiency impact of energy management devices in consumer facilities.
- Analyzing the ramifications of smart grid capabilities on distribution, transmission, and generation planning.
- Analyzing the impact of transmission & distribution automation on integrating high penetration of variable renewable resources with coordinated use of distributed energy resources.
- Determining potential smart grid-facilitated capacity amounts from demand response, distributed generation, and improved asset utilization.
- Conducting consumer studies regarding acceptance of demand response, on-site generation, PEV, storage, and energy efficiency programs.
- Examining the business and regulatory policy issues that can help achieve greater consumer participation.

Evaluation & Demonstrations

New technologies and methods are in need of evaluation and demonstrations in terms of performance and conformance with emerging standards & best practices and interoperability requirements. R&D activities will focus on:

- Identifying gaps related to smart grid functionality or gaps in existing technologies and processes that could limit successful, cost-effective roll-out of smart grid systems.
- Developing protocols and methods for testing and evaluating new components and systems.
- Evaluating current industry, laboratory, and government testing capabilities.

1. Introduction

1.1. Building a 21st Century Grid: A National Priority

For over a century we've systematically built a complex infrastructure of power plants, regionally connected with high-voltage transmission lines to load centers where lower-voltage distribution lines provide power to homes and businesses. Our nation's power grid ensures our safety and security, and is vital to our continued growth in productivity and prosperity. This national asset, an infrastructure built and maintained on our behalf, is aging with existing technologies reaching their end of life and others becoming obsolete, overstressed, and unable to meet the demands of high penetration of intermittent renewable energy sources. While it has served us remarkably well until now, it is incumbent upon us to upgrade it to meet the changing demands and future electric needs of our 21st Century economy and society.

We must build a more efficiently operated grid; one that maintains affordability, reliability, safety, and security for every consumer and meets the needs of a digital and highly interactive economy. Building a smart grid is the first critical step of many for the nation to maintain its technology prowess and prosperity, and brings new tools, techniques, and technologies together in a network of devices aligned and interconnected for superior grid performance. The benefits of a smarter grid are myriad and enduring. At its core is a sophisticated information system that would allow grid operators much greater visibility into the complex inner workings of this large machine to achieve wide-area situational awareness. Greater visibility would enable quick decisions to optimize performance, reduce emissions, and improve reliability. This same information system would provide customers with a window into their own energy use, giving them the tools to make better choices that align with their own values and needs and that achieve greater operational efficiency. Through a new paradigm for involving consumers with interactive loads that respond to the overall needs of the grid, the power providers and the power users work together to create the best possible electric grid at the least cost to the economy and the least impact on the environment.

1.2. Smart Grid Characteristics

The DOE's Office of Electricity Delivery & Energy Reliability (OE) defines the smart grid by seven principal characteristics or performance-based functionalities that are needed to meet the demands of the 21st Century. The following characteristics were identified by smart grid stakeholders through regional meetings convened under the Modern Grid Strategy project of the National Energy Technology Laboratory (NETL),[1] with further refinement through the national Smart Grid Implementation Workshop convened by the OE in June 2008:

- *Enables informed participation by customers*: Consumer choices and increased interaction with the grid bring tangible benefits to both the grid and the environment, while reducing the cost of delivered electricity.

[1] The Modern Grid Strategy website is at http://www.netl.doe.gov/moderngrid/

- *Accommodates all generation and storage options*: Diverse resources with "plug-and-play" connections multiply the options for electrical generation and storage, including new opportunities for more efficient, cleaner power production.
- *Enables new products, services, and markets*: The grid's open-access market reveals waste and inefficiency that need to be removed from the system or corrected while offering new consumer choices such as green power and responsive load products. Reduced transmission congestion leads to more efficient electricity markets.
- *Provides power quality for the range of needs in the 21st century*: Digital-grade power quality avoids productivity losses of downtime, especially in digital device environments.
- *Optimizes assets and operates efficiently*: Desired functionality at minimum cost guides operations and fuller utilization of assets. More targeted and efficient grid maintenance programs result in fewer equipment failures.
- *Addresses disturbances – automated prevention, containment, and restoration*: The smart grid will perform continuous self-assessments to detect, analyze, predict, respond to, and as needed, restore grid components or network sections and/or shift flows/demands with, for example, responsive load and power flow control.
- *Operates resiliently against physical and cyber attacks and natural disasters*: With smarter monitoring/control/analysis systems, the grid deters, copes with, and recovers from security attacks and protects public safety.

An evaluation of today's grid and a future smart grid based on the aforementioned characteristics is shown in Table 1.1.

Table 1.1. Comparison of Today's Grid and the Smart Grid[2]

Characteristic	Today's Grid	Smart Grid
Enables informed and greater participation by customers	Consumers have limited information and opportunity for participation with power system, unless under direct utility control	Informed, involved, and active consumers – demand response and distributed energy resources
Accommodates all generation and storage options	Dominated by central generation – many obstacles exist for distributed energy resources interconnection and operation	Many distributed energy resources with plug-and-play convenience; distributed generation with local voltage regulation capabilities to support high penetration on distribution systems; responsive load to enhance grid reliability, enabling high penetration of renewables; frequency-controlled loads to provide spinning reserve.
Enables new products, services, and markets	Limited wholesale markets, not well integrated – limited opportunities for consumers	Mature, well-integrated wholesale markets; growth of new electricity markets for consumers; interoperability of products.
Provides power quality for the range of needs in the 21st century	Focus on outages and primarily manual restoration – slow response to power quality issues, addressed case-by-case	Power quality is a priority with a variety of quality/price options – rapid resolution of issues

[2] Adapted from *The Smart Grid: An Introduction*, available at http://www.oe.energy.gov/DocumentsandMedia/DOE_SG_Book_Single_Pages.pdf

Characteristic	Today's Grid	Smart Grid
Optimizes assets and operates efficiently	Limited integration of operational data with asset management – business process silos limit sharing	Greatly expanded data acquisition of grid parameters – focus on prevention, minimizing impact to consumers
Addresses disturbances – automated prevention, containment, and restoration	Responds to prevent further damage – focus is on protecting assets following a fault	Automatically detects and responds to problems – focus on prevention, minimizing impact to consumers, and automated restoration
Operates resiliently against physical and cyber attacks and natural disasters	Vulnerable to inadvertent mistakes, equipment failures, malicious acts of terror and natural disasters	Resilient to inadvertent and deliberate attacks and natural disasters with rapid coping and restoration capabilities

1.3. Role of the DOE Smart Grid Research and Development Program

The OE carries out a variety of research, development, demonstration, analysis, technology transfer, and technical coordination activities related to modernization of the nation's electric transmission and distribution system and implementation of smart grid technologies, tools, and techniques. The OE – working with the national laboratories, industry, and academia – has the opportunity to provide new leadership to the power industry and accelerate the adoption of new technologies into the power grid so that the U.S. can become a global leader in providing clean, reliable, and affordable electricity.

The Smart Grid Research and Development (R&D) Program within the Research and Development Office of the OE, in accordance with Title XIII of the Energy Independence and Security Act of 2007 (EISA),[3] is tasked with accelerating the deployment and integration of advanced communication and control systems that are needed to modernize the nation's electric delivery network. The electric delivery infrastructure includes all of the subsystems, components, devices, equipment, and systems that are necessary for interconnecting power plants and delivery to consumers, transporting electric power across the transmission and distribution system of the grid, and balancing electricity supply and demand. It also includes the regulatory processes and business practices for long-term electric system planning and day-to-day electric system operations, as well as the appropriate policies and procedures (at the Federal, state, and local levels) for consumer and environmental protection.

1.4. Role of the MYPP

A smart grid would integrate advanced functions into the nation's electric grid to enhance reliability, efficiency, and security, and would also contribute to the climate change strategic goal of reducing carbon emissions. These advancements will be achieved by modernizing the electric grid with advanced control concepts and information-age technologies, such as microprocessors, communications, and advanced computing, information, and sensor technologies. Achieving enhanced connectivity and interoperability between such technologies will require open system

[3] Available at http://www.oe.energy.gov/DocumentsandMedia/EISA_Title_XIII_Smart_Grid.pdf

architecture as an integration platform and commonly shared technical standards and protocols for communications and information systems. To realize smart grid capabilities, deployments must integrate a vast number of smart devices and systems (Figure 1.1).

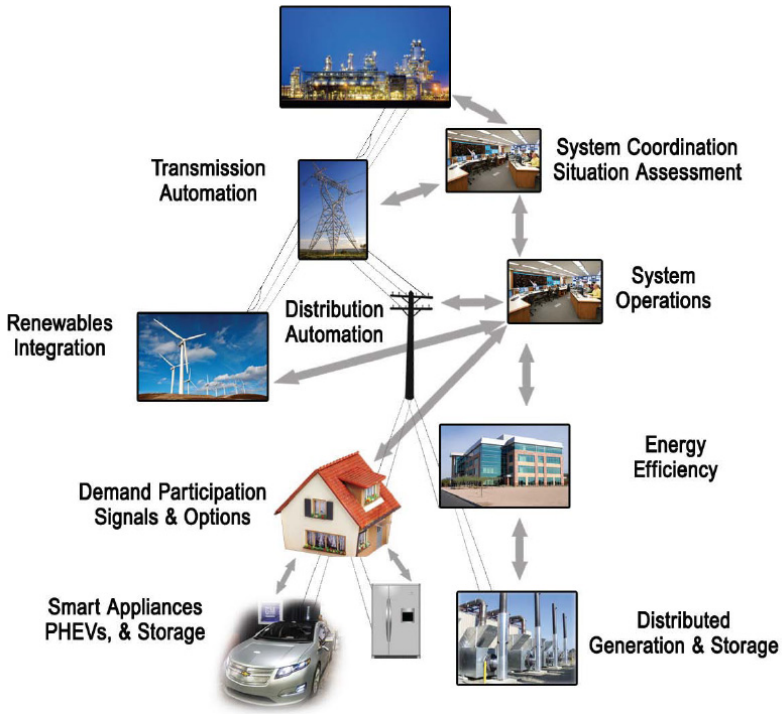

Figure 1.1. Smart Grid Components

Foundational to reaching these capabilities is a comprehensive and rigorous research and development effort that advances both the underlying science and technology required. A proposed R&D plan is discussed in this MYPP, which includes issues such as cyber security, interoperability, and distributed communications/control, as well as the effect of consumer behavior on the operation of the grid; the effect of complex, adaptive, distributed control; and the value of a new generation of simulation tools.

1.5. Vision

The vision of the Smart Grid R&D Program is that:

By 2030, the power grid has evolved into an intelligent energy delivery system that supports plug-and-play integration of dispatchable and intermittent low-carbon energy sources, and provides a platform for consumer engagement in load management, national energy independence, innovation, entrepreneurship, and economic security. This smart grid supports the best and most secure electric services available in the world and connects everyone to abundant, affordable, high quality, environmentally conscious, efficient, and reliable electric power.

This vision is in close alignment with the OE mission – to lead national efforts to modernize the electric grid; enhance the security and reliability of the energy infrastructure; and mitigate the impact of, and facilitate recovery from, disruptions to the energy supply.

Foundational/crosscutting requirements for achieving this vision include:

- High-speed, secure, broadband communications backbone(s) for two-way information flow through smart meters, comparable gateway devices, and electric infrastructure.
- Standards for end-to-end cyber security protection, interoperability, and worker safety, education, and training.

Furthermore, the smart grid infrastructure will include:

- Automated distribution systems and modeling for wide area visibility, outage prevention, and accelerated restoration and optimization.
- Automated customer systems for smart appliances and buildings capable of demand response and maintenance for increased efficiency.
- Mechanisms for electricity cost and price transparency at wholesale and retail levels for widespread use of dynamic and appropriate pricing and demand response.
- High penetration of distributed and renewable resources, including local voltage regulation and energy storage for addressing intermittent sources.

1.6. Scope of MYPP

The Smart Grid R&D Program activities will primarily focus on distribution systems and consumer devices, including interfaces and integration with transmission and generation systems. The major R&D topic areas include:

- **Standards & Best Practices** for electrical and communications interconnection, integration, interoperability, conformance test procedures, and operating practices.
- **Technology Development** in advanced sensing and measurement, integrated communications and security, advanced components and subsystems, advanced control methods and system topologies, and decision and operations support.
- **Modeling** accurately the behavior, performance, and cost of distribution-level smart grid assets and their impacts at all levels of grid operations from generation to transmission and distribution.
- **Analysis** of measured data and simulations to better understand the impacts and benefits concerning capacity usage, power quality and reliability, energy efficiency, operational efficiency, and clean technology, as well as economic/business environment and crosscutting goals.
- **Evaluation & Demonstrations** of new technologies and methods in terms of performance and conformance with emerging standards & best practices and interoperability requirements.

These R&D areas correspond to the strategic opportunities described in the 2007 OE R&D Strategic Plan[4] and support the OE mission.

1.7. Program Coordination

The Smart Grid R&D Program operates a network of partnerships with other Federal offices and agencies, electric utilities and industry, national laboratories, universities, and industry associations. These partnerships include efforts of the Federal Smart Grid Task Force that the OE established under the authorization of EISA Title XIII to provide national leadership in coordinating and integrating smart grid activities across federal agencies. Task Force members include representatives from the DOE's OE, Office of Energy Efficiency and Renewable Energy (EERE) and NETL, the Federal Energy Regulatory Commission (FERC), the Department of Commerce's International Trade Administration and National Institute of Standards and Technology (NIST), the Environmental Protection Agency, the Department of Homeland Security, the Department of Agriculture, and the Department of Defense. Other collaborative efforts in support of the EISA Title XIII implementation include support to NIST in coordinating development of a framework for interoperability standards, and production of reports to Congress with input from the Task Force on the status of smart grid implementation across the country and the security implications of smart grid devices and capabilities. Furthermore, the Smart Grid R&D Program coordinates with the Federal Communications Commission (FCC) on addressing communications technologies for the smart grid. The demand for integrated communication systems and the foreseeable benefits can be accelerated by Federal investment in programs that support the understanding and adaptation of such systems by end users.

The Smart Grid R&D Program also aims to coordinate its activities with private companies, utilities, manufacturers, states, cities, and other partners on cost-shared development projects funded under the American Recovery and Reinvestment Act (ARRA) of 2009, which includes $3.4 billion in smart grid investment grants for commercial applications and $435 million for smart grid regional demonstrations. Furthermore, the Smart Grid R&D Program has been supporting the establishment and maintenance of the Smart Grid Information Clearinghouse established under ARRA to "make data from smart grid demonstration projects and other sources available to the public." Collaboration is also taking place with industry and national laboratories on development of codes and standards, information dissemination activities, and implementing projects. Furthermore, DOE has entered into public/private partnerships with leading champions of the smart grid which include the GridWise® Alliance, EPRI/Intelligrid, Advanced Grid Applications Consortium (GridApp™), the Galvin Electricity Initiative, the Consortium for Electric Reliability Technology Solutions (CERTS), and the Power Systems Engineering Research Center (PSERC). Partnerships with universities, either individually or groups of universities such as those under the CERTS and PSERC, also ensure that the industry supporting smart grid development and the national labs will have an educated resource pool to implement the advanced research concepts and to continue advanced smart grid R&D.

[4] The 2007 OE R&D Strategic Plan is available at http://www.oe.energy.gov/DocumentsandMedia/RD_Strategic_Plan_Final07.pdf

The Smart Grid R&D Program also leverages R&D efforts conducted by other programs and agencies in areas that are complementary and necessary for smart grid development. Among these areas are:

- Basic engineering sciences
- Power electronics materials and devices
- Energy storage systems and technologies
- Building technologies
- Microgrids
- Transmission and distribution efficiency
- Support for the transportation sector

1.8. Program Goal and 2030 Targets

The goal of the Smart Grid R&D Program is to develop an integrated, national electric/communication/information technology infrastructure with the ability to dynamically optimize grid operations and resources and incorporate demand response and consumer participation.

Through implementation of its Research and Development Plan (see Chapter 3), the Smart Grid R&D Program aims to achieve the following performance targets in 2030:

- 20% reduction in the nation's peak energy demand
- 100% availability to serve all critical loads at all times and a range of reliability services for other loads
- 40% improvement in system efficiency and asset utilization to achieve a load factor of 70%
- 20% of electricity capacity from distributed and renewable energy sources (200 GW)

The Smart Grid 2030 Targets present quantifiable, trendable, and verifiable outcomes of the cumulative progress of the five value streams depicted in Figure 1.2. These pillars are cross-cut by inherent standards conformance and cyber security.

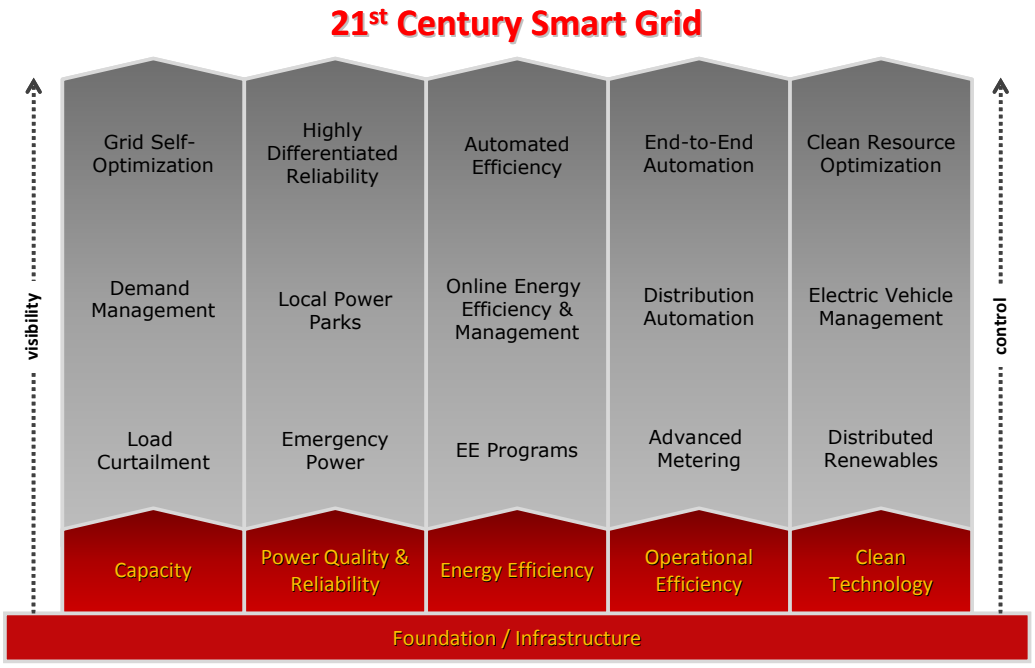

Figure 1.2. Five Value Streams of Smart Grid

The Smart Grid R&D Program goal and 2030 Targets support the 2010 OE Strategic Goals[5] under the Secretarial Objectives of science, discovery and innovation; clean secure energy; economic prosperity; and lower greenhouse gas emissions. The sidebar lists two of these Strategic Goals that resonate with the MYPP goals.

2010 OE Strategic Plan Guidance:

Goal 1: Develop market-deployable advanced electric transmission and distribution technologies and facilitate expansion of our Nation's electricity infrastructure capacity in order to enhance the adaptability, capacity, reliability, and resiliency of the electric system and promote a low-carbon environment.

Goal 2: Identify, prioritize, coordinate, and improve the protection and restorative capability of national and international critical energy infrastructure assets and key resources – including relevant cyberspace assets – with improved situational awareness, analysis, planning and preparation; advanced electric transmission and distribution technologies; and expansion of the electricity infrastructure.

[5] The 2010 OE Strategic Plan is available at http://www.oe.energy.gov/DocumentsandMedia/OE_Successes_0915_Web_sngl.pdf

2. Program Benefits

A conservative estimate of potential savings resulting from grid modernization is 20% (more than $40 billion/year). According to EPRI, "The grid of the future will require $165 billion over the next 20 years" to come to fruition and the benefits to society will be $638 to $802 billion, leading to a benefit-to-cost ratio of 4:1.[6] Similar benefits-to-cost results of 5:1 to 6:1 were attained in smart grid studies on the San Diego region[7] and West Virginia.[8] The widespread and significant societal benefits of realizing a smart grid are summarized below, according to the "Modern Grid Benefits" report[9] by the NETL, and illustrated in Figure 2.1.

- Improved prevention, containment, and restoration of outages. The cost of power interruptions to U.S. electricity consumers is enormous, with a base-case estimate of $79 billion annually and ranging from $22 billion to $135 billion based on particular sensitivity assumptions used in a study by Lawrence Berkeley National Laboratory (LBNL).[10]
- Increased national security through deterrence of organized attacks on the grid.
- Improved tolerance to natural disasters.
- Improved public and worker safety.
- Reduced energy losses and more efficient electrical generation, delivery, and loads.
- Reduced transmission congestion, leading to more efficient electricity markets.
- Improved power quality.
- Reduced environmental impact. The smart grid is capable of providing a significant contribution to the national goals of energy and carbon savings, as documented in two recent reports. One report by EPRI states that the emissions reduction impact of a smart grid is estimated at 60 to 211 million metric tons of CO_2 per year in 2030.[11] Another report by Pacific Northwest National Laboratory (PNNL) states that full implementation of smart grid technologies is expected to achieve a 12% reduction in electricity consumption and CO_2 emissions in 2030.[12]

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[6] "Power Delivery System of the Future: A Preliminary Estimate of Costs and Benefits" report by EPRI is available at http://et.epri.com/publicdocuments.html

[7] The San Diego Smart Grid Study is available at http://www.sandiego.edu/EPIC/publications/documents/061017_SDSmartGridStudyFINAL.pdf

[8] The West Virginia Smart Grid Implementation Plan is available at http://www.netl.doe.gov/energy-analyses/pubs/WV_SGIP_Final_Report_rev1_complete.pdf

[9] Available at http://www.netl.doe.gov/moderngrid/docs/Modern%20Grid%20Benefits_Final_v1_0.pdf

[10] The "Cost of Power Interruptions to Electricity Consumers in the United States (U.S.)" report by Lawrence Berkeley National Laboratory, LBNL-58164 (2006), is available at http://www.escholarship.org/uc/item/1d43k4p9

[11] "The Green Grid: Energy Savings and Carbon Emissions Reductions Enabled by a Smart Grid" report by EPRI is available at http://www.smartgridnews.com/artman/uploads/1/SGNR_2009_EPRI_Green_Grid_June_2008.pdf

[12] "The Smart Grid: An Estimate of the Energy and CO_2 Benefits" report by PNNL is available at http://www.pnl.gov/main/publications/external/technical_reports/PNNL-19112.pdf

- Improved U.S. competitiveness, resulting in lower prices for all U.S. products and greater U.S. job creation.
- Optimized utilization of grid assets.
- More targeted and efficient grid maintenance programs and fewer equipment failures.
- New customer service benefits such as remote connection, more accurate and frequent meter readings, outage detection, and restoration.

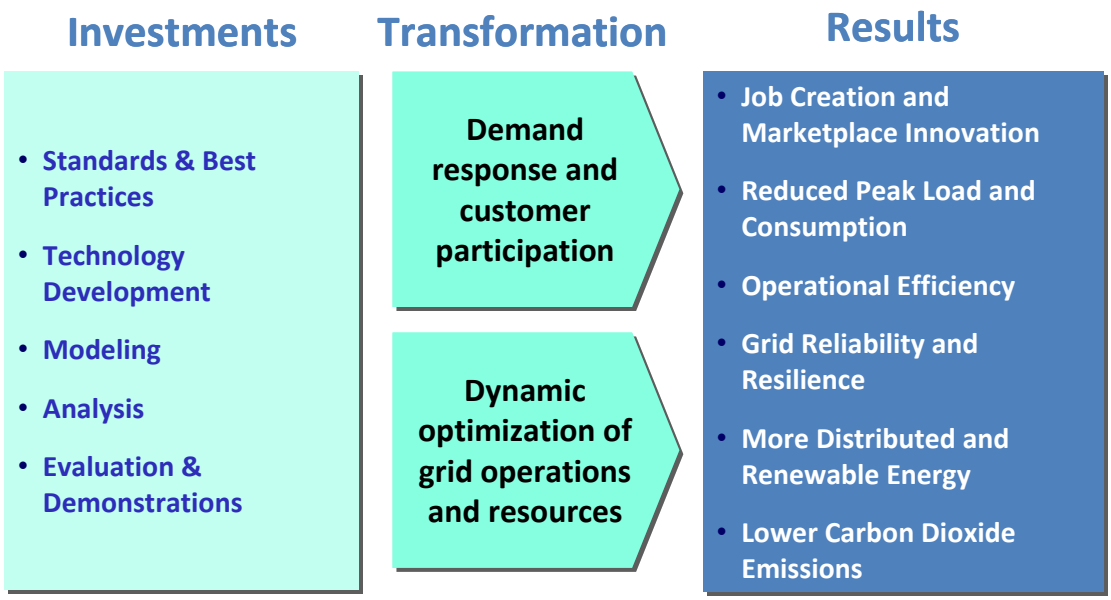

Figure 2.1. Benefits from Smart Grid R&D Investments

3. Research & Development Plan

This chapter describes five R&D areas pertinent to realizing the Smart Grid R&D Program goal and 2030 Targets. Each R&D area description encompasses technical goals and objectives, technical challenges, technical scope, status of current development, technical tasks, and milestones. In deriving technical tasks to be supported by the Smart Grid R&D Program, the following criteria were applied:

- Hindered by lack of standards or in conflict with standards
- Not being addressed by industry or other federal R&D activities
- Longer-term, high-risk developments
- Transformative (e.g., challenge status quo), high payoff
- Feasible given the likely Federal R&D budget

The Smart Grid R&D Program's role is thus to fund *long-term, high risk* R&D in *high impact* technologies to minimize the risk of adoption by stakeholders that are responsible for the development of the smart grid, namely utilities, equipment manufacturers, and consumers. Such activities should have a high impact, enabling the grid to be transformed in a way that would have been impossible or take much longer without a federally supported research program. Short-term R&D should only be funded to close critical gaps that are not being addressed by industry or other federal entities.

It is important that the Smart Grid R&D Program advances research and development concepts far enough to expand their use into subsystems and applications for the smart grid. These advancements need to reach a level where industry is able to pick them up and put them into practical use. The Smart Grid R&D Program, therefore, needs to be broad, reaching into devices and basic concepts as well as system issues, but also reaching end-use customers such as utilities where appropriate. Partnerships between the national labs, industry (including venture capital-funded startups), and universities will help enable this broad spectrum of activities with limited budgets.

3.1. Standards & Best Practices

Standards and best practices support the advancement of smart grid technologies and implementation. Standardized interconnection, integration, and interoperability[13] requirements, conformance test procedures, operating practices, and consumer education facilitate the evolution from our existing legacy electric power system into a smart grid.

Standards and best practices should enhance understanding and defining of smart grid interoperability in the distribution grid with end-use applications and loads. The goal of

[13] Interoperability is the capability of two or more networks, systems, devices, applications, or components to share and readily use information securely and effectively with little or no inconvenience to the user. Reference: GridWise Architecture Council, "Introduction to Interoperability and Decision Maker's Interoperability Checklist, v1.0," available at http://www.gridwiseac.org/about/publications.aspx

interoperability is to achieve seamless operation and control for electric generation, delivery, and end-use benefits while permitting two-way power flow with communication and control. For interoperability, both interconnection and intra-facing frameworks and strategies need to be addressed in the standards and best practices. To accomplish these goals, there should be a focus on interoperability promoting better integration of energy, information, and communications technologies.

Areas of interest include standardized interconnection, integration, and interoperability requirements, test procedures, and operating practices related to: equipment and systems such as distributed energy resources (generators, plug-in electric vehicles [PEVs], and energy storage), interconnection equipment, demand response (DR), communications and control systems, and electric power protection systems.

Interoperability operational considerations include responsiveness to changing (non-steady) normal and abnormal conditions (e.g., intermittency and robustness), asset utilization, and technical requirements related to business and policy cases. Further interoperability operational considerations include systems and equipment that are interactive (load/energy management, voltage and reactive support, etc.). These considerations should be taken into account for standards and best practices applicable to utility portals in residential, commercial, industrial, and distribution grid facilities (e.g., substations and intelligent grid devices) and user portals (e.g., utility customers, Independent System Operators [ISOs]/Regional Transmission Organizations [RTOs], regulators, third parties).

3.1.1. Technical Goals and Objectives

The technical goals and objectives are to facilitate the evolution from the existing power system into a smart grid by:

- Developing, maintaining, and harmonizing national and international standards on interconnection, integration, interoperability, and cyber security requirements and conformance test procedures for distributed energy resources.
- Developing and maintaining legacy and advanced distribution system protection, operations, and automation best practices.
- Developing best practices to allow for improved markets by defining reliability and ancillary service requirements and clarifying roles of entities within the smart grid, such as Load Serving Entities (LSE), aggregators, Energy Management Systems (EMS), and ISOs.
- Developing best practices to manage PEVs charging and “roaming” from one location to another by leveraging lessons learned from industries such as wireless telecommunications.

3.1.2. Technical Challenges

To accelerate the development and adoption of interoperable smart grid technologies, consensus-based standards need to be developed and tested. Development and harmonization of national and international standards and codes and conformance assessment through certification and laboratory accreditation are necessary to assure that electric power system reliability, operation, and safety will not be compromised. Implicit in standards development is the need for concurrent validation and testing. This is especially requisite for the advanced hardware and grid operations and communications for the interconnection, integration, interoperability and control of smart grid equipment, systems, and subsystems.

Many technical characteristics unique to smart grid pose new requirements that must be addressed in standards. Cyber security standards for energy are a relatively new concept compared to regulatory and safety standards that have existed for decades. Historical approaches that can provide valuable lessons learned are lacking. In addition, the smart grid architecture design is technologically diverse, complex, and distributed with numerous accessible components. Standards for other critical infrastructures may be leveraged, but cyber security standards for the smart grid must include guidance for new and emerging technologies, address critical data integrity, and manage the interconnection of dynamic architectures.

Cyber security for energy systems must address both the well-established need for power system reliability and the new area of market confidentiality and consumer privacy. Although utilities have been successfully addressing power system reliability though redundancy, wide area visibility, contingency analysis and other means, and the North American Electric Reliability Corporation (NERC) has developed some security standards for the bulk power system, significant additional work is needed to focus on the remaining areas of the smart grid, such as distribution system reliability and consumer privacy. For instance, it is necessary that cyber security standards address each physical and logical area within the distribution system and its interface to the transmission system and the customer. NIST has identified many of these requirements, but translating the high level NIST requirements into practical standards, policies, and technologies will require significant effort.

While power system reliability and confidentiality are the key security requirements, they rely on data integrity to provide accurate information for operating the smart grid. Layered security measures – including prevention, deferral, detection, coping, recovery, and auditing – provide a minimum level of assurance across a diverse architecture with many technologies. The potentially millions of accessible nodes require significant cyber security considerations, and the role of standards can assist in meeting this requirement at the beginning of the life-cycle. These security standards should address technology, people, and processes (i.e., hardware, software, protocols, data warehousing and management, human interaction, and coordination with physical security).

In addition to cyber security, the protection, operation, and automation of the grid will need to evolve to accommodate new technology as smart grid components are deployed. Currently, electric power system (EPS) operators have maintained distribution system protection, operation, and automation in order to keep reliability of the grid intact without fully addressing cyber

security. Challenges and opportunities will exist with the integration of new protective devices, and best practices for operations will need to be developed. There are many ways to operate the EPS, and best practices vary greatly from region to region, utility to utility, and across diverse markets. Examples include the implementation of conservation voltage reduction, reactive support from the distribution to transmission system, payment methods for reliability services, and reliability services from responsive load.

Improvements are needed in the interfaces between the transmission system and local loads. Reliability services, or ancillary services, can be provided to the bulk power system by responsive loads (demand response). For example, these loads could turn off in the event of a system contingency and thus provide reserve capacity by reducing load rather than increasing generation. Some load could turn off and on in response to an automatic generation control signal providing the regulation service.

There is also a need to improve the reliability and ancillary service definitions that have been used in the legacy power system. Ancillary service definitions and requirements have been based, in large part, on guidelines that have been "handed down" over decades of power system operation. For example, the amount of spinning reserve the operator carries for reliable system operation, or the duration required for the spinning reserve when deployed, is really determined, in some control areas, by historical guidelines and not by rigorous system modeling and analysis to determine the actual required parameters. A determination of the actual required ancillary service parameters may result in a reduction in emissions and improvement in efficiency. Also, it is likely that reliability services supplied by responsive load may actually provide a greater impact, per MW, than the same service from generation because load response is faster and more accurate, and dropping the load also reduces the transmission and distribution (T&D) flows and related losses.

Presently, there are major differences between independent system operators, control areas, and vertically structured utilities regarding the market methods used to provide reliability services for the bulk power system. These differences are not only due to the fact that some areas of the country have restructured markets while others have not, but are also due to differences in philosophy, with some utilities planning to derive a complete range of reliability services from distribution, including spinning reserve, regulation, local voltage regulation, and voltage support up to the transmission grid. Other areas are planning to use the market only for peak shaving. There is a need to conduct research and demonstrations to show the significant emissions reductions and reliability and efficiency improvements from markets for load- and distribution-based services.

There is presently a misunderstanding as to the exact roles in the smart grid of the LSE, customer, aggregator, energy management system, smart appliance, etc. Surveys and studies are necessary to define the exact services each role can provide in the smart grid and to determine the qualifications needed to perform each service reliably and efficiently.

3.1.3. Technical Scope

The scope of this research plan covers standards and best practices for the electric power distribution system and its interface requirements with the transmission system, system markets, EPS operators, and local customers and appliances. The distribution systems in the U.S. include both radial distribution circuits and secondary distribution network circuits. There is a predominance of multi-grounded, mixed-phase distribution circuit systems. Especially at the lower voltage levels, these circuits can be one, two, or three-phase distribution to consumers. This section covers standards and best practices as they relate to smart grid implementation, including:

- Interoperability standards for smart grid components and the overall system
- Interconnection and integration standards for distributed energy resources (DER), including generation and storage
- Cyber security requirements for smart grids
- Exploratory and conformance test procedures related to cyber security standards and interconnection and interoperability
- Interfaces with the transmission system and local loads, including demand response
- Improved reliability and ancillary service definitions based on system analysis
- Market systems clarification and discussion among regions and states
- Improved understanding and definition of roles of entities within the smart grid (LSE, aggregators, EMS, ISOs, etc.)
- Identification of gaps and conflicts within existing standards, including but not limited to NERC, FERC, Regional and IEEE standards
- Distribution system protection, operations, and automation practices

3.1.4. Status of Current Development

Under the EISA of 2007, NIST was assigned "primary responsibility to coordinate development of a *framework* that includes protocols and model standards for information management to achieve interoperability of smart grid devices and systems…"[14] To prioritize its work, NIST chose to focus on standards needed to address the priorities identified in the FERC Policy Statement plus four additional items representing crosscutting needs or major areas of near-term investment by utilities. The priority areas are:

- Demand Response and Consumer Energy Efficiency
- Wide Area Situational Awareness
- Electric Storage
- Electric Transportation
- Advanced Metering Infrastructure
- Distribution Grid Management

[14] EISA Title XIII, Section 1305

- Cyber Security
- Network Communications

As part of the *NIST Framework and Roadmap for Smart Grid Interoperability Standards*,[15] NIST has identified 31 smart grid standards for which it believed there was strong stakeholder consensus. An additional 46 standards were also identified as potentially applicable to the smart grid through the workshop process; NIST seeks further public comment on these additional standards. There is a need to evaluate these identified standards and their relevance to the distribution aspect of smart grids.

Through several NIST workshops, it was determined that many of the identified standards require revision or enhancement to satisfactorily address smart grid requirements. In addition, gaps requiring new standards to be developed were identified. A total of 70 gaps and issues were identified. Of these, NIST selected several for which resolution is most urgently needed to support one or more of the smart grid priority areas. For each, a priority action plan was developed, specific organizations tasked, and aggressive milestones were established. The Priority Action Plans (PAPs) included:

- Meter Upgradeability Standard
- Role of IP in the Smart Grid
- Wireless Communications for the Smart Grid
- Common Price Communication Model
- Common Scheduling Mechanism
- Standard Meter Data Profiles
- Common Semantic Model for Meter Data Tables
- Electric Storage Interconnection Guidelines
- CIM/61850 for Distribution Grid Management
- Standard DR and DER Signals
- Standard Energy Usage Information
- Common Object Models for Electric Transportation
- IEC 61850 Objects/DNP3 Mapping
- Time Synchronization, IEC 61850 Objects/IEEE C37.118 Harmonization
- Transmission and Distribution Power Systems Model Mapping
- Harmonize Power Line Carrier Standards for Appliance Communications in the Home
- Wind Plant Communications

The PAPs are meant to address the full areas of standards that need to be developed. Regarding the areas of interconnection and interoperability, the NIST workshops and reports identified the

[15] NIST Framework and Roadmap for Smart Grid Interoperability Standards Release 1.0 (Draft) – September 2009

following standards gaps, issues, and extensions specific to topics covered by the IEEE 1547 interconnection standards and the IEEE P2030 standard development:

- Energy Storage Systems, e.g., IEEE 1547 extensions for storage system specific requirements (P1547.8) and IEC 61850 modeling extensions
- Distribution Grid Management Initiatives, e.g., Common Information Model (CIM) and IEC 61850 extensions
- Voltage Regulation, Grid Support, etc., e.g., develop specifications in P1547 and/or P2030-series
- Management of DER, e.g., planned island systems (P1547.4)
- Static and Mobile Electric Storage, including both small and large electric storage facilities
- Electric Transportation and Electric Vehicles

In 2009, IEEE initiated the development of P2030: "Guide for Smart Grid Interoperability of Energy Technology and Information Technology Operation with the Electric Power System (EPS) and End-Use Applications and Loads." This standard will provide a knowledge base addressing terminology, characteristics, functional performance and evaluation criteria, and the application of engineering principles for smart grid interoperability of the electric power system with end-use applications and loads.

Several cyber-related standards are under NIST development, including security guidelines as well as smart grid cyber security requirements in the second draft of *Smart Grid Cyber Security Strategy and Requirements*.[16] These documents provide foundational guidance on smart grid structure and logical areas requiring security controls, with a large focus on advanced metering. Industry specific or component level standards are presently not widely available. The NERC Critical Infrastructure Protection (CIP) guidelines can also provide useful cyber security background information. A wide view of requirements can assist a utility or component vendor in understanding how cyber security requirements can relate to their operational process and the system as a whole.

In the area of demand response, Open Automated Demand Response Communications Specification, also known as OpenADR, has been developed as a communications data model designed to facilitate sending and receiving DR signals from a utility or independent system operator to electric customers. The intention of the data model is to interact with building and industrial control systems that are pre-programmed to take action based on a DR signal, enabling a demand response event to be fully automated, with no manual intervention. OpenADR is one element of the smart grid information and communications technologies that are being developed to improve matching between electric supply and demand.

In the markets and reliability areas, huge differences in operational methods exist between regions, but there are still commonalities that can be addressed. The interfaces to use load as a

[16] Available at http://csrc.nist.gov/publications/drafts/nistir-7628/draft-nistir-7628_2nd-public-draft.pdf

resource are well developed and in routine use in some areas of the country, but have not yet been developed in others. In some areas, there are plans for an intermediary agent such as an aggregator or EMS; in other areas, there is direct dispatch to the individual load by the system operator. These responsive load practices need to be further described and their requirements specified.

Currently there is a need not only to assess existing standards and practices, but also to investigate new methods which could significantly increase efficiency and reduce emissions while maintaining reliability. As a result, new standards for residential and non-residential buildings and the interconnections and interoperability with a smart grid may emerge that should be considered for adoption nationally.

3.1.5. Technical Task Descriptions

The proposed technical tasks are organized into the following priority areas:

Interoperability, Interconnection, and Integration

- Develop use cases to identify the requirements for interoperability, interconnection, and integration of smart grid components and systems.
- Develop exploratory and conformance test procedures related to interconnection and interoperability.
- Support accelerated development of priority smart grid interoperability standards.
- Continue to maintain and update interconnection standards.
- Develop distribution system protection, operations, and automation schemes for the smart grid.
- Provide coordinated technical support to authorities having jurisdiction for adopting and referencing smart grid interconnection and interoperability standards and best practices, e.g., states, regional, and federal entities such as NERC and ISOs/RTOs.
- Research and develop home area network (HAN) devices and end-use applications such as vehicle-to-home to give the consumer complete choice in convenience and operation.

Cyber Security

- Assess the cyber and smart grid threat through existing cyber security programs such as the National Supervisory Control and Data Acquisition (SCADA) Test Bed.
- Identify security requirements for all “assets” of the smart grid, including equipment, applications, databases, communications, and information flows; develop a security architecture for the smart grid; and identify the set of required standards as a target for gap analysis.
- Identify architectural, functional, and operational areas not presently addressed in existing standards.
- Identify technologies at the component level that require standards or guidance for security.

- Develop guidance that expands upon the human interaction, life cycle maintenance, and operational controls.
- Develop and validate methods providing cyber secure operation, along with isolation and recovery of systems, to provide a foundation for grid support and allow data exchange among different information system domains and technologies.

Market and Reliability

- Describe system operation models to enhance understanding of power system and market basics.
- Develop clearly defined functional roles for entities in these models.
- Develop clearly defined specifications for reliability services based on system analysis.
- Develop the communication and ratings/specification framework for these functional roles.
- Develop clearly defined specifications for residential and nonresidential buildings and their interconnection and interoperability with the smart grid.

3.1.6. Milestones

Milestones are listed in terms of near-, mid-, and long-term objectives:

Near Term (1-2 years)

- List weaknesses and opportunities in existing standards and practices.
- Confirm NIST priority action plan roles.
- Initiate priority smart grid interconnection and interoperability standards development (e.g., P1547.8; plug-in hybrid electric vehicle [PHEV], electric vehicle [EV], etc.).
- Develop research plan to address needs.
- List better defined entity functions.
- List and explain opportunities for efficiency and emissions improvement.
- Establish publishable case studies and best practices for the smart grid industry covering interoperability standards, conformance, and certification to support both large and small businesses.

Mid Term (3-4 years)

- Update standards to address smart grid functionality.
- Complete IEEE guide for conducting distribution impact studies on distributed energy resource interconnection (IEEE 1547.7).
- Complete IEEE recommended practice for establishing methods and procedures that provide supplemental support to implementation strategies for expanded use of IEEE 1547 series (IEEE 1547.8).
- Develop new standards and best practices to address smart grid gaps.

Long Term (5+ years)

- Complete IEEE P2030: "Guide for Smart Grid Interoperability of Energy Technology and Information Technology Operation with the Electric Power System (EPS) and End-Use Applications and Loads."
- Complete conformance test procedures and certification program for smart grid interoperability.

3.2. Technology Development

3.2.1. Technical Goals and Objectives

The objective of the Technology Development topic area is to pursue critical technological advancement in components, integrated systems, and applications that are required to achieve the full potential of the smart grid and transition from the existing EPS. The R&D activities focus on technologies deployed in the distribution system; however, the benefits extend to the entire grid. The goal is to foster the development of smart grid technologies that support high penetration of renewable generation and other distributed energy resources (DER); diversified service reliability; integration of the electric transportation sector; reduction of system losses; improved security and resiliency to failure and attack; provision of ancillary services by DER; greater customer participation and choice; reduction in operation, maintenance and integration cost; and increase in overall system efficiency. Technologies should seek to incorporate increasing automation, in alignment with the overarching vision for the smart grid, as automation is the key to efficiently deliver many of these benefits. In addition to increasing functionality and performance, the R&D activities support improvements in safety, reliability, interoperability, and security.

To achieve these objectives, short-term as well as long-term R&D activities are needed. Short-term R&D activities target priorities that are not being addressed by industry, but are critical for initial demonstration and acceptance of smart grid concepts. Long-term activities aim to advance transformative technologies that address long-term sustainability of the electric industry. A key objective is to leverage related technology development R&D efforts within DOE and elsewhere, in partnership with industry, the National Laboratory system, and academia.

3.2.2. Technical Challenges

Technical challenges that relate to Technology Development include the following:

- **Unclear definition of smart grid architecture and business models**. Grid system architecture can be defined by the topology of the power and communications network and the control algorithms and strategies used. Definitions or visions of smart grid architectures and functionality are still evolving. Therefore, technology requirements to support that architecture are not fully defined, particularly in the case of long-term needs. It is premature to define the smart grid architecture too rigidly, for example to use distributed versus centralized controls. To do so would suppress important research concepts and discourage potentially significant breakthroughs. While it is possible to identify the key functionality, several technology solutions may be possible, depending on the ownership, scale, and business models that are envisioned.
- **Integration with legacy systems.** The North American power grid is a large interconnected system that involves thousands of service providers and system operators, tens of thousands of electric generators, hundreds of thousands of miles of lines and interconnections, and hundreds of millions of customers. It is reliable and provides electricity at low cost. While it is clear that smart grid concepts enable an evolution to a more sustainable power grid in the long run, emerging smart grid technologies must be

deployed incrementally in the context of a very large, capital-intensive, and complex legacy infrastructure. Addressing intergenerational interoperability is critical to allow the evolution to continue. In this environment, achieving large-scale deployment and adoption of fundamentally new technologies, with potentially new distribution systems topologies and operations practices, is a significant challenge.

- **Wide scope of technologies and domains.** The range of smart grid technologies, even if limited to the distribution system, is quite broad. The smart grid is expected to include renewable energy generation, larger deployment of controllable resources (generation, load, storage), improved and differentiated levels of reliability, customer choice, increased power efficiency, reduced operations and maintenance (O&M) costs, support for an increasing hybrid-electric transportation sector, and improved security. At its core, these benefits are enabled by improved sensors and diagnostics for equipment performance and energy measurement and a sophisticated information system that will provide greater visibility on the operation and performance of the grid. Delivery of these benefits will require fast and secure communications, better system awareness, more sophisticated protection and control approaches, electric power storage, and systems to aggregate, manage and control distributed resources (including customer generation and loads). New materials, devices, subsystems, systems, algorithms, and topologies will be needed to realize the smart grid vision. This intelligent grid will rely on ubiquitous sensing, measurement, and communication of that information to the appropriate control locations. It will require new power electronics control of electric power flow within the network and inside the home and enterprise, as the smart grid extends beyond the boundary of the meter. Additionally, this will require new power electronic control in support of the transportation sector. New algorithms and levels of automation are required to realize control of the grid in this information-rich environment. Smart grid technologies are expected to perform varied functions depending on the domain (home, building, microgrid, utility, market); yet, they are expected to interoperate as an integrated system.
- **Evolving nature of standards.** It is obvious that each of these drivers implies the need for development of components, systems, subsystems, and applications that are low cost, safe, reliable, secure, and deployable. One of the key challenges is that potential cost savings and other advantages are pushing for deployment of many of the smart grid elements before performance, interoperability, and cyber security standards are finalized. Development of technology in the absence of clear standards represents added risk.
- **Expected service longevity.** Power system assets are expected to have a long service life, often decades. This translates into a significant challenge from the technology development perspective. Smart grid technologies need to have a high level of reliability while operating in a physical environment that is often harsh. In addition, hardware and firmware platforms need to have the capability and flexibility to adapt to future needs. It is difficult to meet these needs at a reasonable cost to consumers.

3.2.3. Technical Scope

The Technology Development topic area focuses on components, integrated systems, and applications deployed in the distribution system under utility, customer, and third-party ownership or control. R&D activities cover technologies within the following areas:

- *Advanced Sensing and Measurement* to support faster and more accurate response such as remote monitoring, time-of-use pricing, and demand-side management.
- *Integrated Communications and Security*, connecting components to open architecture for real-time information transmission and control.
- *Advanced Components and Subsystems* for storage, power electronics, and diagnostics.
- *Advanced Control Methods and Topologies* to monitor essential components, enabling rapid diagnosis and precise solutions appropriate to any event, and to automate operations and controls.
- *Decision and Operations Support* to reduce operator error and latency in responding to ordinary and emergency grid events, enable informed customer participation in the smart grid, and provide greater observation/visibility of the distribution system and its interface with the transmission system.

3.2.4. Status of Current Development

A survey of the status of current development in each of the technology areas is provided below. For a more detailed discussion of specific commercial and emerging smart grid technologies, refer to the compendium created by NETL's Modern Grid Strategy.[17]

3.2.4.1. Advanced Sensing and Measurement

Sensing and measurement can be considered the eyes and ears of the smart grid. Without it, the utility operator, customer, and automated control systems are blind and cannot operate effectively and efficiently. Several key technologies are under development in this area, notably smart meters, cost-effective sensing and energy measurement for home automation and smart appliances, and distribution network sensing. Deployment of sensors that monitor weather conditions such as irradiance, wind velocity, and ambient temperature would help make wind and PV energy more predictable, easing operational difficulties associated with their variability. Broad adoption of these systems will only occur if the cost of these systems is sufficiently low.

- **Advanced Metering Infrastructure (AMI).** Smart meters are a key sensing component of the smart grid, in particular for the early deployments due to a more favorable business case. In addition to automated meter reading and sensing of power quality at the point of utilization, smart meters provide an interface between the utility and its customers, allowing for advanced functionality and applications such as time-of-day or real-time

[17] The NETL compendium of smart grid technologies is available at http://www.netl.doe.gov/moderngrid/referenceshelf/whitepapers/Compendium_of_Technologies_APPROVED_2009_08_18.pdf

electricity pricing and accurate load characterization. They allow customers to more easily track their electricity usage and can interface with smart appliances that respond to pricing signals. Today's meters are limited in upgradeability, memory and code space for local intelligent control, and temperature tolerance. AMI reliability needs to be improved to extend longevity. Significant improvements in power consumption, processing capabilities, cost, and reliability are possible and desirable. Next generation AMI should have expanded functionality and be able to interface to distributed generation and PHEVs both for 'smart charging' (e.g., mitigating an early-evening charging peak and optimizing the use of existing generation capacity) and for intelligently using the capabilities of the PHEVs (e.g., providing controlled real and reactive power to aid in compensating for the variable generated power of renewable resources) in alignment with the objectives for PHEV controllers in the *Advanced Components and Subsystems* area.

- **Customer-side sensing.** Sensors within HAN and buildings can provide the customer additional information on energy usage and power quality. Current home sensing appliances typically provide the customer with overall power usage information only. Reliable sensors at a more granular scale, coupled with automatic control systems, can optimize energy use and effectiveness in homes and buildings. R&D activities should focus on new low-cost, low-power sensing technologies needed for home and building automation and interaction with the smart grid. Both measurement and verification methods should be developed to express energy savings as a difference relative to what would have happened had consumers made different choices. Providing actionable data requires accuracy while adoption will be aided by keeping costs low.
- **Distribution system sensing.** In the distribution system, ubiquitous low-cost, high-speed sensing of voltage magnitude, current magnitude, real and reactive power flow direction, and phase angle can provide the utility or automated control systems the ability to more optimally manage distributed resources and support adaptive protection and control. Phasor measurement units (PMUs) already allow for accurate measurement of phase angle, which could be used to prevent unintentional islanding or facilitate grid synchronization after islands are intentionally created. However, current products are intended for transmission and are too costly for widespread deployment in distribution systems. Technology R&D activities can help increase sensing capability at the distribution layer at cost points that will enable its adoption. Coupled with geographic information systems (GIS) applications, distributed sensors can also improve how system power quality issues, faults, and equipment failure are detected and isolated. Statistics on the resulting data can be used to determine system weaknesses or vulnerabilities.
- **Embedded sensors.** Low-cost sensors embedded in components can improve prognostic health management (PHM), which can increase the reliability of the grid and the lifetime of the components themselves. The first aspect of PHM is a set of technologies that monitors the components for signatures of incipient failure. Monitoring technologies include antennas for remote discharge, frequency response analysis, acoustic signatures, gas monitors, and infrared imagery. The second part of PHM is to use the sensed information to adapt the operating points of equipment to extend their life and avoid unplanned outages. For example, temperature sensing can improve the reliability of distribution transformers and other components by monitoring their state-of-health and detecting impending failures. Temperature sensing can also allow operators to manage

temporary overload conditions through dynamic rating of components such as transformers and lines.

- **Distributed weather sensing.** Low-cost, widely distributed solar irradiance, wind speed, temperature, and humidity measurement systems can improve the predictability of impending increases or decreases in electricity demand and renewable resources, which can then be compensated by demand response, storage resources, or adjustments in conventional generation dispatch. Distributed weather sensors can improve upon today's output forecasting by adding more localized, finer spatial and temporal resolution measurements. It is beneficial that both the long-term and short-term forecast data are integrated into the operations and support systems used to control grid operations.

3.2.4.2. Integrated Communications and Security

If sensing and measurements are the eyes and ears of the smart grid, communications are its nerves, transmitting information to where it is needed for optimal control of the smart grid. There is a need for integrated communications at all scales in the smart grid from the home through the distribution system, and even through the transmission system. Integrating communications technologies with sensing and measurement at the core of the smart grid along with control and actuation functions is also expected to bring efficiencies to the grid at lower cost points. On the other hand, security issues are a major consideration in the expansion of integrated communications into distribution systems. While the smart grid is not expected to lead the advancements in communications technologies, R&D activities should foster the development of specialized components that leverage the communications infrastructure for smart grid applications.

- **Communications integration and coverage.** Integrated communications encompasses the physical layer (equipment, carrier) as well as the information layer (messages, higher layer protocols). Physical layer needs span the grid infrastructure, from inside the home (HAN) through distribution and transmission networks, and needs to have sufficient bandwidth for application. Technologies are available at all levels, from wireless and power line communications in the home to microwave and optical technologies in transmission systems. Public networks such as cellular and internet that are already in place could be leveraged, but issues such as cyber security, data reliability, and privacy would have to be addressed in a more comprehensive manner. Investigation into the different reliability and latency requirements of smart grid components may reveal where such networks can be prudently and rapidly deployed to accelerate adoption and maintain network security. The underlying technologies are somewhat mature, but product availability in some cases is limited. Since each technology offers its own strengths and weaknesses, solutions could include coordinated combinations to optimize both security and features such as utilizing the AMI network to deliver highly secure communications to the home while relying on public networks to deliver powerful consumer features. Standards associated with the information layer are still evolving, which represents a major challenge to expand coverage and achieve full interoperability between different domains of the system (distribution management system [DMS] applications, HAN, building EMS). R&D activities can target improvements in power usage, electromagnetic interference, bandwidth, and latency.

- **Information security.** Cyber security is imperative to widespread acceptance and adoption of a smart grid that is more dependent on information for control purposes. Encryption, authentication, and other security measures are available for information protection, but these measures are generally used only in critical components (such as smart meters) because of the lack of a viable business case. As control systems become more decentralized, physical security presents additional challenges because intelligent equipment and control systems owned by customers, as opposed to utilities, could be exposed to security threats that have the potential to negatively affect the grid. In addition to improving the cost effectiveness of security solutions, new technologies are needed that can detect threats and respond to limit their propagation or effects. These technologies can play a key role in the development of an attack-tolerant, rapid recovery smart grid. This future secure smart grid will be 'self-healing' in that the grid will detect compromised information, support forensic analysis, determine and close the offending leak, and use redundant uncompromised information to control its decisions. Such cyber security measures should be integrated into the design of communications systems for the smart grid.

3.2.4.3. Advanced Components and Subsystems

Advanced components and subsystems can support sensing, communications, transmission of electricity, actuation, and controls. This R&D area should encompass protection and control equipment, energy conversion and management, energy storage subsystems, and integration of advanced components. Today's distribution system equipment operates in a harsh outdoor environment through exposure to internal and external heat sources, electric and magnetic fields, and large mechanical stress and strain – all of which contribute to increased fatigue, failure, and corrosion. R&D should support integration of new materials and components needed to improve functionality, reliability, and efficiency of smart grid components and systems.

- **Power electronics subcomponents**. Today's key distribution system components such as breakers, transformers, tap changers, reclosers, relays, and transfer switches can be augmented or replicated and improved with solid-state power electronic devices to provide more precise, flexible, and automated control, as well as higher efficiency and reliability. In some instances, it may be more cost effective to modify the existing components to add smart grid functionality. For example, a power electronics distribution transformer could provide voltage regulation, harmonic suppression, and power factor correction. It can also facilitate the integration of energy storage. While silicon-based power electronic transformers have been demonstrated in laboratory environments, the cost-benefit has not proven favorable for implementation in the existing grid. With the anticipated improvements in post-silicon devices, for example silicon carbide (SiC) and gallium nitride (GaN), coupled with the need for these advanced capabilities for the smart grid, power electronics distribution transformers could become a new key device for long-term deployments of the smart grid. In addition, new post-silicon devices can improve the efficiency and functionality of DER inverters and controllers. It is critical to maintain a strong link between the materials and device research and the subsystem or component research because successes in both areas are required to realize the full potential of power electronics subsystems.

- **Power electronic converters.** Application of flexible AC transmission systems (FACTS) at the distribution system level can transform the way distribution networks are operated. Small-scale, back-to-back DC converters can be used to tie together feeders to increase reliability and actively balance load. This technology exists for transmission applications, but has not been applied to distribution systems. Static switches can enable microgrids to seamlessly and safely separate from and re-synchronize to the grid. Power electronics converters can provide dynamic and steady-state reactive support for voltage control. While FACTS devices have been heretofore associated with transmission to reduce the need for additional facilities, this flexibility will also be needed in the distribution infrastructure. Application of electronic converters can greatly increase operational flexibility of distribution systems, which is the key to enable the full range of smart grid functionality.
- **Intelligent loads and active sources.** Components that allow loads and active sources (such as PV and energy storage) to be controlled either by price signals or system reliability needs or to maximize efficiency benefit are another important advancement required for smart grid implementation. Today, controllable loads and appliances capable of automatically responding to price signals are commercially available, but market penetration is very low and closed loop control of those loads is generally lacking. Low-cost controllers with further levels of intelligence are necessary, too. Certain motor loads such as air conditioners could be designed to draw less current during turn-on and low voltage conditions by integration of low-cost relay or electronic interfaces. For example, the ability to intelligently adjust heating and cooling load as a fast-acting demand response resource can improve grid performance without significant inconvenience to consumers. Controllable loads and sources should be closely integrated with home and building energy management systems. Identifying and extracting energy efficiency throughout the system is a fundamental element of the vision for the 21st Century Grid.
- **Vehicle-to-grid and grid-to-vehicle technologies.** Further development of technologies that enable efficient integration of electric vehicle charging is also needed. PHEV controllers present an unprecedented challenge in managing loads and an unprecedented opportunity for using commercial devices to improve grid operation via their storage capabilities. For example, a home charger for an electric vehicle from Tesla Motors consumes up to 16.8 kW (70A @ 240V) for 4 hours. Therefore, if a large percentage of PHEV batteries were to be charged in the summer evenings when residential electric consumption is already high, it would potentially cause or exacerbate feeder or transformer overload. Therefore, vehicle-charging systems must include programmable charging profiles and the necessary communications equipment to allow for integration with energy management and smart meter systems. In the future, technologies that enable vehicle-to-grid applications may also be provided. A positive aspect of the PHEVs is that the tens of kWh of storage might be used as a power supply to compensate for the variations in renewable resources. This functionality requires intelligent control of PHEV battery charging and discharging. Moreover, the reliability and longevity of the batteries needs to be increased above that needed for transportation alone, and a solution needs to be found for the automakers that provide warranties for batteries used beyond transportation needs.

- **Energy storage and associated controls.** Energy storage mechanisms owned by utilities, consumers, or third parties will become an integral part of the smart grid. At the distribution system level, these storage mechanisms may be electrochemical (e.g., batteries), mechanical (e.g., flywheels and compressed air), or thermal (e.g., ice storage). Their initial use will be primarily to increase power quality and reliability of critical loads, and time-shift demand to reduce peak loading on the system; however, in the long term, such devices might be controlled differently to provide other grid services, including local voltage regulation to allow for integration of high levels of intermittent renewable generation. The basic challenges related to energy storage are efficiency, reliability, and capital and O&M cost. Overcoming these challenges with solutions that reduce environmental impact aligns with the imperatives set forth for the 21st Century Grid. Additionally, low-cost, more robust, and "plug-and-play" inverters, controllers, and interface technologies need to be developed and introduced to drive adoption of storage from the residential level, 5 kW range, to the MW level for applications such as transmission services. The Smart Grid R&D Program must complement existing DOE programs in storage technologies to include the development of integrated, distributed energy storage systems with improved cost, performance, and energy efficiency. While energy storage options exist, few applications are reported due to today's relatively high cost and uncertain return on investment. This equation will change in favor of energy storage as the need for flexibility in the system increases.

3.2.4.4. Advanced Control Methods and Topologies

Almost all of the technologies described so far require advanced control methods to govern their operation. Most grid controls today are centralized and involve human interaction. As the smart grid evolves to one with a plethora of distributed renewable generation, storage, and load management, more complex automated control systems will be necessary to maintain optimum operation of the grid. The control algorithms will be strongly influenced by the smart grid topology (centralized vs. distributed control).

- **Distributed controls.** Research is needed on optimal topologies, decentralized control approaches, and non-linear and robust control theories to guide the design of automated controls. An example of new topology is a microgrid: a small section of the grid that can operate disconnected from (islanded mode) or connected to the rest of the grid. Microgrids might be individual homes or businesses, campuses or industrial parks, or isolated systems. The ability to island from the grid presents challenges in control, safety, security, reliability, and stability in the face of a large percentage of renewable resources that require distributed and potentially complex controls. However, the benefit is an islandable microgrid that can operate for an extended period of time in the face of transmission line or large generation plant outages. At present, the application of microgrids is limited to military bases, islands, universities, and large industrial complexes given existing business structures and policies. Technology development is needed to implement robust, microgrid-friendly features – such as adaptive, distributed, agent-based controls – into active sources, energy management systems, energy storage, and network components to support microgrid operation.

- **Distribution grid automation.** One of the overall goals of the smart grid will be the development of a more automated and flexible distribution system, capable of anticipating and responding to disturbances or malicious attacks while continually optimizing its own performance. Self-healing features such as the ability to dispatch DER and reconfigure power flow to isolate faulted or damaged equipment could be implemented to increase grid security in response to malicious attack. The overall benefits from cost-effective distribution grid automation will include not only enhanced reliability, but also innovative customer services, reduced O&M costs, and increased throughput on existing lines via more effective power flow control. Distribution automation is already in early deployment; however, the evolution of the distribution grid from one with radial power flow and little automation to a more flexible, automated, and self-healing grid with many distributed resources will have to address new challenges, including control complexity and protection.
- **Mixed AC/DC circuits.** As the smart grid contains an increasing number of power electronics control devices, greater efficiency and reliability might be achieved through the use of DC distribution circuits and converters. This would require development of DC power system components (i.e. breakers, outlets) and conversion of end-use equipment. Mixed AC/DC systems can enable the grid to provide highly differentiated quality and reliability service to customers. For instance, DC power conversion R&D is needed to selectively determine in real-time which source is most available, desirable, and cost-effective, and reliably convert the source to 48V DC and 24V DC.
- **Adaptive protection and control.** There is a need to develop network control protection technologies that work safely, efficiently, and reliably in the presence of high-penetration DER and changing network conditions. Distributed generation introduces power and current flow in the 'upstream' direction, necessitating more sophisticated protection and control strategies. To allow for system reconfiguration, and the presence of high levels of DER, protection and control systems might have to be 'adaptive.' Today's standards prevent DER from controlling voltage and tolerating grid disturbances, even though, in principle, inverter platforms have the flexibility to perform those functions. These requirements impact DER's ability to intentionally island and to collaborate with other DER to sustain voltage and frequency – functions that are needed for advanced smart grid applications. Highly adaptive protection and control systems are needed to enable smart grid functionality.

3.2.4.5. Decision and Operations Support

Sensors, advanced components, and integrated communications and controls contribute to decision and operations support. Large scale deployment of smart grid with high penetration of DER, along with associated control and market functions, will make system operations and customer participation more complex. New technologies will be needed to process information, operate the system, and perform service and maintenance.

- **Information aggregation, processing, and visualization**. Deployment of a smart grid on the distribution system means that system operators will need to process larger volumes of information quickly and accurately to make operating decisions and take action as required for maintaining reliability. Data from prognostic health management

systems, distribution sensing forecasting subsystems, real-time markets, and distribution phasor monitor units need to be integrated into the distribution level management systems. Technology advances in software and hardware data aggregation and data-set reduction techniques can reduce the information to a meaningful set that the operator can use. Display visualization is another form of data aggregation and reduction, displaying only the critical information based on measurements. R&D for decision and operations support will greatly reduce operator error and latency in responding to ordinary and emergency grid events. Similarly, the increased information that will be made available by the smart grid can provide new opportunities for consumers to make decisions regarding their energy usage. Robust modeling engines for managing load coupled with dynamic inputs such as weather patterns, consumer comfort thresholds, demographic and load profile information, consumer preference and tolerance for outage of specific devices, and electricity pricing can be incorporated into grid management systems as well as consumer-facing applications such as HAN management systems. By developing the required hardware and software solutions on both sides of the meter, consumers can make informed decisions and load management can be accomplished in real-time.

- **Diagnostic, service, and maintenance tools.** In terms of operations support, as smart grid technologies are deployed and become a part of the mainstream T&D system, new tools for line crews will be required for installing, monitoring, maintaining, repairing, replacing, and disconnecting these devices in the field. Technologies include phase detection, fault location, communications diagnostics, equipment functionality diagnostics, and remote disconnects. In addition, because the smart grid may contain islanded systems with power flowing in either direction independently of the grid connection, new safety techniques will likely be needed. Early examples of industry needs around smart grid tools include devices for live line work on advanced conductors that may be operating at temperature extremes in excess of 190 °C or the ability to locally troubleshoot advanced sensors that are not communicating. Crew training, tools, and techniques need to be developed to enhance capabilities and allow them to accomplish these tasks in a safe and effective manner. Applications could include robotics that assist T&D line crew members in smart grid technology installation or allow crews to work at a much safer distance from an energized line, or robotics to increase security and reliability on the T&D system by providing continual monitoring, patrol, and investigation of the infrastructure.
- **Operations support tools.** Advancement in technologies that integrate measurements and forecasts as part of on-line operations support or automatic control systems are also needed. These include:
    - Management and forecasting of demand response, distributed generation, and storage resources
    - Dispatch of active and reactive power (through aggregation of DER) for optimization of losses and voltage profile
    - Optimal operation of voltage control and distribution automation
    - Detection, isolation, and response to faults, vulnerabilities, and threats
    - State estimation to facilitate accurate and near real-time reliability and security assessment

These decision support tools rely on advanced models and simulation. R&D activities related to modeling and simulation are included in the *Modeling* chapter. Technologies that support these applications exist or are emerging; however, deployment levels are generally low. As the penetration level of other smart grid technologies increase, the need for decision support tools will also increase.

3.2.5. Technical Task Descriptions

This section assesses the activities described in Section 3.2.4 with respect to meeting the Federal role criteria listed in Section 3 and specific smart grid applications. These results also consider such factors as providing tangible improvements in technology readiness and reducing the risk of adoption by utilities, industry, and consumers.

A grade of H (as a match), M (partial match), or L (no match) is assigned to each Activity under each of the five Federal criteria categories as shown below. Activities with a high percentage of matches are candidates for funding. However, those with a low probability of success given the budget may still be candidates for funding because valuable progress can be made in areas that are identified as high impact. Activities that show a high overall ranking with respect to the Federal Role criteria are indicated with an asterisk.

Research and Development Area (*italic*)/Activities	**Hindered by standards**	**No other entity**	**Long-term, High risk**	**Transfor-mative, High payoff**	**Budget possible**
Integrated Communications and Security					
Communications Integration and Coverage	H	L	M	M	H
*Information Security	M	H	H	H	H
Advanced Sensing and Measurement					
Sensors and Automated Meter Infrastructure	H	L	L	M	M
*Distribution System Sensing	M	M	H	H	M
*Customer-Side Sensing	M	H	M	H	H
Embedded Sensors	L	M	M	H	H
Distributed Weather Sensing	L	M	M	M	H
Advanced Components and Subsystems					
Power Electronics Subcomponents	L	L	H	H	M
Power Electronic Converters	L	M	H	H	M
Energy Storage Technologies	L	H	H	H	L
*Grid-to-Vehicle and Vehicle-to-Grid Tech.	H	M	H	H	M
Intelligent Loads and Active Sources	M	M	M	H	H
Advanced Controls and Topologies					
*Distributed Control Technologies	H	H	H	M	M
Distribution Grid Automation Technologies	L	L	M	M	M

Research and Development Area (*italic*)/Activities	Hindered by standards	No other entity	Long-term, High risk	Transfor-mative, High payoff	Budget possible
*Protection and Control Technologies	H	H	H	H	H
*Mixed AC/DC circuits	H	H	H	H	M
Decision and Operations Support					
Information Processing and Visualization	M	M	M	M	H
*Diagnostic, Service, and Maintenance Tools	M	H	M	H	H
*Operations Support Tools	H	M	H	H	H

Each activity is qualitatively assessed for support of the smart grid characteristics (Section 1.2):

1. Enables informed participation by customers
2. Accommodates all generation and storage options
3. Enables new products, services, and markets
4. Provides power quality for the range of needs in the 21st century
5. Optimizes assets and operates efficiently
6. Addresses disturbances – automated prevention, containment, and restoration
7. Operates resiliently against physical and cyber attacks and natural disasters

High rankings in multiple categories indicate a good business proposition for the technology.

Research and Development Area (*italic*)/Activities	1	2	3	4	5	6	7
Integrated Communications and Security							
Communications Integration and Coverage	H	M	H	L	M	H	M
*Information Security	H	M	H	L	L	L	H
Advanced Sensing and Measurement							
Sensors and Automated Meter Infrastructure	H	H	H	M	H	M	M
*Distribution System Sensing	M	H	M	H	H	H	H
*Customer-Side Sensing	H	H	L	H	L	L	M
Embedded Sensors	L	L	L	M	H	H	H
Distributed Weather Sensing	L	M	M	L	M	H	L
Advanced Components and Subsystems							
Power Electronics Subcomponents	L	M	M	M	H	M	L
Power Electronic Converters	H	H	H	H	H	L	M
Energy Storage Technologies	H	H	H	H	H	L	M
Grid-to-Vehicle and Vehicle-to-Grid Tech.	H	H	H	M	H	L	M
Intelligent Loads and Active Sources	H	H	H	H	H	M	M
Advanced Controls and Topologies							
*Distributed Control Technologies	H	H	H	H	H	H	H
Distribution Grid Automation	H	H	H	H	H	H	H

Research and Development Area (*italic*)/Activities	1	2	3	4	5	6	7
*Protection and Control Technologies	L	H	M	H	M	H	H
*Mixed AC/DC circuits	H	H	H	H	H	H	H
Decision and Operations Support							
Information Processing and Visualization	M	M	M	L	L	L	L
Customer Information Systems	M	M	M	L	L	L	L
*Diagnostic, Service, and Maintenance Tools	L	L	M	H	H	H	H
*Operations Support Tools	L	H	H	H	H	M	M

H = enables goal, M = somewhat enables goal, L = does not enable goal

3.2.6. Milestones

The milestones for the prioritized technical tasks are listed as near-, mid-, and long-term projects:

Near Term (1-2 years)

- Novel additions and improvements to the advanced metering infrastructure
- Concepts in home-area and distribution-level, low-power, secure communications
- Silicon-based power electronics subsystem in a smart grid demonstration at the distribution level (e.g., smart transformer, reactive power compensator)
- Intelligent control of PHEV charging
- Data reduction and visualization for utility operator assimilation

Mid Term (3-4 years)

- Advanced ubiquitous voltage, current, and phasor measurements in distribution
- Demonstration of attack resilience and rapid restoration
- Novel materials for passive smart grid components (conductors, insulators, outer packaging)
- Novel advanced load components
- Advanced power electronics control of distribution and home storage, including vehicle-to-grid (PHEV) and other storage mechanisms.
- Novel tools for line personnel for operations and installation in the smart grid

Long Term (5+ years)

- Sensors and sensor networks for renewable resource prediction
- A self-healing smart grid
- Prognostic Health Management in the smart grid
- Post-silicon power electronics subsystem at the distribution level (e.g., smart transformer)
- Distributed controls of loads, storage, and generation
- Technology for advanced market concepts

3.3. Modeling

This chapter focuses on the capabilities required to model the behavior, performance, and cost of distribution-level smart grid assets and their impacts at all levels of grid operations from generation to transmission and distribution. Smart grid assets – from demand response, distributed generation and storage, to distribution and feeder automation – can be applied to provide benefits ranging from peak load management, reliability, ancillary services, renewables integration, and carbon management. Modeling the smart grid requires fundamental characterization of the physical aspects of a smart grid in forms suitable for rapid computation and estimation. The physical models range from power flows to customer loads and distributed resources, but also must include the function of communication systems, control systems, and market/incentive structures that enable these assets to form a smart grid. Also required is the ability to portray smart grid performance and economic impacts on both actual and representative segments of the U.S. distribution grid, in context with surrounding bulk generation and transmission systems, market structures, reliability coordination, and utility operations.

3.3.1. Technical Goals and Objectives

1. Make comprehensive smart grid components and operations modeling capabilities available in distribution engineering tools so that smart grid options can be considered on an equal footing with today's strategies during the system design process.
2. Establish benchmark test cases to validate smart grid models and software tools.
3. Add high-performance computational capability to smart grid models for use in operational controls and decision support tools.
4. Develop the capability to model impacts of smart grid operations on the entire grid.
5. Provide for continuously updating the distribution system model in distribution engineering tools so that they accurately reflect the current configuration, which will be increasingly dynamic as smart grid technology is deployed.
6. Develop and demonstrate techniques for integrating communication network models, wholesale market models, and renewable resource models to form more comprehensive smart grid modeling environments.
7. Support development of open standards for describing distribution systems, customer loads, and smart grid components.

3.3.2. Technical Challenges

Although many power-system modeling tools currently exist, new modeling capabilities will be needed because of the differences between current power-system technologies and the next-generation, smart-grid approaches. Three key overarching challenges are to:

- Model the engineering characteristics, control, and operation of wide variety of smart grid assets with sufficient fidelity so that options for the design and configuration of a smart grid can be explored and continue to evolve.

- Incorporate modeling capabilities and costs for smart grid assets in the engineering tools with which the utility industry plans and designs their distribution systems so that smart grid assets can be considered in context with traditional system designs.
- Increase the computational efficiency and speed of smart grid models so that they can serve as the foundation for real-time operational control and decision-support systems. (The development of control systems and decision-support tools *utilizing* the underlying high-speed modeling capability is discussed in the *Technology Development* chapter.)

The technical challenges for modeling a smart grid are considerable, because they involve the capability to model impacts in a variety of dimensions, including:

- smart grid business case and consumers
- capacity and asset utilization
- wholesale markets
- reliability
- environment
- alternative control strategies for distribution, distributed resources, and demand response
- communications network and loss of communication contingencies
- cyber security measures and breaches
- distribution planning and engineering design practices
- generalizing and extrapolating ARRA grant and demonstration project results
- smart grid's role in context with scenarios for the design and operation of the future grid

3.3.3. Technical Scope

Modeling the impacts of a smart grid in these various dimensions involves the ability to model many components and aspects of a smart grid, which are summarized below. Modeling may take place in an off-line, planning mode or as part of real-time operations. While both must model the effects of smart grid operations, models embedded in real-time operations must be capable of very rapid computation, albeit focused on the coming minutes or hours. Conversely, off-line analyses may span time scales of a year or even decades. The sidebar lists some other important, general attributes of smart grid models.

Some important attributes of smart grid models are the ability to:

- Explicitly model control strategies and interfaces among control domains
- Flexibly model different smart grid system designs and topologies
- Track all economic impacts on consumers and utility expenses and revenues
- Record time-series histories of all operational and financial impacts.

- **Distribution system operations and control** – Smart grid models must include all aspects of today's distribution systems (see discussion of engineering tools in Section 3.3.4). They must also be able to model emerging smart grid control schemes for functions such as load management for capacity-constrained components; dynamic reconfiguration for outage mitigation and recovery; and advanced voltage and VAR

control for reducing system losses and customer energy consumption, and for integrating high levels of renewables on the distribution system.

- **Sensing and communications** – Sensing and communications are a foundational component of the smart grid with AMI as an initial deployment. Smart grid models must incorporate capabilities to communicate with grid systems, devices and customers, improve forecasts, assist with outage recovery, and support state estimation for distribution systems, among other functions.
- **Communication network latencies, redundancy, traffic** – Smart grid models need the capability to explicitly model the effects of the communication networks involved so that their design characteristics in terms of bandwidth, latency, reliability, and redundancy and their impact on the control and operational strategies can be evaluated.
- **Demand response resources and customer behavior** – Modeling consumer behavior as it shapes the availability and sustainability of demand response over the course of the day, extreme weather events, and the seasons of the year is critical to understanding the reliability of this important smart grid asset.
- **Service to critical and non-critical loads** – Modeling how a smart grid can be designed and controlled to serve critical as well as non-critical customer loads is important to developing an understanding of how it can differentiate reliability services among various types of loads and customers.
- **Dispatchable, distributed generation and storage** – Smart grid tools must be capable of modeling how distributed generation and storage resources (including thermal, mechanical, and electrochemical) can be dispatched for managing peak loads, providing ancillary services, and increasing local and global reliability. New methods for analysis and modeling of the operational and market values of promising locations for storage-supporting renewables (solar, wind, hydro, etc.) integration across regional transmission organizations can help accelerate the deployment of large and appropriate storage operations.
- **Renewable (non-dispatchable) resources** – Smart grid tools must be able to accurately estimate resource data on wind and solar availability for a given location and orientation. Dynamic models should be able to include the impacts of resource variability such as cloud cover and wind gusts.
- **Charging of PHEVs and EVs** – An important potential role for a smart grid that needs to be incorporated in models is the management of large numbers of PHEVs and EVs, both in their charging cycles as well as their ability to provide ancillary services.
- **Wholesale (and retail) market operations** – Power markets can provide a competitive environment in which to base incentive signals to smart grid participants that truly reflect marginal costs for energy, capacity, and ancillary services. This includes the ability to model market clearing and real-time pricing mechanisms, and examine market structure, equity, and power issues.
- **Impacts of forecasts (of prices and renewable wind and solar conditions)** – Forecasts of prices allow market participants to direct their energy consumption and production behavior more comprehensively and calculate payoff and risks. In many circumstances, wholesale prices in real-time operations are driven by re-dispatch costs resulting from errors in day-ahead forecasts. Hence, it is important to incorporate the effects of errors in

load forecasts, especially for wind and solar availability as the renewable share of generation increases.

- **Effects of distribution-level assets on transmission planning and operations (including ancillary services)** – Detailed modeling of distribution-level smart grid assets would provide planners with the ability to understand impacts on transmission planning and operations.
- **Effects of distribution-level assets on generation planning and operations** – Models of distribution-level assets (demand response, distributed storage and generation, and energy efficiency from a smart grid) are needed to allow generation planning and operation to account for smart grid impacts on capacity expansion, power system costs, and reliability.
- **Effects of a smart grid on carbon emissions** – Models of a smart grid must be able to account for reduced net greenhouse gas emissions from smart grid functions such as optimized distribution voltage control, demand-side resource management, charging of PHEVs, and more efficient control of distributed and renewable energy sources.

3.3.4. Status of Current Development

This section identifies categories of existing modeling tools that *facilitate and are pertinent to analysis* of a smart grid. For each category, we identify the basic use and purpose of that type of tool, summarize its technical capabilities, and briefly describe its role in modeling the smart grid. The categories used are:

- distribution engineering tools
- dynamic analysis tools
- transient analysis tools
- communication network models
- renewable resource models
- market models
- building models
- research-oriented simulation environments

Distribution Engineering Analysis Tools

Traditional distribution engineering analysis tools are *used by utility distribution engineers and planners for engineering design of classical distribution systems*, including, but not limited to, expansion planning, sizing of equipment, project costing, fault current analysis, and protection design.

Examples of distribution engineering tools are listed in the sidebar. Distribution engineering tools primarily model some variation of unbalanced steady-state, 3-phase power flow, in the frequency

Examples of common distribution engineering tools:

- WindMil (Milsoft)
- Feederall (ABB)
- PSS Sincal (Siemens)
- CYMDIST (Cyme)
- Analysis Dapper (SKM Systems)
- Distribution Engineering Workstation (EDD)
- Distriview (Aspen)
- Paladin (EDSA)
- PowerFactory (DIgSILENT)
- NEPLAN (BCP Switzerland)
- OpenDSS (EPRI)
- CAPE (Electrocon)

domain, and with load represented as a real- and reactive-power (P/Q) boundary condition for an instant of time being analyzed. A few also have power quality, flicker, and dynamic analysis capabilities. They are driven from databases used to manage distribution system facilities and assets (automated mapping [AM]/facilities management [FM]/GIS systems). They typically also contain databases of equipment selections.

Distribution engineering tools have the ability to model power flow in traditional distribution systems and components, including:

- *substations* – including step-up and step-down transformers, switches, and distribution buses
- *distribution feeder circuits* – including circuit breakers, switches, overhead lines (grounded and ungrounded), and underground cables (concentric neutral and tape shielded)
- *protective equipment* – including relays, reclosers, fuses and disconnect switches
- *voltage control devices* – including capacitors (for voltage regulation and power factor correction) and voltage regulators (including compensator settings)
- *secondary systems* – including center-tapped transformers with triplex cables and three-phase transformers with quadraplex cables
- *switches* – installed to cut off or redirect power flow and for load balancing, including circuit breakers, self-protected disconnects, switch gear, group-operated switches (3-pole), and normally open intertie switches
- *distribution transformers* – including three-phase, single-phase, center-tapped, open-delta configurations, as well as other less common configurations

Traditional distribution engineering tools have limited capabilities for modeling smart grid operations. Many have some capability for incorporating distributed induction-, synchronous-, and inverter-based generators including engine generator sets, micro-turbines, wind generators, and PV arrays. They have little or no modeling capability for demand response, two-way power flow, distributed storage, or dynamic feeder reconfiguration. They are not designed for simulating the hour-by-hour operation of distribution systems over the long time periods (years to decades) required to analyze benefits of smart grid assets and their respective operational strategies. It is also worth noting that the distribution system descriptions used by these models today often lack information on secondary distribution system and customer characteristics that will be needed in the future. These tools also lack the capability to model power electronics and distributed generation dynamics.

Dynamic Analysis Tools

Dynamic analysis tools are primarily *used by utilities, ISOs and RTOs for transmission system engineering and planning*, including offline studies of dynamic stability issues and the production of nomograms describing stability limits. They primarily model the grid's voltage and frequency response as a function of the behaviors of the generators. Examples of models used for dynamic stability analysis are listed in the

Example tools with dynamic analysis capabilities:

- PSLF (GE)
- PSSE (Siemens)
- PowerFactory (DIgSILENT)
- NEPLAN (BCP Switzerland)

sidebar. (Two of these models are distribution engineering tools).

These tools have limited built-in abilities to model smart grid capabilities. They do have an important near-term role to play in analyzing the impacts and stability benefits for the bulk grid from the under-frequency and under-voltage load shedding made possible by a smart grid. They also have an important near-term role in modeling frequency and voltage in outage scenarios as a boundary condition for detailed smart grid models. Tools that have distribution engineering capabilities may be particularly useful in modeling microgrids where the voltage and frequency are likely to experience larger variations.

Transient Analysis Tools

Transient analysis tools are primarily *used by engineers in the utility, vendor, and research communities to design interconnection standards, automatic disconnect gear, and inverters for distributed energy resources* (generation and storage) and to analyze their impacts on distribution system protection schemes. Some examples of these models are listed in the sidebar. These tools primarily model sub-cycle voltage and frequency response, switching transients, and the power electronics and high-speed data acquisition on systems used for interconnection.

Examples of models that have transient analysis capabilities:

- PSCad (Manitoba HVDC Research)
- SimPowerSystems (The Mathworks)

Communication Network Models

Communication network models are *used by information technology companies and national defense researchers and application developers for communication network design, engineering, and planning*. Some examples appear in the sidebar. They are used to model network characteristics such as topology, traffic volumes, latency, redundancy, and the effects of disruption, including cyber attacks. They have not generally been integrated with power system models although, in one example, Washington State University has a model integrating phasor measurement units and their data network communication systems. Research has also been conducted on cyber security for SCADA systems at Idaho National Laboratory using Qualnet and Opnet.

Examples of communication network models:

- Qualnet
- Opnet
- Washington State Univ.
- IT network companies: IBM, Cisco, Google, AT&T, etc.

Renewable Resource Models

Renewable resource models are *used by utility planners and operators, researchers, and investors to understand resource availability and energy output for wind and solar generation*. These models primarily estimate the energy production potential on average years and provide economic analysis of renewable generation. Some examples appear in the sidebar. Currently, these models have little if any integration with distribution engineering tools or smart grid simulations.

Examples of renewable resource models:

- LEAP
- BCHP Screening Tool
- energyPRO
- Solar Advisor Model (SAM)
- TRNSYS16

Market Models

Market models are *designed for use by regulatory institutions to study market design and consumer impact issues, by transmission companies and market operators to analyze system and market performance, and by generation companies to analyze corporate strategies*. Some organizations developing market models are:

- *Iowa State University* – AMES is an agent-based model of power producers, load-serving entities, and an ISO in a wholesale power market over a realistically rendered AC transmission grid. It currently implements the market design outlined in the business practices manuals of the Midwest Independent System Operator (MISO).
- *Argonne National Laboratory* – the EMCAS model couples markets with DC power flow, using agent-based simulation over six decision levels: determining electricity consumption (customers), unit commitment (generation companies), bilateral contracts (generation and load-serving companies), and unit dispatch (power system operators). It has been used to study restructuring issues in the U.S., Europe, and Asia.
- *Cornell University* – experimental economics and decision research studies using human subjects interacting with power flow simulation and markets. Used to study market design and human decision making with actual financial incentives as motivation.
- *Danish Technical University* – studies NORDPOOL markets, particularly focused on the interactions between Denmark's wind resources and Norway's hydropower resources.

Building Models

Building models are *used primarily by researchers on energy conservation design practices and technologies, and by developers of energy codes and standards, to simulate the time-series thermal performance of building envelopes and heating/ventilating/air conditioning (HVAC) systems*. These tools explicitly include the effects of other end-use loads like lighting, appliances, and electronic equipment on heating and cooling to predict whole building loads, but these other end uses are input assumptions rather than model predictions.

Building models such as DOE-2 and BLAST operate at hourly time steps. These tools embed traditional HVAC control schemes, and so are not conducive to the addition of user-specified controls, such as for demand response. The latest generation model is EnergyPlus. Extensions for it have been developed by the National Renewable Energy Laboratory and LBNL that allow users to specify demand response control strategies, for example. Full thermal system transient modeling tools such as TRNSYS can be used to model arbitrarily complex mechanical systems and controls. There is little or no integration of these models and smart grid. They are best suited to developing demand response control strategies for large commercial buildings with complex HVAC systems. They are not well suited to modeling entire populations of buildings.

Research-Oriented Simulation Environments

Research-oriented simulation environments are *used by researchers, technology developers, and policy analysts for analysis of distribution and smart grid assets, controls, and operational strategies*. Their primary purpose is for exploring the technical and economic potential of smart grids, developing and analyzing operational strategies, control algorithms, market/incentive structures, and communication requirements.

These research tools are fundamentally characterized by being extensible – that is, users can add their own component models, control algorithms, and dispatch strategies to explore options for a smart grid. Therefore, they serve an important role in bridging the gap until distribution engineering tools integrate more comprehensive smart grid modeling capabilities.

Examples of research-oriented tools with user-extensible simulation environments:

- GridLAB-D (PNNL)
- OpenDSS (EPRI)
- Distributed Engineering Workstation (EDD)
- PowerFactory (DIgSILENT)
- NEPLAN (BCP Switzerland)
- PSCad (Manitoba HVDC Research)
- The Mathworks (SimPowerSystems)

Some examples of such environments are listed in the sidebar. All have basic power flow capabilities; all but the last two focus on distribution system operations. The first two models listed are unique because they are open-source projects, giving users full access to modify and improve them, and because they are oriented toward simulating annual time-series. These two models are summarized below.

OpenDSS is receiving substantial EPRI investment:

- Analysis of both system planning and real-time operations.
- Several built-in solution modes, including:
  - power flow as a real-time snapshot
  - cumulative daily and yearly power flows
  - harmonics, dynamics, & fault studies
- Experienced software developers can customize OpenDSS by:
  - downloading source code
  - writing software controls through a component interface
  - developing DLLs

GridLAB-D has received substantial DOE investment to integrate distribution, loads, and smart grid assets:

- Real-time price retail market
- Most distribution components
- Populations of buildings
- Voltage-dependent, weather-driven, end-use loads
- Actual feeders (importing some vendor formats)
- Statistically representative feeder prototypes
- Demand response
- CVR and volt-VAR control
- distributed generation & storage, inverters
- PV, wind turbines

3.3.5. Technical Task Descriptions

The following technical tasks and corresponding proposed Federal investments link back to the Modeling topic area's technical goals and objectives.

1. ***Goal:*** Make comprehensive smart grid components and operations modeling capabilities available in distribution engineering tools so that smart grid options can be considered on an equal footing with today's strategies during the system design process.

   Task: Create a public library of smart grid component models, controls, operating strategies, and test cases for the vendor community and utilities to draw upon when upgrading their tools. The library should also prove useful to the research and policy analysis communities. Component and control models could be developed for the library in the form of algorithms,

pseudo-code, procedures in MatLAB or MathCAD or a research-oriented simulation environment. At a minimum, any model must be thoroughly documented.

Operating strategies and smart grid designs may have to take the form of written documentation, but ideally, their embodiment in the form of the distribution system description and other model inputs would be placed in the library. This should include publicly available distribution models and data for validation, including distribution topology and component characteristics, loading histories with current dynamic load and supply variation models, customer characteristics, outage frequencies, and upgrade histories and plans.

Federal investment: Fund the development and maintenance of such a library. Require that all federally funded modeling exercises should be archived in the library. Fund the development of key component models and control strategies to seed the library.

2. ***Goal:*** Establish benchmark test cases to validate smart grid models.

   Task: Expand IEEE distribution test cases (now focused primarily on power flow) to include smart grid assets and operations. Test cases should be developed for components, modeling loads and other smart grid assets in conjunction with load flows. The assets of immediate importance are using demand response, distributed generation,[18] and storage (including electrochemical, mechanical, and thermal storage types in accordance with the objectives of the *Advanced Components and Subsystems* Technology Development area) for the functions of reducing peak loads and ancillary services; conservation voltage reduction (CVR) and advanced voltage control for efficiency improvements; dynamic feeder reconfiguration for outage prevention and recovery; and the integration of PV. Other priorities are test cases for market operations models and communication models integrated with smart grid assets.

   Federal investment: Fund the development of a steadily growing body of test cases, rather than rely on current volunteer efforts. Today, test cases are typically validated by comparing one tool to another. Data from ARRA demonstrations may ultimately form an empirical basis for testing and validation.

3. ***Goal:*** Add high-performance computational capability to smart grid models for use in operational control and decision support tools.

   Task: Develop fast computational algorithms and parallel computing capabilities to increase the speed of smart grid models so that they can be embedded in real-time controls and decision support tools (more than 100X real-time). Applications for real-time models include management of demand response, distributed generation and storage assets, distribution state estimation, fault location, service restoration, volt-VAR optimization, dynamically

[18] Some distributed generation test cases exist.

reconfigured protection schemes, and emergency response plans (see the *Technology Development* chapter for discussion).

Federal investment: Fund the development of advanced algorithms and parallel computing techniques that accelerate the computational speed of smart grid models.

4. ***Goal:*** Develop the capability to model impacts of smart grid operations on the entire grid.

   Task: Develop reduced-order models of quasi-steady and dynamic response of a smart grid on the transmission and generation system. Detailed models of the operation of smart grid assets would be used to characterize their response to prices, incentives, or control signals in quasi-steady operations to develop simpler response-function models suitable for use in generation capacity planning, market design, and integrated resource planning tools. Similarly, develop simpler response-function models of the dynamic and transient response of a smart grid to changes in frequency and voltage, suitable for use with dynamic and transient models at the transmission level.

   Federal investment: Fund the development of these reduced-order models once the fully detailed models are well established and validated.

5. ***Goal:*** Provide for continuously updating the distribution system model in distribution engineering tools so that they accurately reflect the current configuration.

   Task: Link distribution engineering models with the work order, outage management, and AM/FM/GIS systems. Due to the constantly changing nature of distribution systems, a major challenge for model-based analysis is capturing and maintaining an accurate representation of the distribution system in real- or near real-time. Changes to the circuit topology due to events such as outages, switching orders, protective device operation, and phasing often need to be propagated through several independent data management systems within a utility before they are updated in the engineering tools. In many cases, the distribution system model must be updated manually.

   To efficiently use the capabilities of engineering modeling tools for the smart grid and to better equip utilities to handle the increased volume of data associated with smart grid monitoring and communication, interoperability and communication between utility management systems and data stores and the engineering modeling and analysis tools need to be developed. The combinations of vendors and software configurations make integrating these systems a challenge. Some possible approaches include the following:

   - A flexible software layer which translates among vendor tools and facilitates communication between data systems from various vendors.
   - Standardization of communication information and protocols for the utility management systems and modeling software
   - Goal-oriented, vendor-led, market-transformation approaches to system integration, perhaps utilizing approaches such as golden carrot and vendor shootout.

Federal investment: Develop and fund an approach that spurs development of continuous update processes.

6. ***Goal:*** Develop and demonstrate techniques for integrating communication network models, wholesale market models, and renewable resource models to form more comprehensive smart grid modeling environments.

   Task: Create pilot projects that will design, demonstrate and construct smart modeling environments that integrate network models, market models, and renewable resource models.

   Federal investment: Fund at least one integration pilot project for each of the ancillary modeling capabilities.

7. ***Goal:*** Open standards for describing distribution systems, customer loads, and smart grid components.

   Task: Create an open standard for how the characteristics of distribution systems, in general, should be described and extend them to include the characteristics needed to model system network parameters, end-use loads, demand response, distributed generation and storage, and renewable generation sources.

   Federal investment: Fund the participation of members of the smart grid modeling community to work with standards development processes like CIM, MultiSpeak, etc.

3.3.6. Milestones

The milestones toward achieving the aforementioned seven technical goals are listed below, organized according to near-, mid-, and long-term objectives:

Near Term (1-2 years)

- Establish a public library for smart grid component models, controls, operating strategies, and test cases.
- Demonstrate an operational public library with initial component models & test cases.
- Issue a request for proposals on component & control model development.
- Initialize funding for development of test cases to validate smart grid models.
- Develop test cases for load and demand response.
- Initialize funding for high-performance computation for smart grid models.
- Launch a pilot project for integration of communication network model.
- Establish participation of smart grid modelers in standards development.

Mid Term (2-3 years)

- Populate library with examples of most smart grid components, control and operations strategies, and test cases.
- Develop test cases for output and control of distributed generation and storage.
- Develop test cases for CVR and advanced voltage controls.
- Develop test cases for renewables integration.
- Develop high-performance state estimation techniques.
- Develop high-speed models for distributed asset management.
- Develop reduced-order quasi-steady modeling of response to price and dispatch signals.
- Develop concepts for continuous updates of the distribution system model and vet them with the utility and vendor industries.
- Fund a project that spurs the process of continuously updating the distribution system model.
- Launch a pilot project for integration of wholesale network model.
- Launch a pilot project for integration of renewable resource model.
- Standards organizations recognize the scope of smart grid modeling needs.

Long Term (5+ years)

- Distribution engineering tools used by utilities have embedded capability to model smart grid assets and control strategies.
- Develop test cases for integrating communications.
- Develop test cases for integrating market models.
- Develop high-performance algorithms for volt-VAR optimization.
- Develop high-speed models for reliability applications.
- Develop reduced-order dynamic modeling of response to voltage and frequency.

3.4. Analysis

This section presents goals, challenges, and activities proposed for the Analysis topic of the Smart Grid R&D plan as organized by the five pillars of smart grid value streams in Fig. 1.2: capacity, power quality and reliability, energy efficiency, operational efficiency, and clean technology. An additional category, economic/business environment, is added to capture investigation of value propositions and the incentives to bring about deployment of smart grid capabilities. The analysis activities include a foundational/crosscutting section to capture the fundamental attributes of smart grid that cut across the various categories.

3.4.1. Technical Goals and Objectives

The Analysis plan attempts to address the important questions the Nation faces in moving forward with smart grid decisions and related deployments. This section presents the goals that influence the selection of analysis activities.

- Foundational/Crosscutting Goals
  - Assess progress of smart grid deployments and investments.
  - Effective cyber security and information privacy practices accepted by industry.
- Capacity Goals
  - Understand the impact of different smart grid designs and deployments on the capacity available to the grid.
  - Understand the influence of dynamic prices, load control, or other demand response processes on capacity availability at critical periods.
  - Characterize the impact of distribution automation on availability and functionality of distributed resources.
  - Understand the influence of high-penetration distributed generation and local voltage control on capacity availability.
  - Understand impact of smart grid on the mix, size, and location of future generation and storage options.
- Power Quality & Reliability (PQR) Goals
  - Provide an analytic basis for the delivery of appropriate levels of PQR at the various levels of "smart" distribution infrastructure and end-use systems, recognizing the differentiated costs and benefits.
  - Establish methods that maximize cost effectiveness of PQR delivered to sensitive loads, e.g., emergency services.
  - Characterize the maintenance of desirable PQR in the face of countervailing forces and policy objectives (such as high renewable resources penetration, active markets, high equipment utilization, limits to supply chain expansion, growing electricity demand - including transportation electrification) and their dynamic interactions.
  - Create opportunities to capture the potential of distributed resources (including microgrids, more localized electricity hubs, and building systems) for better targeting of PQR.

- Describe the consequences of infrastructure interdependency and propose remedies.
- Assess the impact of a smart grid on the number, duration, and extent of electricity outages, including cascading events.

- Energy Efficiency Goals: enable incorporation of energy efficiency approaches
  - Apply information gained from demand response programs to encourage end-use conservation.
  - Leverage measurement and verification (M&V) for efficiency programs.
    - Use measurement data to ensure energy efficiency programs work and to determine necessary improvements for increasing efficiency at load points.
    - Apply smart grid enabled diagnostics in buildings, residences, and businesses in a continuous manner to detect inefficient operation or behavior.
  - Conserve energy by using voltage reduction and advanced volt/VAR control.
  - Evaluate the energy efficiency impact of energy management devices in consumer facilities.
- Operational Efficiency Goals
  - Effectively integrate distributed energy resources and distribution automation to provide ancillary services and optimize asset utilization.
  - Reduce cost for wholesale and retail operations by efficient coordination of supply-side and demand-side resources.
  - Use measurements, diagnostics, and automation to reduce maintenance cost and the impact of failures.
- Clean Technology Goals: establish smart grid as an enabler to mitigate environmental impact, particularly CO_2.
  - Enable high penetration of renewable energy resources throughout the system, particularly at the distribution system level.
  - Enable plug-in electric vehicle benefits for emissions reduction and energy storage.
  - Manage environmental consequences of load growth.
- Economic/Business Environment Goals: economic/business value proposition for smart grid investments and deployments.
  - Provide credible information for effective legislative and regulatory decision-making to form an appropriate economic environment for smart grid deployment.
  - Propose appropriate incentives for individual/corporate decision-making or scenarios for socialized cost allocation.
  - Articulate and substantiate values/benefits for smart grid functionality for all smart grid applications, including the value proposition for storage in system operations.
  - Provide alternatives and directions for standard integration agreements (common, commercially accepted patterns).

- Determine appropriate allocation of smart grid benefits to electric service providers, consumers, and society.

3.4.2. Technical Challenges

The challenges for the analysis aspects of smart grid fall into the categories of data challenges, modeling and simulation challenges, and socio-economic challenges.

- Data challenges
  - Accessibility, sufficiency, and management of large data sets for analysis and diagnostics.
  - Coordination with existing and emerging data sets related to smart grid, such as those gathered through international efforts and the Smart Grid Information Clearinghouse project. Common standards and formats for data are required.
  - Diversity and selection of regions for scenario development.
  - Different scales associated with data involved in the analyses
    - Geographic: local, regional, national
    - Time dynamics: physical transients, operations, planning horizons
  - Determination of the incremental cost and benefits of smart grid when comparing grid performance before and after implementation of smart grid components due to operational differences (e.g., weather, load, routine equipment maintenance/upgrade) during the baseline (i.e., pre-smart grid) time period and the smart grid time period.
- Technology modeling and simulation challenges
  - Variability, variety, and technical immaturity of potential DER mixtures
    - Type and structure of loads
    - Renewable alternatives and their variability
    - Power quality and reliability of new technologies
  - Inexperience with distributed control theory of smart grid system operations
    - Unfamiliarity with market-based signals in distribution system
  - Inexperience with aggregated DER behavior at systemic level
    - Stability and reliability are multidimensional and not easily aggregated or summarized
  - Complex interactions of power, communications and other national infrastructures.
  - Complexity of modeling many nodes of generation/storage accompanying dynamic and automated changes in grid operation.
- Socio-economic challenges
  - Customer acceptance and behavior regarding smart-grid capabilities.
  - Effective incentives for providers and end-users are hard to assess.
  - Complex landscape for coordinating regulatory policy with market/business drivers.
  - Actual savings and intangible benefits can be hard to quantify and assign.

- PQR costs/benefits are poorly understood (including tradeoffs associated with CO_2).
- Cyber security vulnerabilities and risks, especially systemic impacts.
- Safety of active DER in the distribution system (e.g., reverse flows).
- Complexity and variability of each state regulating smart grid implementation and cost recovery.

3.4.3. Technical Scope

The Analysis section focuses on investigating the important questions that surround potential capabilities, deployment, and performance scenarios of related devices and systems (anticipating the internal and external benefits), and the path (economics, business plans, and regulatory/policy environment) to achieving smart grid objectives at the distribution level. In addition, questions concerning the impacts/benefits of distribution level capabilities on the higher, bulk energy levels of the system fall within this scope. The analysis tasks include the articulation of questions to be addressed, the structure and approach for addressing each question, as well as the answers and insights that are gained from the analysis of these questions.

Analysis activities are interdependent with the methods and tools that are the subject of the *Modeling* chapter. The analysis activities also coordinate with the *Evaluation & Demonstration* chapter, particularly in the use of information gained from ARRA-funded smart grid deployments and demonstrations. Significant knowledge can be gained through analyzing the performance of these projects in terms of what they accomplish, as well as what technical barriers and challenges will continue to exist but must be overcome for a successful smart grid transformation. Analyses of these projects and their results will thus provide critical information in identifying gap areas in need of longer-term R&D. These gap areas will help guide the Smart Grid R&D Program in making base-program investments in smart grid technologies and systems.

3.4.4. Status of Current Development

3.4.4.1. Foundational/Crosscutting Analysis

Several analysis items are so fundamental to smart grid capabilities that they cut across many or all of the analysis topic areas. The various states of development for such items are described below:

- Smart grid deployment assessment: EISA 2007 directs the Secretary of Energy to provide a biennial status report to Congress. The first report was delivered in 2009 and the next is due the end of 2010.
- Cyber security, information privacy, and interoperability: DOE, FERC, NIST, and industry are investigating cyber security issues on many fronts. Awareness is heightened; however, best practices and procedures to address cyber security issues are only emerging.

- Smart grid impacts on system planning: Smart grid capabilities have had little impact on power system operations thus far. There is a long history and inertia to the best practices for planning that will take time to change.
- Consumer acceptance: Smart grid pilot projects and some advanced metering implementations have provided insight into human behavior for services such as price-responsive demand programs. The ARRA investment grants and demonstrations provide opportunities to understand consumer interaction at a far grander scale.
- Adequacy and maintenance of data for analysis: DOE is establishing the data capture needs and processes as of this writing. The rules for gaining access to the data have yet to be defined. The description and format of the data also still need to be specified so that researchers can understand and reasonably use it in their investigations. Coordination is also needed with data collection and management across DOE efforts including the ARRA programs, the Smart Grid Information Clearinghouse, the Energy Information Administration (EIA), and non-government smart grid data collection programs.
- Distribution system performance data: The National Transmission Grid Study (May 2002) encouraged DOE to work with government, industry, and consumer representatives to determine what economic and reliability data related to the transmission and the electricity system should be collected at the federal level and under what circumstances these data should be made publicly available. DOE was also encouraged to work with FERC, state PUCs, and industry to ensure the routine collection of consistent data on the frequency, duration, extent (number of customers and amount of load affected), and costs of PQR events so as to better assess the value of reliability to the nation's consumers. EIA collects some information related to the distribution system, particularly reliability indices. The ARRA-funded projects will collect information related to smart grid deployments, which may shed new light on existing power system operational performance. This may influence new metric definitions related to distribution system performance for measurement.

3.4.4.2. Capacity Analysis

A smart grid provides increased grid capacity through facilitation of distributed generation resources participation, dynamic demand response based on capacity needs and constraints, and distribution infrastructure reconfiguration (T&D automation) that improves the utilization of existing assets. Analysis of capacity issues involves the study of how much power (or power savings) could be facilitated by a smart grid. While a smart grid by itself does not create capacity, the communications system makes larger amounts of demand response from end-users feasible. Smart grid also improves the integration of distributed generation or storage at end-user locations into the grid to provide additional capacity. Besides generation capacity, transmission and distribution capacity is of issue here. Inadequate T&D capacity may be a more critical problem. Smart grid can improve asset utilization and thereby avoid the need for new capacity.

There have been many active analyses by national organizations on the amount of capacity potentially available through demand response facilitated by smart grid. Renewable energy potentials of all kinds, including distributed renewable resources, have also been the subject of

numerous studies. Delivery infrastructure asset utilization improvements through smart grid deployment have been studied through the GridWise initiative.

- Demand Response analyses
  - FERC, "A National Assessment of Demand Response Potential," Federal Energy Regulatory Commission, June 2009.[19]
  - EPRI, "Assessment of Achievable Potential from Energy Efficiency and Demand Response Programs in the U.S.: (2010-2030)," 1016987, EPRI, Palo Alto, CA: January 2009.[20]
  - LBNL, Demand Response Potential for Large C&I, January 2007.[21]
- Distributed renewable resources analyses
  - Renewable Energy Futures project
  - Renewable Systems Integration – Sandia (2008)
  - Many studies on renewable energy projections – some break out small distributed versus centralized
- Delivery infrastructure asset utilization analysis
  - W. S. Baer, B. Fulton, S. Mahnovski, "Estimating the Benefits of the GridWise Initiative," RAND report, May 2004.

3.4.4.3. Power Quality & Reliability Analysis

Smart grid concepts rest heavily on the notion that North American PQR needs to be improved significantly to support the requirements of a *digital society*, as well as to improve *emergency response*, *convenience*, and *general productivity*. Much less clear are the desirable levels of PQR, both universally (at the substation) and locally (at the meter, the building circuit, the end-use device, and within the device, i.e., to serve its various functions). The costs and benefits of PQR as well as the desirable equipment and market mechanisms for providing it need study. Further, little is known of the impact to system stability as smart grid technology and market signals emerge and reliance on information networks becomes more pervasive. Thus, models and analyses are an integral part of understanding how smart grid needs to evolve to best achieve the desired goals.

A considerable body of literature exists on PQR, although it is skewed heavily towards studies of headline regional and international outages, which represent a small fraction of the overall PQR problem. Further, virtually all technical literature in the area addresses defining PQR problems and establishing and meeting performance standards. Questions regarding the economics, public policy, standards, or analysis of the PQR requirements of end-uses remain largely unexplored.

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[19] Available at http://www.ferc.gov/industries/electric/indus-act/demand-response/dr-potential.asp

[20] Available at http://mydocs.epri.com/docs/public/000000000001016987.pdf

[21] Available at http://eetd.lbl.gov/ea/emp/reports/61498.pdf

- CYME, Milsoft, μGRD, and other power flow tools have been developed and extended to consider PQR.
- Classic outage studies include analysis of the Aug. 14, 2003 U.S.-Canada Blackout[22] and the 1965 and 1977 N.Y. blackouts.[23]
- More recent analysis of delivered reliability includes the LaCommare & Eto review of estimated outage costs, including prior work by EPRI and others[24] and the same authors' review of state reliability filings.[25]
- A discussion of the Federal role in reliability data collection appears in the EIA's "Electricity Transmission in a Restructured Industry: Data Needs for Public Policy Analysis," DOE/EIA-0639, December 2004.
- Reviews of emerging smart grid technology include: EPRI's "Integrating New and Emerging Technologies into the California Smart Grid Infrastructure," CEC 500-2008-047, September 2008.
- The classic reference on power quality is Surya Santoso, H. Wayne Beaty, Roger C. Dugan, and Mark F. McGranaghan, *Electrical Power Systems Quality,* 2nd ed., McGraw Hill, N.Y, 2002.
- A recent discussion of the business implications of strict PQR requirements for the digital economy is: Robert Galvin, Kurt Yeager, and Jay Stuller, *Perfect Power: How the Microgrid Revolution Will Unleash Cleaner, Greener, and More Abundant Energy,* McGraw Hill, New York, 2009.

3.4.4.4. Energy Efficiency Analysis

The ability to sense, collect, and report information related to electricity operations is a smart grid trademark that lends itself to enhancing energy efficiency objectives. By providing operators and end-users with performance information, energy inefficient problems can be diagnosed, expectations can be monitored, and habits can be changed. This area focuses on energy efficiency from an end-use perspective, while operational efficiency includes efficiencies in the electricity delivery infrastructure (e.g., line losses).

The analysis of smart grid impacts on energy efficiency is in its infancy. While collecting information to understand and diagnose equipment and building energy inefficiencies has a history of analysis, being able to use additional information gained from smart grid deployment expands the reach and scale of analysis to new levels. Using smart grid capabilities to encourage and support energy efficiency goals can be subtle. A few reports have come out in the past few months extending analysis into this area.

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[22] Available at http://www.oe.energy.gov/our_organization/blackout.htm

[23] Available at http://blackout.gmu.edu/archive/a_1965.html and http://blackout.gmu.edu/archive/a_1977.html, respectively

[24] Available at http://eetd.lbl.gov/ea/emp/reports/58164.pdf

[25] Available at http://eetd.lbl.gov/ea/emp/reports/lbnl1092e-puc-reliability-data.pdf

- Pratt, R. G., et al., "The Smart Grid: An Estimation of the Energy and CO_2 Benefit," December 2009.
- "The Green Grid: Energy Savings and Carbon Emissions Reductions Enabled by a Smart Grid," EPRI-1016905, Electric Power Research Institute, Palo Alto, California, 2008.
- Hledik, R., "How Green Is the Smart Grid?" *The Electricity Journal*, 2009, 22(3):29-41.

3.4.4.5. Operational Efficiency Analysis

Transmission system balancing authorities and local distribution system operators use sophisticated planning, energy management systems, and power scheduling technologies to project required demand, monitor margin of available supply side resources, and control system challenges to stable operation. The entire process rests on the requirement to match instantaneous demand with sufficient supply-side resource. Determination and supply of adequate additional resources to cover contingencies (lumped here as ancillary services) is a complex and vital operational necessity. Smart grid capabilities can have a strong impact on efficiently operating the power system.

The relationship of ancillary services to adequate power reserves (capacity) and minimum acceptable power quality requirements (typically voltage and frequency bands) is so interdependent that analysis R&D for operational efficiency, capacity, and PQR will often overlap. Close coordination of effort in these three analysis areas should be an ongoing part of R&D planning integration.

Quantification and documentation of required reserve margins and markets for generators offering ancillary services is well established. NERC was formed to bring international North American standardization to these practices. NERC and regional reliability councils will be indispensable partners in analyzing the use of smart grid-enabled, demand-side resources as ancillary service providers. NERC and the industry in general are just beginning to assess how smart grid capabilities will influence local and regional transmission operating processes. The impact of distribution system advancements (including the engagement of distributed energy resources) on efficient transmission and distribution system operations has been investigated in a preliminary way in the following studies:

- National Energy Technology Laboratory, "The Modern Grid Strategy," 2008.
- W. S. Baer, B. Fulton, S. Mahnovski, "Estimating the Benefits of the GridWise Initiative," RAND report, May 2004.

3.4.4.6. Clean Technology Analysis

One of the most significant benefits of the next-generation smart grid includes the flexibility to support high penetration of renewable energy resources. These resources have the potential to provide clean energy to consumers and to reduce CO_2 emissions.

Smart grid is still a relatively new area that has received most attention at research organizations. However, the electric power and end-user automation industries are now also actively engaged in the advancement of smart grid and the integration of clean energy technologies. Before the last

decade, most deployments of renewable resources were by consumers and were on a small scale at the distribution level. In this last decade, we have seen new large-scale deployments of both wind and concentrated solar power, primarily at the transmission level. There have also been a limited number of utility-scale deployments of PV. At the distribution level, however, consumer deployments of PV are still the norm. There have been major advancements in technologies that allow integration of renewable resources with the distribution grid, including grid-tied inverters. These technologies are fairly mature. However, few places in the world (Denmark being one) have confronted high penetration of renewable resources. The effective management of high-penetration, non-dispatchable, renewable resources using smart grid capabilities, particularly at the distribution level, remains largely unknown and therefore is of major concern.

3.4.4.7. Economic/Business Environment Analysis

There has been a great deal of excitement surrounding potential economic windfalls from the deployment of a smart grid. Further investigation reveals regulatory and business uncertainty which is impeding the development of smart grid commerce. Analysis is immediately required to help inform national policy makers (both legislative and regulatory) on how to create a vibrant, level commercial playing field that is consistent throughout a national smart grid.

Although there is significant academic research on energy markets and demand-side management, regulatory and business model barriers must be overcome for smart grid to reach its full potential. While many of the problems have been identified, as yet no concerted effort has been made to fund solutions and/or identify who will confront the regulatory barriers in order to permit the development of new business models for a smart grid.

- Brattle Group, et al., "A National Assessment of Demand Response Potential," Staff Report to the FERC, June 2009.
- FERC Staff with support of Brattle Group and GMMB, "Possible Elements of a National Action Plan on Demand Response: A Discussion Draft," FERC Docket No. AD09-10, October 28, 2009.
- ISO/RTO Council, "2009 State of the Markets Report."
- Hammerstrom, et al., "Pacific Northwest GridWise™ Testbed Demonstration Projects: Part I", PNNL-17167, 2007.

3.4.5. Technical Task Descriptions

The technical analysis tasks for the strategic value streams of smart grid are listed below.

3.4.5.1. Foundational/Crosscutting Analysis

1. Assess progress of smart grid deployments and investments.
2. Understand the issues and potential remedies to support effective cyber security, information privacy, and interoperability practices and their acceptance by industry. Investigate ways to measure the cost/benefit of steps to address or improve the situation in these areas.
3. Analyze the ramifications of smart grid capabilities on distribution, transmission, and generation planning.

4. Conduct consumer studies regarding acceptance of demand response, on-site generation (renewable or fossil), PEV, storage, and energy efficiency programs.
5. Investigate issues and propose mechanisms to ensure sufficient data are collected to support analyses, and to ensure effective access and use of measurement data collected as a result of smart grid implementations and experiences, including those supported by ARRA funding. Research appropriate mechanisms to coordinate and manage such large datasets.
6. Collect and disseminate unbiased data on the performance of the national distribution system.

3.4.5.2. Capacity Analysis

1. Analyze the potential capacity, benefits, and issues involved in smart grid-enabled demand response:
   a. By different customer types,
   b. By technology and level of technology penetration (e.g., percent penetration of smart meters),
   c. By market design (real-time pricing, time-of-use, critical peak, capacity bidding, etc.),
   d. By type of service provided (energy, reserves, regulation, reactive power, etc.),
   e. By industry types.
2. Analyze localized capacity issues that can be helped by smart grid (distribution congestion, local load growth, outages, mobile PEV capacity) and the potential for a locational marginal price as a self-optimizing incentive to engage these resources.
3. Analyze capacity shifting through end-use demand response and distributed generation and storage in conjunction with building energy management systems and the smart grid.
4. Analyze impacts of PEV interactions with the smart grid such as:
   a. Locational provision of capacity (source of load and supply is mobile and may move between utility territories).
   b. Potential level of PEV interaction with electric market through smart grid (delay charging time, variable charging level, price-sensitive charging, sensitivity to local grid conditions, vehicle provision of ancillary services or power).
5. Analyze long-term change in generation and T&D capacity utilization due to smart grid, such as:
   a. Flatter load curves lead to better economics for baseload capacity (high fixed, low variable cost),
   b. Demand response, distributed resources, and storage provide additional load following capacity and reserves,
   c. Higher asset utilization of local distribution grid.

3.4.5.3. Power Quality & Reliability Analysis

1. Available PQR data are not sufficient for effective policymaking, and widespread data collection, archiving, and analysis are needed.
   a. Methods and tools must be developed for comprehensive data collection on both sides of the meter (see *Modeling* chapter).

   b. The roles of other levels of government and other organizations in data collection are unclear.
   c. International comparisons of delivered PQR could inform standards setting, benefits analysis, and policymaking.
2. Analysis of the costs and benefits of PQR and of providing it must be performed.
   a. The benefits estimation might be based on revealed preference for PQR as gauged by investment in back-up generation, uninterruptible power supply, power conditioning equipment, etc.
   b. The costs of providing PQR might be estimated based on: equipment and redundancy costs, value of power transfers and transactions (possibly upstream of the substation), and international comparisons.
   c. The balance between private and socialized costs of PQR provision should be explored.
   d. Trade-offs between the costs and benefits of PQR provision plus public-vs.-private provision should be explored.
   e. Identify the benefits to electric service providers, consumers, and society.
3. Little is known about the actual PQR requirements of various end-uses and how loads might be disaggregated by their PQR needs. In earlier times, similarly little was understood of the various energy requirements at customer sites, and now similar analysis should be extended to PQR needs.
4. Potential provision of ancillary services locally, e.g., voltage support, will require market design, including analysis of consequences of inadequate supply, e.g., market power.
5. The impact to local and regional system stability as the penetration of smart grid technology and market signals grows needs analysis, especially as reliance on information networks becomes more pervasive. The impact of intergenerational interoperability of the existing infrastructure with increasing penetration of smart grid technology and distributed resources needs to be investigated.
6. Cyber security is intimately related to PQR, and analysis of the former will involve consideration of the latter.
7. Smart grid implications to the interactions and dependencies between the electric infrastructure, the communications networks used in smart grid deployments, and other infrastructures (gas, water, transportation, etc.) are critical for normal and emergency support to our society.
8. Consideration of PQR will require review of the technologies available to provide and control it.
9. PQR is a central feature of many, if not all, of the microgrid demonstrations underway in the U.S. and internationally. Review of experience with these aspects is required.
10. Need analysis on the impact that a smart grid will have on the number, duration, and extent of outages.
11. Need analysis on the outages prevented by and negative impacts that were avoided by smart grid.

3.4.5.4. Energy Efficiency Analysis

1. Better understand end-user behavior and motivation for energy efficiency program administration and implementation with regard to related smart grid capabilities. This includes:
   a. Better, timely information (synergy with demand response programs), M&V, diagnostics.
   b. The level of persistence to expect from the energy efficiency gains in these areas.
   c. The uncertainty in the estimated range of energy efficiency benefits thus far investigated.
   d. The regional potential and expectations for energy efficiency from smart grid.
   e. Application of behavioral economics and choice architectures for end-user participation.
2. Technology contributions have been considered in isolation. Study the synergistic aspects of combining technologies for energy efficiency contributions. For example, demand-response technology or PEV integration might also provide feedback to the end user to improve energy efficiency.
3. Analyze the effectiveness of various diagnostic techniques based on information likely to come back from demand response and advanced metering programs. What data are sufficient to support basic diagnostics and what is the most important additional information that can improve diagnostics? Evaluate localized diagnostic approaches with remote diagnostic services.
4. Study scenarios for smart grid deployment (time and cost/benefit) to achieve energy efficiency.
5. Examine the business and regulatory policy issues (money, risk, incentives) that if addressed, can help achieve greater energy efficiency with smart grid technology investments.
6. What are the reasonable levels of penetration of smart grid capabilities to achieve energy efficiency over time? We cannot assume 100% of smart grid-related assets in any or all categories. What is reasonable in each energy efficiency area?

3.4.5.5. Operational Efficiency Analysis

1. Ancillary services cover a number of contingencies.
   a. What kind and size of ancillary services to be potentially met with demand side resources will scale appropriately? Are there minimum penetration levels of demand-side resources needed to participate in practical ancillary service roles (identify penetration relative to functional sub-distribution system levels)?
   b. What resource characteristics or combinations are needed for practical mitigation of supply-side resource inadequacy; response rates, duration of availability, capacity and available energy, VAR conditioning, transient ride-through capability, and so forth?
2. For specific demand-side power resource technologies operating as local and exporting to distribution grid power devices (e.g., PV, combined heat and power prime mover, grid interactive PEV, and others), investigate distribution system operational benefit and economic valuation methodologies. For instance, determine methods to quantify system benefit and value that accrues to others on the same feeder or the system as a whole for voltage support, phase angle correction, transformer longevity, etc.

3. Distributed generation resources with variable output and potentially high penetration rates (PV, wind) will add new ancillary power needs. What is the effectiveness and efficiency of using demand management resources to enable variable generation additions to the system?
4. Investigate ability to use meter and distribution system information to diagnose key system equipment maintenance needs and imminent failure potential.
5. Investigate ability to use distribution system information to identify and report specific failure mode, location, and concurrent subsequent equipment failures for distribution-level loss of load incidents.
6. Investigate efficiency gains for automatic crew and equipment call-up report creation based on fault and damage assessment. Identify minimum repairs needed before re-energizing circuit.
7. How can distribution automation and distributed energy resources be engaged to reduce power losses in the delivery system?

3.4.5.6. Clean Technology Analysis

1. Can distributed energy resources provide support to enable the integration of variable energy from renewable resources (e.g., fast scheduled energy and ancillary services)?
   a. Consider the characteristics and contributions from distributed energy storage, generation, and demand response
   b. Given the variety of distributed energy resources, are there sufficient levels of these resources to support the integration of renewable resource generation? Note the regional aspects of renewable generation and DER when trying to address such questions.
2. How can T&D automation through monitoring and reconfiguration better enable the integration of renewable variable energy resources?
3. How will the deployment of high-penetration renewable energy resources impact power system stability (also see PQR section above)?
4. How can distributed energy resources and T&D automation facilitate the high penetration of PEVs? What are the environmental benefits?
5. What is the impact of PEV penetration on the ability to address high penetration of renewable resources?
6. How can smart grid capabilities help achieve and adapt toward an optimal mix of renewable and non-renewable resources to meet our energy needs?
7. What operation strategies can be employed to effectively manage variable resource integration?
8. How does the effective integration of clean technology change in various areas of the country?

3.4.5.7. Economic/Business Environment Analysis

1. Examine the business and regulatory policy issues (money, risk, incentives) that if addressed, can help achieve greater consumer participation.
2. Analyze the effectiveness of various business models. Investigate scenarios for smart grid deployment (time and cost/benefit) to achieve sustainable businesses. What are the savings and intangible benefits associated with smart grid? To whom do these benefits accrue?

3. Develop various market designs (urban vs. suburban vs. rural). Evaluate their benefits and assess potential risks to consumer acceptance.
4. Regional energy markets have been considered in isolation. Study the synergistic aspects of a national policy and the effect of demand response deployment on regional electricity prices.

3.4.6. Milestones

The milestones for each analysis area discussed above are presented in the table below. The timeframes for completion are indicated as near (1-2 years), mid (3-4 years), long (5 years and beyond), and ongoing (analysis on the same topic expected periodically, such as tracking deployment progress).

Near Term (1-2 years)

- Ensure effective access and use of measurement data from implementations and experiences, including ARRA-funded projects.
- Support effective cyber security, information privacy, and interoperability practices.
- Determine potential smart grid-facilitated capacity amounts from demand response, distributed generation, and improved asset utilization.
- Develop structures and procedures for PQR data collection to support PQR analysis.
- Conduct international comparisons of delivered PQR and experience of smart grid & microgrid demonstrations.
- Analyze the PQR risks posed by cyber vulnerability.
- Determine synergistic aspects of combining technologies for energy efficiency contributions.
- Determine necessary penetration levels of smart grid capabilities to achieve energy efficiency over time.
- Support T&D system failure and maintenance diagnostics using smart grid information.
- Determine effectiveness of demand response and distributed generation & storage to mitigate impacts of renewable-resource variability issues, including system stability.
- Analyze sensitivity of PEV penetration to improve environmental impacts under varying assumptions of smart grid deployments for demand response and T&D automation.
- Examine the business and regulatory policy issues (money, risk, incentives) that if addressed, can help achieve greater consumer participation.
- Analyze the effectiveness of various smart grid business models.

Mid Term (2-3 years)

- Analyze the ramifications of smart grid on T&D and generation planning.
- Analyze localized capacity issues (distribution grid congestion, behind-the-meter capacity impacts) and use of locational marginal price incentives at distribution level.
- Analyze PEV capacity interactions with smart grid.
- Analyze and categorize the PQR requirements of end uses and intra-end-use loads.

- Analyze the PQR lessons of ARRA demonstrations and investment grants.
- Analyze end-user behavior and motivation for energy efficiency program administration and implementation.
- Analyze scenarios for smart grid deployment (time and cost/benefit) and the business & regulatory policy issues to achieve energy efficiency.
- Characterize variable DER (e.g., renewable resources, PEV charging) accommodation using demand-side resources.
- Characterize the impact of DER and distribution automation to reduce losses.
- Analyze the impact of T&D automation on integrating high penetration of variable renewable resources with coordinated use of distributed energy resources.
- Analyze potential of PEV charging and discharging to enable high penetration of variable renewable resources.
- Develop various retail market designs (urban vs. suburban vs. rural), and evaluate their benefits and assess potential risks to consumer acceptance.

Long Term (5+ years)

- Analyze long-term infrastructure changes in generation, transmission, and distribution due to smart grid.
- Analyze smart grid implications to the interactions and dependencies between the electric infrastructure, the communications networks, and other infrastructures (gas, water, transportation, etc.).
- Determine effectiveness of various diagnostic techniques using field information from demand response and advanced metering.
- Characterize DER use in provision of ancillary services.
- Develop an analysis framework for review of optimal mix of renewable and other resources to meet the nation's energy needs using smart grid capabilities.

Ongoing

- Report progress of smart grid deployments.
- Analyze end-user behavior and acceptance of demand response, on-site generation, PEV, and storage.
- Estimate costs and benefits of PQR.
- Examine the PQR consequences of upcoming system changes: load growth (including EVs), high renewable resources penetration, restricted supply expansion, etc.
- Inform policy makers of savings and intangible benefits associated with smart grid and to whom these benefits may accrue.

3.5. Evaluation & Demonstrations

The Evaluation and Demonstrations topic area focuses on assessments and experiments of state-of-the-art technology areas and incentive programs that are indispensable for achieving the full potential of the smart grid. Evaluation and demonstrations will be from the perspective of distribution system interaction with the rest of the electric power system. The scope includes fundamental requirements of existing distribution systems and how these systems need to evolve in terms of new functions and requirements to facilitate smart grid concepts. For instance, evaluation and demonstrations will be used to determine how the existing system with mostly inactive devices in the distribution system should evolve to one in which the distribution system plays a much more active role in supplying local and reactive power to support and integrate with the transmission system. The scope of this topic area will also cover characterization of external interfaces with the transmission system, system pricing markets, EPS operators and local customers, and smart, demand-responsive loads. In the future smart grid, high-speed and time-synchronized data measurements will enable faster control for responding to transients and disturbances and providing information on the dynamic state of the system and how it corresponds to the transmission system. Thus, required technologies will involve those that directly control power and voltage, as well as those that measure system parameters and provide communication and control functions.

In addition, a broad and open sharing of lessons-learned should occur. There will be a wealth of information that will be coming out of the ARRA projects. Significant value can be achieved by documenting and sharing information about these projects in a consistent manner, using a consistent methodology to report on various topics. A scientific process will be used to compare and evaluate technologies, consumer behavior, and costs, benefits and general lessons learned across a broad range of projects.

Evaluation and demonstration activities are closely coupled with other areas of the MYPP. Evaluating and demonstrating smart grid components and systems will meet the high level vision and goal of the OE Smart Grid R&D Program. Innovative components and systems will be evaluated in terms of emerging standards and best practices and future smart grid needs towards achieving interoperability between technologies. Test data gathered from the ARRA smart grid investment grants and demonstrations will be used in smart grid analysis to evaluate performance gains with smart technologies, areas for improvement and to calibrate and validate software models for new methods and technologies.

Evaluation and demonstration activities must be prioritized to provide the greatest value at the lowest funding investment to the OE Smart Grid R&D Program and the industry. Evaluation and Demonstration will be focused on the evaluation and assessment of key projects (technical and market-incentive based) to leverage existing contributions and capabilities and will identify new complementing activities and capabilities. Projects to concentrate on include: 1) Investment Grant projects, 2) Demonstration projects, 3) other DOE sponsored projects and components under Research and Development, 4) relevant projects and components “by others” (states, utilities, manufacturers, industry, etc.) and 5) ongoing projects by the national laboratories. Evaluation and demonstration activities should address important existing and new R&D issues

and determine key application areas for future research and testing. Of particular importance is the need to identify gaps in existing technologies and processes that could limit successful, cost-effective roll-out of smart grid systems or gaps related to smart grid functionality. This chapter will identify a set of high-impact activities where Federal R&D efforts can address barriers and technology gaps, and help bring about or accelerate significant technology advancements and implementation through evaluation and demonstration.

3.5.1. Technical Goals and Objectives

The technical goals and objectives are:

1) Characterize the performance of smart grid systems and components throughout the distribution system: from the substation to the end-user loads. Smart appliances will impact end-user loads in terms of providing load relief, spinning reserve, etc., so this will also be relevant to the area. Large penetrations of responsive loads could free up central generators for providing spinning reserve.

   Including but not limited to:

   - Smart meter systems (AMI)
   - Home area networks
   - Information and communication architectures
   - Smart appliances
   - In-home energy management systems
   - Smart building energy management capabilities
   - Demand response programs
   - Distribution automation technologies (e.g., advanced protective relays, automated switches, etc.)
   - Dynamic monitoring and control interfaces to PMUs
   - Distributed energy resources technology: generators and energy storage at the 5 kW to MW levels, including inverters, controllers, and interface technologies (Balance of Systems)
   - Intermittent renewable generation systems
   - Vehicle charging management and other systems for PEV/EV
   - Communication and software systems and other smart grid industry products

2) Verify and validate intended functionality, requirements, etc. under various modes of operation and in various scenarios. Identify performance gaps in terms of areas of improvement.
3) Develop protocols and methods for testing and evaluating new components and systems.
4) Develop and document capabilities for testing and evaluation.
5) Develop generic methods and procedures for predicting the success of various projects based on demonstrable, definable, and repeatable metrics. This could be of value to projects that are in process and new ones for the future.
6) Evaluate performance and compare to expectations and baselines; identify gaps.

7) Develop and maintain a financial and technical performance results database accessible by utilities to provide proof points to assist with building business cases and encourage them to invest in the highest payback opportunities.
8) Build simulation models that are an accurate representation of technology performance as demonstrated in tests to enable evaluation beyond testing capabilities.
9) Adaptive protection will be needed to accommodate the future distribution system for the short-circuit variations due to distributed resources especially.
10) Develop human factors tools and methods for improved operator understanding and actions.

3.5.2. Technical Challenges

Because of the diverse and nascent nature of smart grid equipment and processes, it will be challenging to create standardized or effective tests in this domain. Many of the testing processes will evolve and set standards once they have achieved some level of maturity. Many of the projects associated with evaluation and demonstration described here are either in process or not started. Furthermore, gathering test data from ARRA smart grid investment grants and demonstration projects may be difficult unless explicitly defined in the scope of work and data design for those projects. Even so, some data that may be determined later to be necessary may not be available. NERC CIPs may restrict some of the data that is needed. Therefore, synthetic data via simulation routines may be needed to fill the data gap. The challenge will be coming up with good methods and models to create such data, possibly through test systems.

3.5.3. Technical Scope

Evaluation and demonstrations will apply to:

1) *Integrated Two-Way Communication*s make the smart grid a dynamic, interactive, real-time infrastructure. It will provide active monitoring and control and determination of dynamic states based on time-synchronized phasor measurements, line and equipment sensors, and load measurements. This should lead to better tracking of the system state as well as development of models. An open architecture creates a "plug-and-play" environment that securely networks grid components and operators, enabling them to talk, listen, and interact. The smart grid is expected to lead to more automatic controls and operations that are too fast for an operator in the loop.
    - High-speed data communication and control system to the electric distribution system and AMI networks
    - Radio frequency
    - Fiber optic
    - Power line communications
    - Broadband and narrowband
    - AMI smart meter communication networks (WAN)
    - AMI home area networks, including SEP2.0

- SCADA
- In-home smart communication systems
- In-home energy management services
- Smart building energy management capabilities

2) *Advanced Components* play an active role in determining the electrical behavior of the grid, applying the latest research in materials, superconductivity, energy storage, power electronics, and microelectronics to produce higher power densities and greater reliability and power quality. This is especially true for power electronics that have thermal management limits with current silicon-based technologies. Silicon carbide is an example of a new material that can offer improved efficiency and capacity while reducing thermal management requirements.
3) *Advanced Control and Measurement Methods* monitor power system components, enabling rapid diagnosis and timely, appropriate responses to any event ranging from a voltage transient due to a load change to a severe fault that activates protection schemes. Additionally, they also support market pricing, enhance asset management, and efficient operations.
4) *Sensing and Measurement Technologies* enhance power system measurements and facilitate the transformation of data into information to evaluate the health of equipment, support advanced and adaptive protective relaying, rapid restoration for an event, enable consumer choice and interaction in the market and help relieve congestion, leading to more reliability and efficiency.
5) *Improved Interfaces and Decision Support* will enable grid operators, managers, and computers to make more accurate and timely decisions at all levels of the grid, including the consumer level, while enabling more advanced operator training.
6) Technologies, applications, and domains of focus:
   i) Smart grid/AMI technologies, including:
      - Smart meters, thermostats, appliances
      - Conductor technology and overhead vs. underground
      - DC vs. AC distribution
      - Distribution automation equipment
      - Large-scale DER technology (PV inverters, generators, and both small and large scale energy storage)
      - Vehicle charging management and other systems for PEV from individual residential through local clusters to regional levels with applications for pricing, billing, vehicle-specific metering, and mitigating exposure from clustered charging and peak use.
      - Associated software and IT systems and processes including demonstration at central offices and data centers with large battery stores and generating capacity.
        - Deployment
        - Commissioning
        - Operations
        - Billing

        - Applications
        - Decommissioning
    ii) Applications and features, including:
        - Dynamic and time-of-use electricity pricing
        - Automated demand response
        - Direct load control
        - Customer portal
        - Distribution management system
        - Outage management system
        - Improve system reliability and energy resource optimization
        - Equipment monitoring and diagnostics (such as circuit breaker operations, transformer loading)
        - Maintenance triggered by monitoring information and reduce system maintenance costs
        - Automate high-load distribution circuits
        - Improve voltage regulation and imbalances, power quality
        - Local reactive power and voltage support, power factor management
        - Minimize overload on distribution lines, transformers and feeder segments
        - Reduce system line capacities and current flows to limit unnecessary power generation and energy loss
        - Self-healing properties (automatic distribution reconfiguration)
        - Interfaces to transmission systems and support of transmission such as voltage stability
            - Synchrophasor measurement units
            - Real-time situational awareness systems
            - Wide-area situational awareness linked to weather, traffic, and other data systems
    iii) Ratepayer types
        - Commercial and industrial
        - Residential
        - Agriculture
        - High power-quality users vs. lower power-quality users
7) DOE research and development: Systems and components
    - DER technology (PV inverters, generators, and both small and large energy storage)
    - Power conversion/power electronics (e.g., FACTS, smart switches, smart rectifiers)
    - Advanced controls technology (EMS, wide area controls, intelligent algorithms)
    - Sensing and measurement (e.g., PMUs, low-cost sensors)
    - Materials (advanced conductors, etc.)

- Decision and management tools for integration of DER into SCADA/EMS
- Energy storage subsystems (distributed, neighborhood [kW] and substation [MW] scale; mobile and stationary)
- Load components (e.g., intelligent appliances, intelligent lighting, variable frequency drive on air conditioning, building energy management systems, monitoring of load degradation)
- Communication infrastructure (reliable, secure, authorized access, high bandwidth, low power)
- Microgrid architecture, control and protection
- Building-scale integration
- PHEV-to-grid infrastructure
- Telecom demand-response control system

8) Process and industry interaction to determine performance metrics
9) Methods to determine relevant testing and compliance criteria for a given project or demonstration.
10) Methods to evaluate compliance with testing criteria.
11) Methods to document results (per defined criteria).
12) High level evaluations of performance, relevant applications, etc. (expert analysis & insight beyond pre-defined criteria, e.g., system effects).

3.5.4. Status of Current Development

- There is ongoing expedited activity by NIST and other organizations to establish standards to "achieve interoperability of smart grid devices and systems…" [EISA Title XIII 1305].
- ARRA Investment Grants and Demonstration projects have been announced and are in the process of being awarded.
- Other DOE sponsored projects and components
- Relevant projects and components "by others" (states, utilities, region, ISO, RTO, etc.).

3.5.5. Technical Task Descriptions

1) Create documents and other deliverables that define processes to achieve goals outlined above. Develop strategy and methods for disseminating findings to stakeholders of all types.
2) Manage processes to achieve goals outlined above.
3) Evaluate projects, processes, and components based on their ability to meet the goals of improving smart grid system value streams discussed in the *Analysis* chapter.
   i) Capacity:
      (a) Shape demand curve with effective participation by end-user resources (load, generation, storage) in system operations (dynamic rates, markets, etc.).

(b) Enable broad range of generation resources integration.

ii) Power Quality & Reliability:

(a) Flexible (adaptable, reconfigurable, restorable) electricity infrastructure for

- Range of generation scenarios
- Outage/attack risks, including physical and cyber security vulnerability and mitigation
- Response to disturbances including graceful degradation and system restoration (islanded operability, black start, etc.)

(b) Enable stable physical system and wholesale market operation, including the coupling of their dynamic interactions.

(c) Characterize opportunities and potential of dispersed resources (including microgrids, more localized electricity hubs, and building systems) for better targeting of PQR.

(d) Discern customer, end-use, and intra-device PQR requirements.

(e) Investigate benefit of "application-specific" reliability (lower than 0.999).

(f) Reduction of harmonics and imbalances with new technology.

iii) Energy Efficiency:

(a) Measured data to ensure energy efficiency programs work

(b) Continuous diagnostics to detect inefficient operation or behavior or equipment degradation

iv) Operational Efficiency:

(a) Effective use of distributed generation, distribution and substation storage, demand response and distribution automation

(b) Increase infrastructure load factor

- Provide ancillary services
- Reduce cost for wholesale and retail operations by efficient coordination of resources

(c) Responsive loads and appliances to provide ancillary services (such as frequency and voltage regulation) locally instead of depending upon the generation and transmission system to improve overall power system operational efficiency

v) Clean Technology:

(a) Enable high penetration of distributed renewables at distribution level and below, especially those that are clean sources of power.

(b) Enable PEV benefits for emissions reduction, especially in high population urban environments such as those identified by the EPA.

(c) Manage environmental consequences of load growth, including impact of trees on overhead lines and water availability for generation plants.

vi) Foundational/Crosscutting

(a) Assess progress of smart grid deployments and investments.

(b) Assess effectiveness of cyber security and information privacy practices accepted by industry.

3.5.6. Milestones

Milestones are listed in terms of near-, mid-, and long-term objectives:

Near Term (1-2 years)

- Develop project prioritization methodology.
- Evaluate outputs from NIST priority action plan standards efforts.
- Evaluate current industry, laboratory, and government capabilities (testing).
- Conduct technology gap assessment.
- Select suitable project types.
- Assist in request for proposals development and execution.
- Gather preliminary data.
- Identify performance gaps in terms of areas of needed improvement, and base ranking on priority and required funding.

Mid Term (3-4 years)

- Verify and validate intended functionality, requirements, etc. under various modes of operation and in various scenarios.
- Develop protocols and methods for testing and evaluating new components and systems.
- Develop and document capabilities for testing and evaluation.
- Develop generic methods and procedures for predicting the success of various projects based on demonstrable and repeatable metrics. This could be of value to projects that are in process and new ones for the future.
- Evaluate performance and compare to expectations, baselines; identify gaps.

Long Term (5+ years)

- Provide feedback to existing projects.
- Provide suggested areas of high impact future R&D.
- Evaluate benefits to the full vision of the smart grid.

4. Program Management

4.1. Program Portfolio Management Process

Principal areas of program management that are integral to the Smart Grid R&D Program include:

- Portfolio development and management
- Communication of the program
- Analysis of the program
- Evaluation of the program
- Technology transfer

These management areas combine to assure that industry, the public, and government are effectively served by the Smart Grid R&D Program. This program follows a multi-step planning and management process designed to ensure that all funded technical R&D projects are chosen based on their qualifications in meeting clearly defined criteria. This process entails the following:

- Competitive solicitations for financial assistance awards and national lab RDD&D.
- Peer reviews of proposals in meeting the Funding Opportunity Announcement goals, objectives, and performance requirements.
- Peer reviews of in-progress projects on the scientific merit, the likelihood of technical and market success, the actual or anticipated results, and the cost effectiveness of research management. The Smart Grid R&D Program and its in-progress R&D projects will be reviewed through this external review process once every two years with evaluation results feeding back to program planning and portfolio management.
- Stage gate reviews to determine readiness of a technology or activity to advance to its next phase of development, pursue alternative paths, or be terminated; these readiness reviews will be conducted on an as-needed schedule based on project progression in meeting the established stage gate criteria.
- OE internal review of the Smart Grid R&D Program annually to ensure continuous improvements and proper alignment with R&D priorities and industry needs.

The value of R&D projects, individually and collectively, to achieving the Smart Grid R&D program goal and 2030 targets will be made transparent by applying this management process consistently throughout the Program. Moreover, this value that is supported by rigorous analysis and evaluation will be transparent in Program communications to the industry, the public, and other smart grid stakeholder organizations.

This MYPP will be used to guide ongoing projects and development of the Smart Grid R&D Program portfolio of projects for 2010-2014, and will be updated annually to reflect the current state of advances, priority needs, and resources availability. The Smart Grid R&D Program's base budget is $32M for FY10 and $39M annually is planned for FY11-14.

4.2. Performance Assessment

The OE defines the smart grid by seven performance-based functionalities; these functionalities will lead to achieving the Smart Grid R&D Program's four primary outcomes of reduced peak demand, improved operational and system efficiency, higher grid reliability and resilience, and lower carbon emissions and higher economic productivity from integration of more distributed and renewable generation. While the smart grid transformation is a continuing process, the Smart Grid R&D Program has defined a target goal for each outcome to support the OE's 2030 vision for grid modernization. The Smart Grid 2030 Targets are:

- 20% reduction in the nation's peak energy demand
- 100% availability to serve all critical loads at all times and a range of reliability services for other loads
- 40% improvement in system efficiency and asset utilization to achieve a load factor of 70%
- 20% of electricity capacity from distributed and renewable energy sources (200 GW)

The performance measures for the Smart Grid R&D Program and its portfolio of projects in support of each outcome/target goal are described below.

- **Peak demand reduction for system and energy efficiency:** Smart grid technologies of AMI, energy management systems, and grid-responsive devices and appliances coupled with dynamic pricing programs will enable informed consumer participation in demand response, as a key focus for peak demand reduction. Key performance measures include cyber security standards for smart metering to address security concerns at all stages of AMI deployments, development of smart appliances responsive to grid conditions and pricing signals, feasibility demonstration of peak demand reduction at select prototypical feeders, and an interim measure to track the progress trend toward the 2030 target.

- **Grid reliability & resilience:** Distribution/feeder automation, microgrid, and modeling tools will enable advanced distribution operations to reduce outage durations and frequencies, provide fast responses to outage events, and provide the differentiated reliability services to meet individual consumer needs. Key performance measures include simulation tool development and integration of models into an operational distribution management system for planning/outage management/customer information services, and feasibility demonstrations of advanced distribution operational designs (adaptive circuit reconfiguration, distributed energy storage, and microgrids) to provide differentiated reliability services and critical load protection.

- **Operational and system efficiency:** Dynamic sensing, monitoring, and control technologies will reduce energy losses and enhance utilization of available assets, all driving to improve the overall load factor. Key performance measures include a near-term reduction in line losses through conservation voltage reduction, smart chargers with grid awareness to charge PHEVs at off-peak periods according to customer choice, and diagnostic tools for condition-based maintenance to reduce the O&M costs.

- **Distributed and renewable energy integration for increased reliability, efficiency, and system security:** Standards, voltage regulation, and protection coordination schemes are critically important for high penetration levels (>15%, as a rule of thumb) of distributed generation into the grid. Key performance measures include development of voltage regulation conditioners to address variability of renewable generation, protection solutions at both the utility and customer sides for voltage rise under conditions where the distributed generation capacity exceeds the connected loads, and DC distribution architectures for buildings or communities to connect DC generation sources directly with DC loads.

The long-term goal of the Smart Grid R&D Program is to develop an integrated, national electric/communication/information technology infrastructure with the ability to dynamically optimize grid operations and resources and incorporate demand response and consumer participation. The Smart Grid R&D Program will apply consistent methodology to quantify smart grid benefits annually in terms of grid reliability, operational efficiency, distributed and renewable electricity generation, and peak demand and carbon emission reductions in support of the Smart Grid 2030 Targets.

Appendix 1: Acronyms

Acronyms	Meaning
AM/FM	automated mapping/facilities management
AMI	advanced metering infrastructure
ANSI	American National Standards Institute
ARRA	American Recovery and Reinvestment Act of 2009
CIP	critical infrastructure protection
CVR	conservation voltage reduction
DER	distributed energy resources
DMS	distribution management system
DOE	Department of Energy
DR	demand response - the adjustment of end-user loads based on communications between the end-user and the service provider or markets
EE	energy efficiency
EIA	Energy Information Administration
EISA	Energy Independence and Security Act of 2007
EMS	energy management system
EPA	Environmental Protection Agency
EPRI	Electric Power Research Institute
EPS	electric power system
FACTS	flexible AC transmission systems
FCC	Federal Communications Commission
FERC	Federal Energy Regulatory Commission
GIS	geographic information systems
GW	gigawatt
HAN	home area network
HVAC	heating/ventilating/air conditioning
IEEE	Institute of Electrical and Electronics Engineers
ISO	independent system operator
LBNL	Lawrence Berkeley National Laboratory
LSE	load serving entity
M&V	measurement and verification

Acronyms	Meaning
MW	megawatt
MYPP	multi-year program plan
NERC	North American Electric Reliability Corporation
NETL	National Energy Technology Laboratory
NIST	National Institute of Standards and Technology
OE	Office of Electricity Delivery and Energy Reliability
PEV	plug-in electric vehicle (includes hybrids and all electric vehicles)
PHEV	plug-in hybrid electric vehicle
PHM	prognostic health management
PMU	phasor measurement unit
PNNL	Pacific Northwest National Laboratory
PQR	power quality and reliability
PUC	public utilities commission
PV	photovoltaic (solar power)
R&D	research and development
RTO	Regional Transmission Organizations
SCADA	supervisory control and data acquisition
T&D	transmission and distribution
VAR	volt-ampere reactive (reactive power)

Appendix 2: Smart Grid Roundtable Attendance List

Bud Beebe, Sacramento Municipal Utility District
Gilbert Bindewald, U.S. Department of Energy
Steven Bossart, National Energy Technology Laboratory
Kourosh Boutorabi, Teridian Semiconductor
Jay Cappy, Verizon
Hon. Paul Centolella, Ohio Public Utility Commission
Frances Cleveland, Xanthus Consulting International
Don Cortez, CenterPoint Energy
James Crane, ComEd
Jennifer Downes-Angus, Energetics Incorporated
Abraham Ellis, Sandia National Laboratories
Greg Fasullo, Lineage Power
Steven Hauser, National Renewable Energy Laboratory
Milton Holloway, Center for the Commercialization of Electric Technologies
John Kern, GE Global Research
Hank Kenchington, U.S. Department of Energy
Ben Kroposki, National Renewable Energy Laboratory
John Kueck, Oak Ridge National Laboratory
Eric Lightner, U.S. Department of Energy
Chris Marnay, Lawrence Berkeley National Laboratory
Terry Mohn, BAE Systems
David Mooney, National Renewable Energy Laboratory
Terri Oliver, Bonneville Power Administration
Rob Pratt, Pacific Northwest National Laboratory
Stewart Ramsay, Consultant
Bob Saint, National Rural Electric Cooperative Association
Rich Scheer, Energetics Incorporated
Le Tang, ABB Inc.
Dan Ton, U.S. Department of Energy
Juan Torres, Sandia National Laboratories
Wade Troxell, Colorado State University
Don Von Dollen, Electric Power Research Institute
Matt Wakefield, Electric Power Research Institute
Joe Waligorski, FirstEnergy
Bruce Walker, National Grid
W. Maria Wang, Energy & Environmental Resources Group, LLC
W-T. Paul Wang, Energy & Environmental Resources Group, LLC
David S. Watson, Lawrence Berkeley National Laboratory
Steve Widergren, Pacific Northwest National Laboratory