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Measurement Challenges and Opportunities for Developing Smart Grid Testbeds

Summary Report

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Thanks are extended to the NIST organizers as well as the speakers and panelists who provided their insights on the smart grid problems and challenges that can be potentially be addressed through testbed demonstrations. We also appreciate the extensive contributions of the participants listed on the following page; this report would not be possible without their valuable insights. Finally, thanks are extended to the Energetics Incorporated team for their assistance in facilitating the workshop and preparing this report.

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TABLE OF CONTENTS

1. INTRODUCTION

Smart grid tools and technologies implemented in the electrical grid infrastructure enable bidirectional flows of energy and communication. These new capabilities can lead to improved efficiency, reliability, interoperability, and security. Smart-grid-related technology and services have been growing rapidly and are forecasted to double between 2009 and 2014 to nearly $43 billion in the United States and to more than $171 billion globally.[1]

The Energy Independence and Security Act (EISA) of 2007 outlined a strategy for developing a domestic smart electric grid through modernization of the U.S. electricity transmission and distribution system.[2] A public investment of $4.5 billion was later authorized by the American Recovery and Reinvestment Act of 2009 (ARRA) for electricity delivery and energy reliability activities to modernize the electric grid and implement demonstration and deployment programs (as authorized under Title XIII of EISA).[3] Private entities were to match this public investment with a 50% cost share.

Since the authorization of EISA and subsequent legislation, substantial progress has been made toward a national smart grid through research, development, and demonstration (RD&D) of new technologies and cyber-physical systems (CPS). CPS have tightly coupled computational (cyber) and physical components with highly integrated intelligence. These can be relatively simple (e.g., a heater, cutting machine) or comprise multiple components in complex assemblies (e.g., vehicles, aircraft, intelligent buildings). The emerging smart grid will be a highly interconnected CPS with significant enhancements to the sophistication and diversity of control, communications, and power systems technologies. This will enable greater and more efficient integration of renewable energy, distributed resources, and demand response.

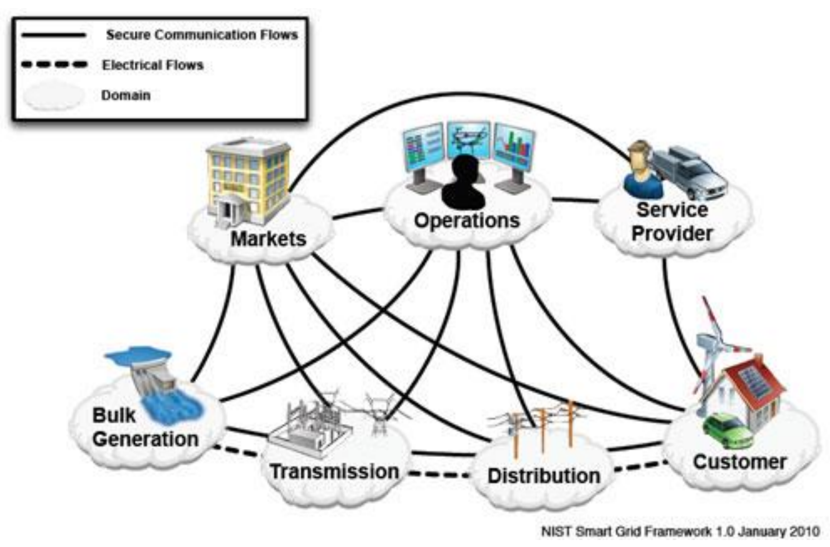

Image: NIST Smart Grid Framework 1.0

Technology plays a key role in the realization of the future smart grid. While many technologies are proven to work well independently, when they are combined into a smart grid cyber-physical system many unexpected behaviors can occur. Creating a resilient, reliable, and safe smart grid thus requires the capability to test how systems perform and interact prior to deployment in practical operating environments. Realistic test environments can fill this role.

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[1] Zpryme Research and Consulting, "Smart Grid: United States and Global Hardware and Software Companies Should Prepare to Capitalize on This Technology," December 14, 2009, http://zpryme.com/news-room/smart-grid-united-states-and-global-hardware-and-software-companies-should-prepare-to-capitalize-on-this-technology.html.
[2] Energy Independence and Security Act of 2007 [Public Law No: 110-140].
[3] The White House, "American Recovery and Reinvestment Act: Moving America Toward a Clean Energy Future," February 17, 2009, http://www.whitehouse.gov/assets/documents/Recovery_Act_Energy_2-17.pdf.

1.1. Role of Testbeds and Measurement in the Smart Grid

Testbeds are essentially platforms for the rigorous and replicable testing of theories, computational tools, new technologies, and systems. The testbed (TB) provides a development environment without the potential hazards or consequences present when testing in a live production environment. A testbed can be used to demonstrate new components or entire systems, and can include software and hardware/physical equipment as well as networking components.

Testbeds are especially important for evaluating performance and identifying any potentially adverse behaviors of interacting cyber-physical systems – before technologies are deployed in the smart grid. Smart grid testbeds can demonstrate “hardware-in-the-loop” and integrated cyber capabilities by combining real, simulated and emulated components or systems, creating an effective simulation of complex cyber-physical interactions in the power system. A list of selected testbeds operating today is provided in Appendix A.

Smart grid testbeds benefit technology vendors, system owners (e.g., utilities), R&D institutions, and even regulatory agencies. The realm of scenarios and technologies that can be demonstrated in testbeds is broad, ranging from assessment of smart meters and data to defense against cyber-attacks. For example, testbeds are key to identifying and resolving potential security issues. It is preferable to explore potential system vulnerabilities in a protected testbed environment without real-world consequences. Alternatively, new risk assessment techniques and security paradigms can be designed and tested using simulated real-world environments.

Vendors of next-generation smart grid products benefit from testing and validation in testbeds, as this allows greater assurance in system design and operation. New systems must also be interoperable, i.e., able to interact with a range of other products with disparate interfaces and configurations, and testbeds can provide a suitable platform for this purpose.

Utilities use testbeds to demonstrate integration of new technologies with existing systems and sometimes train employees on their use. Testbeds can also be used to help utilities demonstrate levels of system assurance and security with new technologies or integrated systems.

Measurement science and standards play a key role in testbeds related to the smart grid. They can be used to test performance and other measurements and ensure effective communication and interoperability of the equipment connected to the grid and the infrastructure that serves the grid. There are also numerous measurement and standards challenges related to key grid technologies (e.g., power electronics, power metering, and energy storage) where testbed environments can be valuable.

NIST Smart Grid Testbed Facility

The NIST Smart Grid Testbed Facility will create a unique set of interconnected and interacting labs in several key measurement areas contiguously located on the NIST Gaithersburg Campus. The facility will accelerate the development of SG interoperability standards via a combined testbed platform for system measurements, characterization of smart grid protocols, and validation of SG standards, with emphasis on microgrids. Measurements will include: power conditioning, synchrophasor metrology, cybersecurity, precision time synchronization, electric power metering, modeling and evaluation of SG communications, sensor interfaces, and energy storage. The testbed will also address measurement needs of the evolving SG industrial community including the measurement and validation issues.

Smart Meter, Photo courtesy NIST

1.2. Scope and Methodology

Dedicated Smart Grid Testbeds (SG TBs) are being developed by industry, academia, and government laboratories to characterize smart grid equipment and systems and validate smart grid performance and standards. At this nascent stage, much remains to be done to develop a shared understanding of needs, opportunities, and approaches for integrating testbed design and operation to achieve the full potential of the evolving smart grid. This report focuses on the desired capabilities, challenges, and approaches for the implementation, federation, and use of testbeds.

To further understand opportunities for testbeds and to guide efforts in testbed design, NIST conducted a workshop on the *Measurement Challenges and Opportunities for Developing Smart Grid Testbeds* on March 13-14, 2014 in Gaithersburg, Maryland. Testbed owners/operators and other key stakeholders from industry, utilities, academia, and the national laboratories were invited to participate and provide their expert views on testbed capabilities, needs, challenges, and opportunities.

By design, the workshop was consensus-seeking rather than tutorial. Discussions were focused around the three breakout areas shown below, along with the pre-defined set of topic questions posed to each group.

- *Smart grid measurement and characterization problems not currently addressed by TBs*
  - What are the key smart grid problems that require test beds? What test beds are out there now? Are these sufficient for testing what is required, and what needs to be expanded/ improved, etc.?
  - What are the specific challenges for developing and operating the important and enabling SG TBs that have been identified?
  - What actions and approaches are needed to address challenges and develop / expand SG TBs to meet needs?
- *Key attributes and design elements of composable/modular SG TBs*
  - What are the ideal elements and components of composable, modular test bed architecture? (i.e., if we want to be able to build and deconstruct test beds easily)? What are the key characteristics desired for a composable, modular test bed architecture?
  - What are the key barriers to developing composable / modular TBs with the characteristics that have been identified?
  - What actions and pathways are needed to develop composable/modular test beds?
- *Design elements/considerations for interconnected SG TBs*
  - What strategies for testbed interconnection should/be implemented or explored?
  - What are the challenges and barriers that limit development of interconnected cross-sector SG TBs?
  - What actions and pathways are needed to pursue interconnected SG TBs?

The consensus-seeking process that was employed is outlined in Figure 1.1. To set the stage, the process was preceded by visionary presentations and panel discussions with experts in the field. Participants then progressed through a series of brainstorming and discussion sessions, culminating in a consensus voting process to identify key actions going forward.

Figure 1.1. Workshop Process

- A series of brainstorming and prioritization sessions were guided by a third party facilitator, with all parties fully engaged.
- Pre-defined topic questions were posed to each breakout group; ideas and concepts were generated and captured in real-time.
- A voting process was used to identify relative importance of TB challenges and opportunities identified by the group; participants were asked to place votes based on the criticality and urgency of the problem to be addressed by TBs and the overall impact on smart grid development/deployment.
- Interactive small group sessions were employed to develop action pathways for the most important TB concepts identified for each topic area; action plans include:
  - Identification of specific barriers/measurement problems to be addressed by the TB solution
  - R&D needed
  - Performance targets, i.e., what the TB should be able to do
  - General outcomes, milestones and timing
  - Benefits, advantages, and impacts on the smart grid
  - Potential stakeholders that should be involved and their roles

The challenges, opportunities, and priorities identified during the March 2014 workshop provide the foundation for this report. Of particular importance are the priority testbed scenarios found in each chapter; these represent some of the most critical SG TB concepts identified for development. Appendix B provides a list of the acronyms and abbreviations found throughout the report.

It is hoped that this report will help (i) build a coordinated smart grid testbed agenda for industry, government, and academia; (ii) identify and remediate strategic gaps in smart grid efforts that could impede progress; and (iii) provide an understanding of the important role of testbeds in the development and deployment of smart grid technologies and systems. NIST will also use the information to guide future research programs in this area and in particular the design of its Smart Grid Testbed Facility.

Note that the ideas presented here are a reflection of the attendees and not necessarily the entire industry. As such, they should be viewed as a good snapshot of the important perspectives but not all-inclusive. The participants were carefully selected based on their high level of technical knowledge related to smart grid technologies and systems and are considered experts in the field.

2. Testbeds to Support Smart Grid Measurement and Characterization

Smart grid tools and technologies enable bidirectional flows of energy and communication for a more efficient, reliable, and secure grid. Testbeds are essential for supporting the rapid development and implementation of smart grid technologies, including development of new devices and software. Testbeds supports smart grid measurement and characterization, which are important enablers of effective communication and interoperability of new smart grid equipment and the infrastructure that serves the grid. Testing also validates the interoperability of heterogeneous technologies for a particular purpose, and helps identify best configuration practices, increasing stakeholder confidence and enabling SG adoption.

Proper testing of equipment, processes, and software in testbeds is essential before smart grid technologies are deployed. Testing helps ensure problem-free integration of new smart grid tools and technologies into existing systems. Testing and development of innovative smart grid technologies are conducted in more than two dozen testbeds currently in-use across the country, but most of them are not focused on measurement and characterization problems. Additional approaches are needed to help testbeds better characterize the smart grid and test a complete spectrum of performance parameters.

2.1. Smart Grid Improvements Enabled by Testbeds

New smart grid tools, software, and equipment are rapidly developing and being deployed into the nation's grid systems. Testbeds have played an important but limited role in the technology developments now in place. Over the next five years, testbeds are expected to be a central enabler of breakthrough improvements to smart grid systems. It is imperative that new technologies perform as expected when deployed; increasingly more sophisticated testbeds will be used to ensure that they can be integrated without disrupting existing systems and help users realize the benefits of a better integrated smart grid. A higher success rate for smart grid RD&D will be possible through testbed validation and testing of new concepts. Table 2.1 highlights specific smart grid improvements that are anticipated to be deployed or partially-deployed over the next 5 years, and where testbeds could play a role.

Table 2.1. Expected Smart Grid Improvements Over Next 5 Years
Stakeholder Engagement
• Improved coordination with stakeholders, including policymakers, utilities, and consumers, during the development and use of testbeds, such that technologies are developed and designed to better meet SG goals
Hardware, Sensors, and Control
• Broad deployment of sensors producing data that enable automated dispatch and control for electricity distribution • Real time control that allows for better energy management and superior demand-response
Grid Integration
• Deployment of grid infrastructure that eases integration of new technologies and systems with the legacy grid • Integration of energy storage systems and distributed generation capacity into the grid, enabling peak power requirements to be smoothed out and/or met at the distribution scale and closer to the load, increasing efficiency • Seamless integration of renewable energy generation into the grid without system instability

Table 2.1. Expected Smart Grid Improvements Over Next 5 Years

Reliability/Stability

- Increased reliability of grids due to shorter response times or use of automated responses with the goal of having no extended power outages
- Improved reliability through integration and independence of microgrids through the use of real time automation and control technologies
- Improved reliability of devices with regard to electromagnetic disturbances that are enabled by updated standards and testing
- Increased stability of a utility dispatch system by analyzing real time data obtained from micro-grids
- Grid resilience incorporated into design stage of development that enables further distributed generation rather than unidirectional generation
- Technologies developed that provide better predictive control to help detect, prevent and mitigate instabilities, including developing methods for measuring and controlling system instabilities

Information Sharing/Communications

- Improved data and information provided to utilities that facilitates better decision making and encourages higher environmental standards (e.g., sensors mounted throughout city that feed data back to utilities regarding types of electricity generators in use)
- Improved information sharing to foster local policies that encourage energy efficient practices
- Better flow of real-time information to consumers for optimal energy use and cost reductions
- Use of technologies and policies such as time-of-use pricing, critical peak pricing, peak time rebate that enables cost reductions

2.2. Specific Testbed Opportunities/Needs for Measurement/Characterization

There are a number of opportunities for testbeds to improve the pre-assured functionality of smart grid components and their secure, reliable, and safe operation. Smart grid innovations can be enabled through pre-integration development in testbeds that can enable researchers to identify and respond to integration issues earlier in the development process. Validation in testbeds can also reduce the costs associated with integrating new technologies in electricity systems. Some of the key testbed opportunity areas identified for measurement and characterization of SG concepts are outlined below.

Security

Security is one of the most critical needs for the future of smart grid development. Testbeds allow for the development and testing of the performance of advanced security mechanisms. This includes testing routine security as well as the performance and restoration of overall system security during/after outages or other events. The security of advanced data and communications hardware and software is an important issue and should be demonstrated prior to grid-wide adoption. As Advanced Metering Infrastructure (AMI) and Home Area Network (HAN) technologies are developed and become an integral part of our homes, businesses, and power supply, robust communication security is essential. Smart grids rely on information technologies (IT) for daily operations, which security is vital. In the case of a smart grid technological malfunction, secure processes need to be in place to ensure quick, successful solutions, including default transitions and 'system restore' options. Continuous upgrades and improvements of devices in the dispatch network of the smart grid can improve security of the system. Zig Bee and WiFi networks need to be considered in the process of developing security solutions. Testbeds are ideal environments to demonstrate and validate security mechanisms that achieve the desired performance, prior to implementation.

Pre-Integration Development

Testbeds provide a platform for advanced hardware and software development in an environment that closely mimics grid conditions. This is different than simply testing a new technology in a testbed; it involves developing products where interactions with a range of proven application parameters can be evaluated during development stage. Pre-integration development enables problems to be identified earlier in the development process. This also enables researchers to test concepts and prototypes in a testbed environment rather than relying exclusively on isolated computer simulations. It can help researchers understand how products work in the larger system before further development is conducted. This presents an opportunity to save development cost and time, and it can help ensure the products are designed to be integrated into larger system to operate effectively under a comprehensive set of proven parameters.

Coordination of Testbeds/Laboratories

Coordination among testbeds can maximize usefulness of the collective set of testbeds whether operated by academia, by government research laboratory, or by industry. For example, through better coordination, testbeds can use various simulation techniques like real-time simulation and hardware-in-the-loop to collectively get a better understanding of how these systems work when embedded within the larger network. Co-simulations using two or more testbeds can further improve the ability to model real grid parameters. Information sharing among testbeds helps build the collective knowledgebase of technologies that have been tested, including the specific operating conditions and the testbed owner. It can also help identify future needs and reduce duplicative efforts. Coordination can support analysis of individual testbed results. A potential example to follow for such results coordination is the phasor measurement unit (PMU) testing program.

Integration

Individual components of a smart grid system, like electrical, communication and IT, must be seamlessly integrated at the system level. Verification of new products and technologies in testbeds can vastly improve the likelihood of smooth integration into the main grid system. Standards and protocols for integration testing can help ensure that new technologies will be able to seamlessly operate with legacy systems. Standards for integration can provide assurance to technology users that system performance has been investigated in a trusted environment before full deployment. Test protocols can also help alleviate the amount of custom integration testing needed by utilities.

Development of Standards

Testbeds can serve as a platform for standards development for smart grids, especially for establishing the interoperability of components. Using testbeds as basis for verification and validation of standards can provide consistency and accuracy.

Customer/User Engagement

Testbeds provide an ideal opportunity to support acceptance of new, advanced, and sometimes more complex smart grid technologies. Utilizing testbeds effectively to encourage market acceptance requires a better understanding of the technology to market challenges. Strategies such as customer/user surveys, focus groups, or other engagements could be employed to gain insights into user acceptance levels for newer technologies and how testbeds can best be utilized to encourage deployment.

Safety

Understanding and characterizing interactions between components and system users is also important for safety of new products. Products are rapidly being developed in the smart grid space and standards or protocols could improve assurances of safety. The use of testbeds as experimental grounds for system interactions can play a central role in the development of updated safety requirements and product testing.

2.3. Challenges to Developing and Operating Testbeds

While progress is being made in developing and operating certain testbeds, significant challenges remain. Those identified are categorized in Table 2.2 and discussed more fully below.

Table 2.2. Challenges to Developing and Operating Testbeds

Technologies and Simulations	
High Priority	• Adequately representing the technical complexities associated with scaling and non-linearity that occur when deploying technologies in the full grid system • Designing and operating testbeds to facilitate technology integration into systems other than smart grids, for example, legacy systems • Working with technology users and stakeholders to understand the hardware development needed during the testbed design stage
Lower Priority	• Developing testbeds and simulations to validate procedures to return to a safe or "default state" under adverse operational conditions, while demonstrating the safety, reliability and security of the system • Understanding the effect of distributed generation on the larger system from testbed models and controls • Linking testbeds together that were developed under various sources and technical purposes
Knowledge and Data	
High Priority	• Lack of knowledge and skillsets to anticipate and prevent internal or external software and hardware intrusions • Lack of accurate models and data for conducting co-simulations of testbeds, including limited information to mimic full range of field conditions during testing • Obtaining an adequate number of vendors to test and implement technologies in testbeds, which would help improve ability to expose potential integration problems/vulnerabilities
Lower Priority	• Little or no access to propriety information from vendors especially in the case of microcontroller testing
Communications/Stakeholder Engagement	
Medium Priority	• Gaining acceptance of testbed results to help drive decision making by utilities and vendors • No coordinated communication efforts about the work conducted and planned by other testbeds; limited understanding of advancements and future plans of various testbeds • Lack of communication to stakeholders about the value proposition of testbeds, including limited communication about testbed results in an unbiased and factual manner
Standards	
Medium Priority	• Developing/testing protocols and standards to return systems to default / previous operating conditions, especially those that accommodate new technologies and potential adverse impacts on the system • Lack of standard operating procedures or protocols for operating conjoined testbeds • Lack of accepted set of tests considered effective and useful among security experts
Financial Barriers	
Medium Priority	• Few testbed operators have the financial viability required for executing various capabilities and tests • Lack of willingness to pay for underlying costs associated with testbed demonstrations

Technologies and simulations are currently limited in their ability to accurately represent the complexities of grid systems. Developing testbeds that cover a broad range of operating parameters requires gathering and incorporating more data and information than is available. In addition, poor information flow between and among testbed operators, the customers of testbeds (e.g., utilities, vendors), and the end-users of the technologies (e.g., businesses, individual consumers), make it difficult to develop integrated testbeds and develop and test technologies that are best-suited for integration with the full grid. Relatively few operating standards are in place that would help resolve key problems with combining testbeds and with security concerns. In addition, an overall lack of attention and perceived value from decision-makers is contributing to limited testbed funding.

Technologies and Simulations for Complex Grid Systems

Smart grid systems involve numerous combinations of components, users, and suppliers, and countless interactions between these elements. In addition, some of the elements in the grid are "smart" (e.g., enable bidirectional data flow and communications) while other elements are legacy systems that do not interact. Testbeds to simulate this environment face challenges to adequately represent the possible combinations of parameters and the associated complexities of interactions. The interactions among grid elements are not linear with system size, so it is difficult for a testbed to accurately demonstrate conditions 'at-scale.' Other examples of technological challenges include linking disparate testbeds that were originally developed for different purposes, and developing hardware and software technologies capable of defaulting to a previous state if a problem occurs during integration with the grid.

Limits to Knowledge and Data

Although myriads of data are collected by smart grid components, limited information is available for the purpose of developing solutions. Some data are considered propriety, while other critical information is simply not collected or shared in a manner that would be useful for testbed implementation.

In addition, researchers and developers do not have training or skills in understanding the mindset of an adversary attempting to exploit a security flaw in their system. This knowledge would enable better testing of smart grid systems in testbeds before they are exposed to real world conditions.

Stakeholder Communications and Engagement

There are currently no broadly accepted mechanisms for coordination among smart grid testbed owners and operators. Therefore, testbed developers may not be aware of the efforts already underway or planned, creating potential redundancies and inefficient use of resources. Lack of engagement among stakeholders is also creating difficulties for testbed operators trying to stay up-to-date on the needs of technology users and designing their systems to be tailored to specific needs. Likewise, limited communication from developers about the benefits of testbeds has resulted in low interested and enthusiasm from utilities, vendors, and other users regarding investments in testbeds. Better communications about the successes and value of testbeds would also help with acceptance of testbed results.

Testbed Operating Standards and Protocols

Test conditions vary substantially between testbed systems; they are each designed to examine a variety of components and issues. It therefore is not practical for standards to be developed that match the full range of possible combinations of system parameters. However, the lack of generally accepted practices, protocols, or standards for key aspects of the smart grid (such as security and default transitions) is inhibiting the ability of testbeds to coordinate with each other and more effectively examine the range of operating conditions.

Financial Resources

Many of the main beneficiaries of the testbeds, including vendors and utilities, are not willing to commit adequate long term funding for the development and operation of testbeds. Meanwhile, the testbed owners and operators are often academia or research institutes that have limited resources and competing priorities. The combination of these two factors contributes to the limited ability of testbeds to expand and enhance their capabilities.

2.4. Proposed Scenarios for Testbeds to Support Smart Grid Measurement and Characterization

Based on the major challenges and opportunities for identified for testbeds focused on measurement and characterization, two scenarios are proposed for new testbeds. These include:

- *Hardware/Device Development and Integration Testbed* – designed to conduct advanced smart grid device and controls testing and verify application performance; will enable pre-integration testing for early-stage device development (Figure 2.1).
- *Testbed for Data Security and Compatibility* – test and evaluation of Advanced Metering Infrastructure (AMI) and Home Area Network (HAN) devices for data security and compatibility (Figure 2.2).

Figure 2.1. Measurement/Characterization Testbed: Hardware/Device Development and Integration Testbed

A unique testbed is proposed that is designed to conduct advanced smart grid device testing, execute controller testing, prove and verify application performance under a range of operating parameters, and conduct pre-integration testing to enable identification and response to device drawbacks early in the development process.

Challenge	Pathway & Actions	Milestones	Targets
Difficulty simulating smart grid device testing under expected grid operating conditions	• Work with stakeholders to understand needs • Conduct research and development that meet the needs of the stakeholders • Define the scope of the testbed operating parameters and devices examined	• Ongoing process to continually understand evolving needs of stakeholders • Two-three years for new hardware	• Reduced cost • Reduced risk validated • Developed proven technologies
Lack of devices with long life conforming with advanced technologies (upgradable)	• Conduct research for improvement of the product quality • Develop cost effective solutions	• Five-to-ten years for devices with longer life	• Extended life of emerging technologies • Reduced cost

Potential Stakeholders and Roles

Industry	Develop products (manufacturer/vendors)
National Laboratories	Develop new products and conduct new research
Academia	Provide research on emerging technologies
Trade Organizations	Coordinate with NEMA, Manufacturer's Association
Standards Organizations	Develop standards for testing that meet criteria and performance targets
Government	Provide funding, coordinate efforts, and provide opportunities for stakeholder engagement and communication

Impacts on the Smart Grid

Reliability	Increased reliability
Performance	Pre-validated devices and user friendly devices
Resilience/System Assurance and Security	Extended product life Conforms with standards and codes
Demand Response	Improved (potentially)

Figure 2.2. Measurement/Characterization Testbed: Testbed for Data Security and Compatibility

A testbed is proposed to test and evaluate Advanced Metering Infrastructure (AMI) and Home Area Network (HAN) devices for data security and compatibility of AMI meters.

Challenge	Pathway & Actions	Milestones	Targets
Lack of compatibility among devices from different vendors within utilities' environments	• Develop functional and application tests that are applicable regardless of vendor and operating environment • Develop AMI and HAN security tests • Apply industry standard test procedures	One year to test the procedure	• Verification of the secure performance of devices in different environments • Secure communication exchange under range of conditions
Difficulty in validating resiliency against intrusion	• Develop industry standard test procedures that is accepted by security experts	One year to test the procedure	• Verification that successful intrusions are unlikely • Verification that the system operates through intrusions, possibly in degraded mode

Potential Stakeholders and Roles

Industry	Participation in test procedure development from utilities and device vendors
National Laboratories and Academia	Advance research in resiliency and operation through attack; develop and recommend best-practice system architecture and configuration
Trade Organizations	Participation and input into development process from Zigbee Alliance, CEA, Home Appliance Manufacturing
Standards Organizations	Development of standards from IEEE, UL, ANSI, NEMA
Government	Facilitating role and expert consultation from NIST, DOE, PUCs, CEC

Impacts on the Smart Grid

Reliability	Reliability improved by reducing security vulnerabilities
Performance	Supports reliable performance
Resilience/System Assurance and Security	Validates and assures security of systems
Demand Response	Higher performance of DR is achieved by better reliability
Other (explain)	Better consumer acceptance is expected through confidence in security
Other (explain)	More secure devices also will contribute to accelerated deployment of smart grid technologies

3. Attributes and Design of Composable and Modular Smart Grid Testbeds

Smart grid testbeds provide real testing environments to evaluate and validate systems before full deployment. They allow the developer to evaluate a variety of architectures and connectivity to emulate different systems, and experiment with software and hardware solutions. Composable and modular smart grid testbeds allow for the simultaneous integration of multiple components in a single platform, providing greater testing flexibility and a more realistic test environment. However, there are barriers associated with the development of these testbeds, including the lack of a business case for testbed customers (e.g., utilities), lack of standards for testbed components, and costs.

3.1. Existing Modular/Composable Testbeds

A number of testbeds related to smart grid technology and systems are in operation today and potentially fit into the description of modular or composable. A selection of these is shown in Table 3.1; this is not an all-inclusive list of existing testbeds with modular/composable characteristics but a selection of those that have been identified.

Table 3.1. Examples of Existing Testbeds with Modular/Composable Characteristics

Testbed Host
• Ameren Technology Application Center (SG products, services, or business models)
• American Electric Power Microgrid Test Bed (microgrid electric reliability, integration of DE)
• Florida International University Smart Grid Test Bed (power systems, communications and control issue, renewables)
• University of Illinois Smart Grid Test Bed (generation, power systems, RTDS, PMUs, PDCs, EMS, meters, consumer devices)
• LBNL Demand to Grid Lab and Smart Grid Facility (low energy experiments/microgrids, demand-side interoperability, wired/wireless communications, controls, architectures)
• University of Wisconsin Power Systems Engineering Research Center (power systems, computing, power electronics)
• University of Tennessee CURENT Center Hardware Test Bed (power systems research and test)
• ENERNEX Smart Grid Labs (multiple functions, communications, security, standards compliance, end-to-end)
• Southern California Edison (microgrid performance, buildings and transportation, DE)
• UCLA Smart Grid Energy Research Center (multiple functions, wireless/communications, sense and control technologies, DR, PEV, microgrids, etc.)
• UT Austin and Pecan Street Inc. Project (power meter data collection, test, and analysis on massive scale)
• California State Smart Grid User Center (grid security, sensor and home area networks, and electrical energy transmission and distribution)
• EPRI Intelligrid Program, Smart Grid Resource Center (interoperability, advanced metering, communications, standards)
• PG&E Emerging Technology Program (duration of outages, electronic circuit maps, home energy devices)
• KEMA/Duke Energy Smart Interop Lab (interoperability testing and compliance verification for low-voltage automation devices, meters, and consumer products)
• Oak Ridge National Laboratory Microgrid (DE, smart inverter and microgrid controls, PEV integration)

3.2. Unique Applications for Modular/Composable Testbeds

Composable modular testbeds facilitate linkages with other testbeds and interfaces and provide greater testing flexibility by enabling the integration of multiple components and controlling the type and number of systems in the test environment. These testbeds also enable testing of distributed generation systems, and provide several enhancements to test and validate the performance of smart grid systems. Some of the important and unique contributing characteristics are discussed below.

Linkage with Other Infrastructures

Modularity and composability improves the ability to interconnect testbeds and infrastructures. This is accomplished through an enhanced capability to:

- Connect and take advantage of disparate domain and institutional expertise among testbeds.
- Connect testing of the smart grid to other cyber physical system (CPS) domains, including health, transportation, and emergency response.
- Provide better communication of smart grid information technology requirements.
- Connect legacy systems with R&D systems (enable private/public partnerships).
- Interface the data and power systems, with inter-system testing capability.

Flexibility

Composable/modular testbeds provide a higher level of flexibility, including the ability to test various systems simultaneously, overcome standardization barriers, and control the number of devices being tested. Some unique characteristics contributing to flexibility include:

- A flexible environment for distributed control test and validation.
- Better defined system and functionality interfaces without "rigid" standardization.
- Informed standardization requirements to prevent testbed customer devices from being stranded.
- Allowance for scalability adjustments, such as load and number of devices.

Testing of Renewable/Variable Resources and Microgrids

The composable aspect of these testbeds allow for testing of variable generation sources with demand-side components. Some of the enhanced capabilities include:

- Testing of the integration of variable generation resources with demand management to ensure grid performance.
- Testing of distributed agents for microgrid participation in market and secure operation of system.
- Linking demand response systems with distributed energy resources.

Enhanced Testing Capabilities

Modularity/composability can provide an enhanced testing environment for some scenarios, such as:

- Obtaining data from real devices in realistic setting without non-disclosure agreements.
- Validation of load forecasting and generation management (centralized versus distributed).
- Time-critical interoperability of complex, heterogeneous systems.
- Rapid validation for grid architecture variants.
- Ability to identify, analyze, and mitigate negative impacts of communication characteristics (e.g., latency, lost packets) on grid control and performance.

3.3. Ideal Characteristics of Modular/Composable Testbeds

Ideal modular/composable testbeds include architectures that are service-oriented, scaleable, and representative of common energy systems. They should also capture and report data characteristics, such as transfer rate and latency in a time-sensitive manner, and work with a variety of interfaces. Table 3.1 illustrates the identified ideal test domains, as well as the important infrastructure components, and functionalities required for modular and composable testbeds.

Table 3.1. Ideal Test Domains, Infrastructure, and Functional Capabilities of Modular/Composable Testbeds

Test Domains	
High Priority	• Common systems, including energy markets, local utility operation, ISO operation, national operation, user energy management systems, and building energy management systems – Testing of inter-domain communication (market, utility control) – Ability to account for institutional and business boundaries that affect configuration and transactions – Operational schemes such as digital relaying and wide area monitoring (WAM) – Controllable (manageable) end-use load modules
Medium Priority	• Multiple interfaces – Energy systems/service interface – Consumers/end users and grid (e.g. grid-ready users) – IP communications – Interconnections (GPS, DDS, WiFi, Ethernet, Zigbee, and HIL)
Lower Priority	• Plug-in electric vehicle (PEV) state-of-charge and state-of-health • Integration of AC-DC systems, multi-agents platform, smart meters • Total grid simulation • Multiple components (e.g., generation, transmission, distribution, regulation/policy aspects, user/loads, sensors) • Testing in extreme scenarios: faults, cyber/physical attack, natural disaster, incorrect operation, component/system malfunctions/failures • Physical and virtual distributed and/or variable generation (DE, renewables) • Security – intelligent protection schemes • Compatibility with specific protocols
Infrastructure	
High Priority	• Architecture - Cloud local – Service-oriented – Scalable – interoperable – Generic in nature – Hardware-agnostic
Lower Priority	• Flexible, reconfigurable structure from centralized to fully decentralized • Testbed software platform to combine SCADA, online monitoring, and online analysis • Embedded test procedures • Experimental data storage (e.g., repository of experimental data)

Table 3.1. Ideal Test Domains, Infrastructure, and Functional Capabilities of Modular/Composable Testbeds

Functional Capabilities	
High Priority	• Capture/reporting of data characteristics and graphic representations); transfer rate and latency
Medium Priority	• Time-criticality, interaction, and initial conditions
Lower Priority	• Module self-description functionality (e.g., safety envelope, capability to publish data models) • Test harness for flexible experiment provisioning • Interoperable/standardized data format/archival (access control/security) • Phasor measurements • Voltage measurement calibration capabilities • Field-test ready capabilities

3.4. Challenges to Developing Modular/Composable Testbeds

There are a number of challenges to developing modular/composable testbeds. These range from solving technical issues to demonstrating a solid business case and navigating regulatory and policy barriers. The list of challenges identified is outlined in Table 3.2.

Technical Complexity

A high level of complexity and scale represent development barriers for any testbed scenario, including modular/composable testbeds. Other significant challenges include the ability to deal with latency in communications, developing adequate connection architectures, incorporating security/protection devices, and modeling and testing in real-time. Another key challenge is the ability to design testbeds that encompass long distances, such as the North American Synchrophasor Initiative Program (NASPI), which operates over hundreds of miles.

Business /Economic

The high-cost of testbed components represents an important challenge for the development of modular/composable testbeds. In many cases, high costs will necessitate the formation of consortia or other alliances to move development forward to scale. High costs also require the development of a strong business case if costs will be passed on to consumers. Once developed, the business case must clearly demonstrate goals, objectives and benefits to the market and consumers.

Policy, Regulation, and Standards

Policy and regulatory barriers was identified as a major challenge to the development of composable/modular testbeds. Examples are current and future requirements for security and data privacy, which impact the smart grid as well as testbeds. There is currently a lack of standards to support testbed operation and compatibility; only a limited set of standards currently exists.

Institutional/Workforce

Institutional issues include a lack of guidance and/or governance for conducting R&D and specifically in testbed environments. For example, a roadmap does not currently exist to provide overall guidance for development of the smart grid, or to prioritize and direct testbed activities. The definition of the smart grid is now loosely defined, and can mean different things and evokes different priorities depending on the stakeholder or organization.

Workforce issues include a lack of specialized curricula concentration in smart grid technology and subsequently this skill set is not emerging from universities or trade schools. A future workforce with strong expertise in smart grid technology and operations will be needed. For example, today technical expertise is lacking in many mart grid subsystems. The smart grid also requires multi-disciplinary skills and merging of expert knowledge in various fields. Challenges can arise across disciplines when merging different technical languages and perspectives; this requires finding common ways to communicate.

Table 3-2. Key Barriers to Developing Composable/Modular Testbeds

Technical Complexity	
Medium Priority	• Challenges of complexity and scale
Lower Priority	• Dealing with communication latency • Incorporating security/protection devices and effective connection architectures • Modeling and testing in real-time • Developing modular testbeds that adequately represents physical assets • Complexity of different component ratings, protocols, and computation speeds • Creating testbeds for covering long distances
Business/Economic	
High Priority	• Making a business case for testbed customers – demonstrating clear goals, objectives, and benefits • High cost of physical components; this can require cross-institution alliances to achieve scaling
Lower Priority	• Limited public/private partnerships to support testbed development • Protection of IP
Policy, Regulation, and Standards	
High Priority	• Policy and regulatory barriers • Lack of standards • Security and data privacy requirements
Institutional/Workforce	
Lower Priority	• Loose definition of smart grid, with differences in meaning and priorities across groups/organizations • Lack of specialized concentration/expertise in smart grid subsystems • Merging of expert knowledge across disciplines and technical fields • Lack of a time-sequenced roadmap for the smart grid

3.5. Proposed Scenarios for Modular/Composable Testbeds

Based on the major challenges and opportunities identified, a number of scenarios are proposed for modular/composable testbeds. These include:

- *Increasing the Penetration of Renewable Power through Various Approaches* –testbeds using various approaches such as storage, demand response, communications, and CPS infrastructure that require a flexible configuration of multiple test-beds and multi-disciplinary federated testbeds (Figure 3.1).
- *Increasing the Penetration of Renewable Power across Multiple Smart Grid Domains* –testing of approaches for integration of renewables across multiple smart grid demands (distribution, demand responses, markets) with validated in federated testbeds (Figure 3.2).

Figure 3.1. Modular/Composable Testbed Scenario: Increasing the Penetration of Renewable Power through Various Approaches

Composable modular testbeds provide a test environment to develop and validate approaches integrating renewables, storage, demand response (DR), communications, and infrastructure. It will require a flexible configuration of multiple test-beds – multi-disciplinary federated testbeds.

Challenge	Pathway & Actions	Milestones	Targets
• Enabling a key role for demand response in addressing intermittency in renewable generation. • Controlling the integrated use of renewables, DR, storage distributed energy resources, to ensure the stability of grid (controls, communication, security, etc.)	• Assess existing testbeds with potential composable/modular approaches to DR, and renewables, and other elements • Identify testbed(s) adequate for experiments and validation of the approaches developed • Develop testbed capabilities to fill gaps in existing testbeds • Identify communication needs and protocols for testbeds and path for development • Interconnect testbed(s) to address integrated components and challenges	• Determine load types to be tested, and communication requirements • Identify interfaces in the grid that require interaction • Identify existing federated testbeds and testbed customer types or sectors • Develop TB capabilities to fill gaps in validation of DR for renewables integration • Assess the impact of stochastic functions in the use of renewable resources	• Identification of intended and unintended consequences of the use of renewable technologies, such as stability problems • Understanding of technological needs to help reach the renewable portfolio standards (RPS) target • Identification of new markets to enable integration of renewables
Maximizing the use of renewables via integrated storage technology	• Assess existing testbeds with approaches to testing storage concepts • Develop testbed capabilities to fill gaps • Identify and develop standards and protocols for integrated/ interconnected testing of storage with other grid components	• Develop validated methods and technology to maximize the use	• Successful demonstration of integrated storage in testbeds

Potential Stakeholders and Roles

Industry	Utility provides a realistic test environment and data
National Laboratories	Provide testbed capabilities that identify unique areas of expertise and challenges to solve
Academia	Provide theoretical advances, test environments, education and training, and students
Trade Organizations	Advocacy, requirements, outreach, regulations, pre-competitive research advancement
Standards Organizations	Define best practices for integrating renewables at different scales.
Government	R&D and R&D funding (NIST, DOE, DHS, DOT)

Impacts on the Smart Grid

Reliability	Integrate renewable with no impact to grid stability
Performance	Provide power at lower carbon footprint
Resilience/ System Assurance and Security	Diversify energy resources. Enable security at interfaces.
Demand Response	Provide cost effective means of integrating renewables into the grid at consumer level

Figure 3.2. Modular/Composable Testbed Scenario: Increasing the Penetration of Renewable Power Across Multiple Smart Grid Domains

Integration of renewables across multiple smart grid domains, including distribution, demand response, markets, etc. Technical advances in solar and wind (particularly inverters and power electronics), storage, transactive energy, and more. Technical approaches and ultimately integrated approaches will be validated in federated testbeds focused on grid domains, with different testbeds providing complimentary capability. This testbed federation will be a significant benefit in itself.

Challenge	Pathway & Actions	Milestones	Targets
Advances in technology to overcome stability issues with high renewable integration	• Storage "grid shock absorbers" distribution level spinning reserve, microgrids, bidirectional meters, home and building energy management	• Identify which of these exist in what testbed • Develop capabilities to all gaps • Federate securely	• Validated approaches integrating renewable generation, storage, demand response, and other solutions, to achieve RPS goals

Potential Stakeholders and Roles

Industry	Grid-tied testbeds (SCE, AMEREN) validate findings
National Laboratories	Lab test beds, potentially disruptive testing
Academia	Advances in emulation/simulation / consolidation. Academic test environments
Trade Organizations	Advocacy, requirements
Standards Organizations	Best practices for integrating renewables at different scales and grid points
Government	R&D and R&D funding (NIST, DOE, DHS

Impacts on the Smart Grid

Reliability	Integrate renewables with no impact on grid stability
Performance	Power at lower carbon footprint
Resilience/ System Assurance and Security	Diversity of energy sources. Enable security at interfaces.
Demand Response	Enables consumer level renewable integration

4. INTERCONNECTED SMART GRID TESTBEDS

The smart grid opens up many opportunities for achieving new functionalities by interconnecting cyber-physical systems across domains and applications. For example, connecting electric vehicles to a smart grid, with two-way information and electricity exchange, would allow vehicles generating excess electricity to push that power back to the grid. Smart building systems interconnected with utility operations via a smart grid would allow for better building energy operations while providing utilities with information on demand, and better enable the use of energy efficiency as a resource. There are also many technologies and systems that will be interacting within the smart grid. For example, wireless networks will interconnect with a myriad of sensors and power equipment; utility operations will need to interconnect and communicate with offsite renewable and distributed energy sources.

In all cases, establishing interconnections between disparate systems and domains can be challenging, as unexpected behaviors can occur. Testing interconnected systems and components in testbed environments is one approach to understanding how disparate systems interact and ensuring they perform as expected when implemented. This topic explores the potential interconnections that are enabled via the smart grid, some of the challenges encountered when interconnecting smart grid components and testbeds across disparate domains, and the potential pathways forward for effectively addressing interconnection issues.

4.1. Domain Interconnections Enabled by the Smart Grid

Smart Cities and Services

The smart grid will make it possible to create domain interconnections that lead to smarter cities and services. This could include, for example, better response to storms or catastrophes by relaying information to utilities, fire and rescue, and other critical services. The smart grid can also enhance protection of critical infrastructure (e.g., banking, telecommunications, etc.) through integrated systems that ensure greater reliability. The smart grid enables smart communications, which then allow municipal operations and power systems to become unified and highly integrated, from operator to end use.

Energy and Natural Resources

The smart grid could enable connections to other energy and natural resource systems, such as municipal water supplies and natural gas pipelines. The potential to jointly view energy and resource infrastructures made possible by a smart grid could create new opportunities to optimize our precious natural resources.

Microgrids and Connected Grids

The smart grid enables interconnection of microgrids so that they can effectively interact and contribute to the national grid. There is also the potential for connected national grids (e.g., Eastern, Western, etc.); this would create opportunities for sharing of common operations for load balancing, for example, which could optimize distribution strategies across a greater area. This would require common cybersecurity platforms and certificate management.

Renewables, Energy Efficiency, and Distributed Energy

Sustainable energy use and services (e.g., renewable, more efficient, distributed energy) will be enabled by smart grid interconnections that reach a variety of energy sources. Smart grids will also enable better real time understanding of the local cost of electricity, providing actionable information to many users and utilities through a wide range of interconnections. Both providers and users will be empowered to optimize the cost of power more effectively through these interconnections.

4.2. Interconnected Testbeds to Support Smart Grid Deployment

By allowing for the demonstration of new concepts in a protected environment, testbeds can drive smart grid innovations, particularly in sustainable and disruptive technology, as well as market structures. Connecting two facilities (e.g., R&D and real utility environment) allows for the testing of a wide range of parameters and variables that are important to practical smart grid operations. Interconnections also provide a bridge to developing and validating protocols and models, conducting virtual data management, and testing Cloud or other new environments.

Federated test beds, for example, contain formal interconnections and structure to enable broad experimentation and demonstration extending beyond individual testbeds. An example is GENI, the Global Environment for Networking Innovation, a distributed virtual laboratory for experiments in network science, services, and security.[4] GENI enables experiments in a range of areas, such as clean-slate networking, protocol design and evaluation, social network integration, content management, and many other areas important to networks and the Internet.

As illustrated in Table 4.1, there are a number of interconnected testbed scenarios that could facilitate successful development and deployment of the smart grid. Some of the most important interconnections involve demonstration of new or emerging concepts, such as transactive energy[5]; interoperability of control systems and architectures; analytics for massive data sets and open data exchange; and security and reliability of systems at all levels. Integrating standards and protocols into testbed demonstrations is a common theme throughout.

Control scenarios can also be demonstrated in testbeds and are critical to adoption of smart grid technologies. These can be distributed or centralized. Controls need to be redesigned to avoid risk and testbeds are a critical path to testing new systems prior to implementation. With a smart grid, there will be an increasing need for automation control (e.g., actuators, values, relays) which will increase efficiency but also creates some risk.

Testbeds also play a key role in standards development and conformance assessment of new devices. For example, testbeds will enable the conformance testing and limitations of connecting new devices, applications, and systems to the grid, and enable simulation of impacts on reliability and performance.

Table 4.1. Interconnected TBs to Facilitate Smart Grid Development and Adoption

Transactive Energy	
High Priority	• Transactive energy test bed connected to microgrid and technology user device lab (smart inverters) for economic analysis – TB to demonstrate choice and value – TB for transactive energy experiments, protocols, operations, and policy – Wholesale market simulation lab connected to retail market/distribution system, operating lab, and micro grid lab – TB for "competitive metrics" allowing homeowners, buildings, and towns to compare demand and generation – Service broker access module to test potential solutions

[4] http://www.geni.net/ accessed May 12, 2014
[5] Transactive energy is defined as a combination of economic and control techniques to improve grid reliability and efficiency.

Table 4.1. Interconnected TBs to Facilitate Smart Grid Development and Adoption

Control Systems	
High Priority	• Demonstration of data-driven controller interoperability between two testbeds to demonstrate standards and test two separate controllers – Interconnected test beds that focus on interoperability between systems and product controllers (meters, Phasor Data Units /PDUs) – Connected smart grid test beds that operate under a joint control architecture which is configurable
Medium Priority	• Test bed to validate grid control actions from multiple control/sources to ensure stable operating condition
Low Priority	• Test bed for event response experiments – stochastic control theories that are human augmented
Data Analytics and Exchange	
High Priority	• Big Data Grid Analytic Lab connected to production data repositories – Mechanism (e.g., from TB to Phasor Measurement Units/PMUs) for sharing data that is currently non-accessible, between utilities, labs, and researchers • Open access resource sharing of end-user test bed datasets – Easy way to temporarily exchange experts between organizations – Shared governance knowledge base between labs
Low Priority	• Second generation large scale user community TB with data abstractions
Security and Reliability	
High Priority	• Security and communications TB incorporating cloud (cyber-attack defense, distributed control, architecture) – Link advanced metering infrastructure TBs to test distributed and scaled cryptography key management solutions – Cyber-security test lab connected to smart grid system lab (control systems) – Quantum cryptography secure communication channels TB – Variety of communication architectures for cybersecurity testing – TBs to demonstrate and test cyber security architectures between participants and allow attacks from both sides and middle
Medium Priority	• TB for normal and abnormal operation of a smart grid (e.g., overload) • TBs to test various types of environmental conditions and severity (e.g., cold, heat)
Protocols and Standards	
High Priority	• TBs to standardize communication and control protocols for real time operation of the smart grid, and to support TBs, equipment and systems
Medium Priority	• Understanding how to define standards/protocols for controls at distributed levels
Low Priority	• Conformance testing of smart information: share data with TB, then TB shares data with demonstration project; create new standard and new conformity tests
Wireless / Communications / Device Testing	
High Priority	• Test bed to directly connect utility to national lab or other research organization
Medium Priority	• Integrated WAMPAC TBs for resiliency testing: wide area monitoring; feed phasor to single center to test latency; wide area power system model lab connected to grid automation labs • Connection to remote lab that allows RF/EMC testing in a radiated manner; and with radiated testing of devices in operation • Connected smart grid remote substation labs for automated latency and security testing of controls and other functions • TB for wide range of legacy, current, prototype hardware/software to enable certification testing

Table 4.1. Interconnected TBs to Facilitate Smart Grid Development and Adoption

Low Priority	• Connection between remote labs to support in-field wireless testing at remote sites; this allows testing of new wireless communications systems as a communication backbone
Integration of Renewables, Demand Response, and Distributed Generation	
High Priority	• Test bed to directly connect utility to national lab or other research organization
Medium Priority	• Virtual aggregation of distributed non-dispatchable generation to enable higher penetration of renewable energy • Test bed to characterize interconnection of residential photovoltaic deployments with central storage to allow a microgrid • Connect modular load side TB connected to transmission level test beds with distributed system visibility between (simulation or real data) • Test bed for penetration and location of distributed generation
Low Priority	• Interconnect university campus to show benefits from demand response storage, etc. • TB for competitive metrics that allow homeowners, buildings, municipalities to post and compare metrics or aggregated metrics (e.g., demand and generation metrics) • Connection of commercial building TBs to distributed utility to test appropriate hierarchical control between distribution and BMS, and effectiveness of signal types
Simulation and Visualization	
High Priority	• Test bed to directly connect utility to national lab or other research organization • Virtual TB experiments: – Connected smart grid test beds that bring in different asset types to facilitate diversity studies (EVs, buildings, DG) – Virtual community substation microgrid experiments – Data/service/control aggregation detached from physical space – Coordinating co-simulator of existing test beds; utilities must participate – Hawaii Island TB – virtual simulators with systems being deployed together
Medium Priority	• Transmission simulation to distribution models
Low Priority	• Utility data exchanges with experiments – simulation and modeling of operational scenarios based on real time virtual data • TB to validate models for TBs, i.e., prove accuracy of models, predict events, etc.

4.3. Challenges to Developing Interconnected Testbeds

Interconnection of testbeds carries a unique set of challenges related to sharing infrastructure, interoperability of systems, and data and information exchange and analytics. In addition, non-technical challenges exist that are related to community awareness of existing testbeds and capabilities, business models, and incentives that encourage testbed connection and federation. Some of the major challenge areas are outlined below.

Shared Infrastructure and Needs

A number of significant challenges can arise when there is a need to share infrastructure between testbeds. Some of these are organizational, i.e., differences in the way organizations operate and manage testbeds, the compatibility of key infrastructure (e.g., architecture, platforms), and the policies governing such interactions. While some barriers can be readily overcome or negotiated, others may create incompatibilities that make it difficult to interoperate testbeds between organizations. In some cases, individual testbeds have been constructed for unique purposes and do not lend well to interconnection.

A common research agenda is currently lacking among the many governing bodies involved with the smart grid (e.g., thousands of utilities, multiple Public Utility Commissions, many Federal and state governing bodies, etc.). So while interconnections are possible, finding consensus on the most important problems that need to be solved via shared testbeds can be problematic.

Data and Knowledge

Data sharing is important to creating useful outputs from interconnected testbeds. Testbeds provide instrumented environments where this data can be collected under controlled experimental conditions. Sharing real data from utilities would allow testbeds to demonstrate and validate the performance and key

Table 4.2. Barriers and Challenges for Interconnecting SG TBs

Shared Infrastructure and Needs	
High Priority	• Organizational barriers between testbeds (utilities/universities/national labs) • Testbeds built for disparate purposes, leading to technical incompatibility
Medium Priority	• Lack of a common research and test agenda for smart grid, among many governing bodies (over 3000 utilities, 50 PUCs, divisions between federal and state jurisdiction, etc.) • Lack of collaboration/coordination among stakeholders (industry, labs, universities) • Slow stakeholder processes for creating new interconnections • Finding/attracting testbed customers (e.g., utilities, vendors) in developing markets with no standards or compliance requirements • Interconnecting legacy hardware and software • Lack of an overarching governance model for SG TBs
Low Priority	• Lack of tooling for managing integrated resources across organizations with different agendas and needs (e.g., software programs specific to labs or organizations); heterogeneity of TBs • Geographic limitations to interconnecting hardware components • Cultural perspectives that favor current ways of doing business (rather than new) • Limited flexibility in testbed environments
Security	
Medium Priority	• Complexity of cybersecurity makes it difficult to define exactly what to test and security success criteria (e.g., how to quantify security) • Defining standards, criteria, and protocols for cybersecurity
Data and Knowledge Sharing	
Medium Priority	• Data and knowledge are not routinely shared among testbeds • No language to enable communication across disciplines (e.g., cybersecurity versus power) • Proprietary controls, connectors, and software that limits collection and comparison of data
Low Priority	• Limited data abstraction models • Lack of real world system data availability and access for use with testbeds • Data access and privacy issues that limit use of data as well as collaboration • Lack of information protocol requirements for TB data • Lack of common information models for supporting testbed objectives

Table 4.2. Barriers and Challenges for Interconnecting SG TBs

Incentives / Business Models	
High Priority	• Inertia to change; lack of incentives to change organizational structure or improve ease of interconnecting between organizations • Lack of incentives and business models for testbed federation and collaboration
Medium Priority	• Regulation and policy does not incentivize information sharing or innovation (e.g., NERC penalty risk is high) • Constrained funding environments for R&D • Limited profit incentives for testbed development • Lack of clear goals for interconnection of testbeds and defined benefits • Costs of building, maintaining, and operating testbeds
Low Priority	• Lack of trust between utilities, ISOs, and unregulated startup companies where business models cannot co-exist • Fear of change and impacts on reliability (e.g., fast cycle technology versus slow cycle utility) • Conflicting, confusing, or adverse regulation
Testbed Awareness	
High Priority	• Lack of an accessible, central inventory or repository of testbeds (capabilities and equipment, location, owner/mission, point of contact, technologies) leading to some duplication of capabilities and needs • Limited visibility into current SG labs, capabilities, and services, so limited understanding of gaps in testbeds • Lack of a broker to assure/assign testbed availability based on needs, or a centralized consensus on R&D priorities

elements of new technologies before implementation in the operating environment, reducing the barriers to adoption. In some cases, there is a need to share data and knowledge between testbeds or as a sector-wide resource (e.g., open to the academic community or others involved in research). Data sharing in this case can be limited by a lack of common language or data protocols and incompatible data exchange systems. Testbeds (and data generated) may be proprietary within a utility or vendor, for legitimate reasons. Data from operational settings is subject to issues of confidentiality (system architectures, operational parameters) and privacy (customer data).

Data sharing from testbeds will thus vary depending on the agreement and capabilities of operators and users/customers. Data sharing issues will depend on whether the data is operational or experimental (i.e., testbed), with the latter often less sensitive to privacy and other constraints.

Interconnecting testbeds can represent quite different domains, and no common language exists to enable effective communication across disciplines (e.g., cybersecurity versus power). Proprietary controls, connectors, and software can further limit collection and comparison of datasets.

Incentives/Business Models

The smart grid stakeholder community is relatively conservative and exhibits a general inertia to change. Business incentives are lacking to change organizational structures or improve the ease of physical or virtual connections between entities; this represents a major challenge for interconnected testbeds. Similarly, both incentives and business models are lacking for testbed federation and collaboration.

Today's regulatory and policy environment does not provide incentives for information sharing or innovation and can even have conflicting or adversarial impacts on collaboration (e.g., NERC penalty risk is high). The cost of building, maintaining, and operating testbeds can be high, with limited profit incentives for testbed development. The benefits of operating interconnected testbeds are also not clearly defined, making it difficult to build a business case.

Testbed Awareness

There are a number of testbeds operating around the United States that are working to test and demonstrate elements of the smart grid. However, no accessible, central inventory or repository of testbeds exists, resulting in limited awareness of the capabilities that are currently available as well as potentially some duplication of effort. There is also limited visibility of current SG labs, capabilities, and services in general, which contributes to the limited understanding of current gaps in testbeds as well as opportunities for interconnecting testbeds. The lack of centralized consensus on SG R&D priorities also limits coordination among testbeds; no central entity is operating to assure or assign testbed availability based on needs or problems. A trusted hub or repository would go a long way toward fulfilling testbed coordination.

Workforce

Developing and maintaining the skilled workforce needed to support the smart grid as well as related testbeds is a continuing challenge. There is currently a lack of educational programs needed to build a future skilled workforce with competencies in SG technology. In the testbed arena, technical competence is often being directed elsewhere (e.g., the best and brightest are working on technology rather than infrastructure).

4.4. Proposed Scenarios for Interconnected Testbeds

Based on the major challenges and opportunities for interconnected testbeds, a number of scenarios are proposed for interconnected testbeds. These include:

- *Application of Data Analytics to Utility Big Data to Create Actionable Information* – tools to enable development of data analytics for a wide range of datasets that can provide input to and/or enhance testbed capabilities (Figure 4.1).
- *Architecture for Federation of Interconnected Testbeds* – general requirements and fundamental architecture principles needed to federate testbeds, including frameworks for applications and interoperability of testbeds (Figure 4.2).
- *Inventory of Testbed Entities and Capabilities* – an accessible inventory of testbed capabilities and resources to serve the testbed community and enable identification of opportunities for interconnecting testbeds (Figure 4.3).
- *Multi-Level Control Architecture Testbeds* – multi-level control architectures to support changes in conventional grid control paradigms and support the new ways of doing business enabled by the smart grid (Figure 4.4).

Figure 4.1. Interconnected Testbed Priority: Application of Data Analytics to Utility Big Data to Create Actionable Information

An open database and repository is proposed to enable development of analytics for the large volumes of data made possible by the smart grid. This could include smart meter data, asset health data, phasor measurement unit data, and other data that could be used to improve decision making, grid reliability, and security. This data could provide input to testbeds to enhance capabilities for validation and testing of analytics and other components.

Challenge	Pathway & Actions	Milestones	Targets
Data that is inaccessible to researchers and policy makers due to privacy and security concerns	• Identify an objective, trusted steward of the data and repository • Work with data owners to determine / decide who can access data and for what purpose; establish guidelines for a repository • Classify data according to level of sensitivity	• One-two years to create a repository, if data is made available • Milestones dependent on resource availability and utility participation	• Data availability for researchers, policy makers, and others, as appropriate
Data existing in different forms and levels of quality, usefulness	• Define a standard for validating data and possibly compressing/filtering data	• One-two years to create standards, depending on resources	• Guidelines and standards for validation of data and filtering
Large volumes of data beyond the ability to process it; utilities not experts in big data analytics	• Define processing, analytics, and abstractions that can be performed closer to the source thereby limiting the volume of data stored centrally	• One-two years to create a repository, if data is made available • Milestones dependent on resource availability and utility participation	• Analytical tools are developed to improve the efficiency, reliability, and security of the smart grid

Potential Stakeholders and Roles

Industry	Data owner and beneficiary of analytics; could be trusted steward
National Laboratories	Provide analytical expertise and tools
Academia	Provide analytical expertise and tools
Trade Organizations	Define standards and protocols
Standards Organizations	Define standards and protocols
Government	Define incentives and regulations; could be trusted steward

Impacts on the Smart Grid

Reliability

Performance

Resilience/ System Assurance and Security

Demand Response

Better information leads to better overall decision making at multiple levels

Figure 4.2. Interconnected Testbed Priority: Architecture for Federation of Interconnected Testbeds

This effort will focus on the development of general requirements and fundamental architecture principles needed to federate testbeds (e.g., for existing testbeds and laboratories, capabilities, resources, etc.). This will include a framework and guidance for potential application scenarios and interoperability of interconnected testbeds. A Federation Testbed Working Group is proposed to provide governance.

Challenge	Pathway & Actions	Milestones	Targets
• Achieving scale-ability at all levels • Lack of general requirements and fundamental architecture principles to federate test beds	• Establish a Federation Testbed Working Group to provide governance • Develop overarching guiding principles; requirements will follow from guiding principles • Ensure requirements support scale-ability	• 6 months – principles/ requirements (after kickoff meeting • One year – Project charter, project value and scope, stakeholders (project lead)	• Actual technical connection/successful demonstration (Physical) between three interconnected testbeds • Increased testbed capabilities (e.g., safety protocol /processes)
Increasing expandability and capabilities of testbeds; lack of application scenarios and interoperability (framework/ guidance) for interconnected test beds	• Conduct inventory of existing test beds/facilities • Develop framework architecture and guidebook; outside consultants to refine guidebook • Articulate and disclose application scenario	• Concurrent with principles/framework effort • Ongoing roadmap with initial sessions at kickoff. • 6 months – Guidebook draft • 1 year – Guidebook complete, clearly written	• Actual technical connection/successful demonstration (Physical) between three interconnected testbeds • Increased testbed capabilities (e.g., safety protocol /processes)

Accelerating interconnections (R&D, Deployment)	• Design methodology for a common process
	  ○ Cradle agreement (IEEE)
	  ○ Technical process
	  ○ Legal framework
	• Establish higher order way of prioritizing/ scheduling resource commitments
		• 6 months – Participation from 10 disparate participants (test labs facilities) representing different sectors
		• 1 year – successful interconnected testbeds
		• 2-3 years – increased capabilities
			• Actual technical connection/successful demonstration (Physical) between three interconnected testbeds
			• Increased testbed capabilities (e.g., safety protocol /processes)

Potential Stakeholders and Roles

Industry	Resources, represent interests with an eye towards finding value
National Laboratories	Resources, represent interests in R&D
Academia	Research
Trade Organizations	Promotion
Standards Organizations	Promotion, involvement later during the process; mature the process, consider patent issues
Government	Resources, coordination

Impacts on the Smart Grid

Reliability	TB simulations critical to communications and data reliability
Performance	Improved efficiency of TB efforts and outcomes
Resilience/System Assurance and Security	Facilitates interconnection of testbeds , providing more accurate simulation of smart grid with subsequent improvement of reliability/resilience
Demand Response	Enables via development and sharing of best practices

Figure 4.3. Interconnected Testbed Priority: Inventory of Testbed Entities and Capabilities

Information on current and emerging testbeds and capabilities (national or global) is limited, incomplete, and inaccessible to the public and/or testbed owners, users, and developers. An inventory of testbed capabilities and resources is needed that can be readily accessed and updated by the testbed community. This would enable identification of opportunities for interconnecting testbeds while providing expanded access to testbed capabilities.

Challenge	Pathway & Actions	Milestones	Targets
Lack of problem ownership (e.g., working group, standards body) that would set agenda of work and disseminate results	• IEEE 2030 identifies interfaces of methods and communication for accessible database • Assess/identify methods for models and simulations	• Model for simulations • Validation of implementations of the process/methods	• Identify testbed entities (e.g., testbeds and interoperable functions) • Identify suitable technical interconnection architecture (e.g., Internet 2)
Lack of a comprehensive database of testbed capabilities	• Conduct industry survey	• Identification of testbed owners, expertise, and capabilities	• Public data base with entity names/capabilities/contact information
Validation of information collected on testbeds	• Review / validate information on testbed capabilities (e.g., industry consortium such as SGIP, or third party such as NIST)	• Development and publication of validation criteria	• Published catalog of qualified entities and capabilities (e.g., testbeds, experts)

Potential Stakeholders and Roles

Industry	Identify required capabilities, consensus on approach, financial support
National Laboratories	Perform R&D and validation methodologies
Academia	Perform R&D; foster graduate program for future testbed developers
Trade Organizations	Participate: SEIP, Edison Electric, EPRI, NEMA
Standards Organizations	Develop consensus on standards through an open process, e.g., IEEE, IEC, NERC, NEMA
Government	Provide resources and leadership as a partner to industry

Impacts on the Smart Grid

Reliability	TB simulations critical to communications and data reliability
Performance	Improved efficiency of TB efforts and outcomes
Resilience/System Assurance and Security	Facilitates interconnection of testbeds , providing more accurate simulation of smart grid with subsequent improvement of reliability/resilience
Demand Response	Enables via development and sharing of best practices

Figure 4.4. Multi-Level Control Architecture Testbeds

Testbeds are proposed to demonstrate multi-level control architectures that will be needed to support changes in conventional grid control paradigms related to adoption of smart grid technologies and systems. These will also support new ways of doing business, such as Transactive Energy. Standards and protocols for information exchange will be a critical component of this effort. Integration across testbeds at multiple facilities will be important to enable broad participation in experiments.

Challenge	Pathway & Actions	Milestones	Targets
Controlling interoperability use, validation and demonstration	• Develop multilevel control architecture • Develop standards/protocols for information exchange	• 6-8 months – Software Engineering in Practice (SEIP) white paper • 18 months – Use cases, Smart Grid Interoperability Panel Subgroup C, Micrograids and Hierarchical Distributed Control	• Standards gaps identified • Proven demonstration of TB use cases
Creating effective approaches for Transactive Energy	• Explore/design Transactive Energy approaches – establish a mathematical foundation	• 6 months – Demonstration of Transactive Energy approach	• TB to demonstrate Transactive Energy
Changing the conventional grid control paradigm	• Create architecture – interactive control (e.g., DyMonDS) • Utilize high bandwidth devices (PMUS, Power Electronics) • Explore Powernet (PNNL) for interconnection of TBs	• 6 months – Dymonds workshop in smart grid • 1 year – 1 System Dymonds deployed • 2 years – Multiple systems deployed	• Demonstrated interoperability of multi-layer controls • Demonstration of high bandwidth devices in distributed testbed
Achieving testbed integration to support distributed experiments	• Benchmark provable TB experiments	• 6 months – Workshop on Powernet • 1 year – Powernet deployed for integrated TBs	• Capability established to enable labs to participate in joint experiments

Potential Stakeholders and Roles

Industry	Provide use case definitions; access to data testbed access
National Laboratories	Participate in experiments with Powernet (NREL/PNNL/Oak Ridge)
Academia	Develop theoretical foundations; participate in testbed integration
Trade Organizations	Contribute to protocols/standards for test beds
Standards Organizations	Develop standards: IEEE-S221, IEC-17, IEC 21
Government	DOE technology and demonstrations, DOD - SPIDERS

Impacts on the Smart Grid

Reliability	Demonstrated resilient control paradigms
Control Performance	Control – optimize wide bandwidth and Transactive Energy demonstration
System Assurance and Security	Defined architecture needed to implement cyber security
Demand Response	Demonstrated transactive-based and demand response

5. KEY FINDINGS AND NEXT STEPS

This report outlines some of the important smart grid challenges that would benefit from the application of testbeds, and proposed actions that can be undertaken to develop new testbeds or expand existing testbed capabilities. While the findings described here are based on the perspectives of a diverse segment of the smart grid community, it is not intended to be all-inclusive, but rather a snapshot of the participants. Note that the individuals contributing to this work were selected based on their unique expertise, knowledge, and ongoing testbed experience relevant to the development of smart grid technologies, systems, and business models.

5.1. Key Findings

The key findings of this report indicate that:

- Testbeds are critical to enabling development and deployment of a wide range of smart grid technologies, systems, business models, and consumer devices.
- While testbeds are operating today, coordination and awareness among testbeds and central understanding of priorities for RD&D are significantly lacking.
- Significant measurement, characterization, performance, and other challenges remain that will benefit greatly from testbed analysis and demonstration. A range of testbed scenarios are needed, including 1) targeted testbeds for unique problems; 2) modular/composable testbeds; and 3) interconnected testbeds – across domains, with multiple interconnected smart grid technologies, and those that connect the different capabilities of R&D laboratories or organizations.
- Priorities for developing/expanding testbeds include:
    - Hardware and device development and integration
    - Testing of data security and compatibility of Advanced Metering Infrastructure (AMI) and Home Area Network (HAN) devices
    - Support systems for viable renewable power sources, including storage, demand response, communications, and infrastructure.
    - Integration of renewables across multiple smart grid domains, including distribution, demand responses, markets, and validated in federated testbeds
    - Data analytics for actionable information from large volumes of utility data and a wide range of datasets
    - Architectures for federation of interconnected testbeds, including frameworks for applications and interoperability
    - Multi-level control architectures needed to support changes in conventional grid control paradigms

In addition, there is a compelling need for the creation of an accessible inventory of testbed entities and capabilities across the nation. This would enable more effective coordination of RD&D and resources, provide insights into ongoing work and outcomes, and enable the identification of collaborative opportunities and partnerships, potentially leading to important interconnections between testbeds.

5.2. Next Steps

It is anticipated that this report will be used by the stakeholder community to guide future directions for development and operation of smart grid testbeds, as well as identify new opportunities for valuable interconnections. Those organizations involved in conducting smart grid-related RD&D, developing new products and services, and directly involved with electricity generation, transmission and distribution will potentially find this report useful.

NIST will use the key findings of this report to aid in articulating the vision for the NIST Smart Grid Testbed facility. The Smart Grid Testbed Facility will create a unique set of interconnected and interacting labs in several key measurement areas—contiguously located on the NIST Gaithersburg site—that will accelerate the development of SG interoperability standards by providing a combined testbed platform for system measurements, characterization of smart grid protocols, and validation of SG standards, with particular emphasis on microgrids. A microgrid is defined as a subset of the grid which has the capability of being quickly disconnected from, and functioning independently of, the larger grid.

The testbed will serve as a core Smart Grid Program research facility to address the measurement needs of the evolving SG industrial community, including the full range of measurement and validation issues. It will empirically address measurement science challenges relating to smart grid performance and interoperability not being adequately addressed by industry and universities, including (but not limited to):

- Microgrid- and residential-size power conditioning measurements
- Synchrophasor measurements
- Cybersecurity for the grid
- Precision timing for the grid
- Electric power metering accuracy
- Communication system characterization/modeling/reliability.
- Sensor interface reliability
- Storage metrology and characterization

NIST is already working on identifying potential host organizations for a publicly accessible listing of smart grid testbeds that each testbed could keep up to date with content/description. There was strong consensus among the contributors to this report that such a testbed inventory is an important priority. Potential host organizations include the Smart Grid Interoperability Panel (SGIP) which already reaches out to the testbed community in various ways. There are also interactions possible with the new Industrial Internet Consortia (IIC), which has an interest in CPS testbeds as well as the smart grid domain.

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Appendix A. Examples of Existing Testbeds Applicable to the Smart Grid

Testbed/Host Organization	Description
Ameren Technology Applications Center (Smart Grid Test Bed); **Ameren Illinois**, Champaign, IL	Provides applicants with ability to connect new products onto a live electric distribution system. The facility can accommodate both utility-scale testing as well as residential products testing.
Consortium for Electric Reliability Technology Solutions (CERTS) Microgrid Test Bed; **American Electric Power** (AEP), Columbus, OH	Demonstrates the CERTS Microgrid Concept, an advanced approach for enabling the integration of multiple distributed energy resources (DER) into an electric utility's distribution system/power grid. Small sources (<100 kW each), no stand-alone storage, no power flow onto the grid.
Northeast Solar Energy Research Center (NSERC)/ Smarter Micro-Grid (SMG) Demonstration Project; **Brookhaven National Laboratory** (BNL), Upton, NY	Grid-connected 1MW solar energy research array with reconfigurable architecture for field testing innovative new smart grid technologies. Evaluating smart sensors in the campus electrical network to enable using the site as a microgrid test bed with options for utilities to test on their grids. Connected to BNL electrical distribution system.
CS Smart Grid User Center; **California State** (CS), Sacramento, CA	Testing for grid security, sensor and home area networks and electrical energy transmission and distribution. http://www.ecs.csus.edu/csgc/
ComEd Smart Grid Testbed; **ComEd,** Chicago, IL	Open opportunity for testing programs, technologies, business models and other innovative Smart Grid-related technologies and services. On-grid location provides testing for power distribution grid and promotes new products and services for retail and residential customers.
Smart Grid Labs (SGL); **EnerNex**, Knoxville, TN	Multi-faceted assessment for communications, security, standards compliance, technology/ vendor maturity. Helps to assess technology readiness; focused on end-to-end application oriented evaluation of distribution volt/var device controllers, DG interface controllers, field area network access points, smart meters, line current sensors, commercial/home gateways, in-home DR devices, smart appliances, etc.
Intelligrid, Smart Grid Resource Center; **Electric Power Research Institute** (EPRI), Palo Alto, CA	Leads industry effort to develop open, interoperable advanced metering systems; contributes to standards/emerging standards, conducts interoperability tests of products using standards; analysis of emerging communications technologies, synchrophasor communications infrastructure to support grid control, conducting field demonstrations of 4G technologies for utility operations. http://portfolio.epri.com/ProgramTab.aspx?sId=PDU&rId=277&pId=7537
Energy Systems Research Laboratory Smart Grid Test-bed Research Lab; **Florida International University**, Miami, FL	Focus on implementation of test bed power system as a micro-scaled smart grid, with focus on communications and control issues. Currently using induction motors to simulate the behavior of turbines to prepare power for the generators. Renewable energy is one of main sources to be implemented on the testbed. Considers all five generation stations; batteries, fuel cells, wind simulator, and PV simulators are connected.
Center for Advanced Power Systems (CAPS); **Florida State University**, Tallahassee, FL	Houses one of the largest real-time digital power systems simulators along with 5 MW AC and DC test beds for hardware in the loop simulation. Includes hardware testbed to test prototype motors, power electronics converters, control systems and other power system components at ratings up to 5 megawatts level.
Distributed Grid Intelligence, Hardware in the Loop (DGI-HIL) Testbed; **Future Renewable Electric Energy**	One of the world's first real-time, distributed, hardware-in-the-loop (HIL) testbeds for a smart grid took shape under the guidance of researchers from the FREEDM Systems Center. The testbed allows for smart grid experiments (such as power and energy management or fault injection) to be validated against a simulated electric power system without risking damage to

Testbed/Host Organization	Description
Delivery and Management (FREEDM) Systems Center, Raleigh, NC	the real power system. Real-time tests (simulating the system in the same time that it would take to actually run) show how hardware and software can operate in concert to achieve distributed grid intelligence for a real power system.
1 MW Green Energy Hub; **FREEDM**	Serves as a large scale and realistic testbed to eventually demonstrate the overall FREEDM system concept and operation (functionality) in a realistic 12 kV distribution system, but also to power the whole center headquarters space by renewable and sustainable energies. Real-world Smart Grid Test-bed for FREEDM and industry technologies. 1 MVA 12 kV three phase distribution grid.
Missouri S&T Smart Grid Test Bed; **FREEDM,** Rolla, MO	The Missouri S&T Smart Grid Test Bed provides a testbed for renewable and small conventional energy sources, energy storage devices, and communications and control methods inherent to developing future smart grids. The existing system comprises a 5.4 kW power array (twenty-seven BI-156-200W-G27V Brightwatts panels) with two Flexmax 80 maximum power point trackers, a Bergey XL.1-24 wind turbine rated at 1 kW, a fuel cell and electrolyzer (Ballard FCGen 1020), a battery bank (totaling 48 V at 258 A-hr), an ultracapacitor bank (totaling 48 V at 660 F), a diesel generator, and a number of power converters for interface and regulation.
Robert W. Galvin Center for Electricity Innovation, Microgrid; **Illinois Institute of Technology**, Chicago, IL	Initiative to improve reliability, security, efficiency, and sustainability of the nation's electrical grid and overcome obstacles to the effective adoption and implementation of the Smart Grid. The Center brings together researchers, industry, government, and innovators to "plug-in" to IIT's smart microgrid, research laboratories and technology park, creating a hub - or sandbox - for new innovations in advanced grid technology.
PowerCyber testbed; **Iowa State University,** Ames, IA	The PowerCyber testbed provides a realistic electric grid control infrastructure based on a combination of physical, simulated, and emulated components. The testbed integrates industry standard control software, communication protocols, and field devices combined with power system simulators to provide an accurate representation of cyber-physical grid interdependencies.
Smart Grid Interop Lab; **KEMA/Duke Energy**, Erlanger, KY	Conducts independent verification of device interoperability and compliance validation of low-voltage automation devices, meters and consumer products in four areas: reliability, optimization, regression testing to ensure compatibility with older components, and cyber security. Main services include supplier product testing, utility architecture testing to validate compatibility, adherence to NIST Smart Grid Interoperability Standards and interoperability of AMI and Smart Grid products to system designs; third-party service provider testing; experimental testing environment; and performance and compatibility testing for products/services. http://www.dnvkema.com/innovations/smart-grids/smart-grid-interop/default.aspx
Demand to Grid Lab (D2G); **Lawrence Berkeley National Laboratory** (LBNL), Berkeley, CA	Demand to grid lab for testing and improving strategies and standards for demand-side interoperability, wired and wireless communications, communication architectures, devices, and monitoring and controls technologies. http://eetd.lbl.gov/news/article/56144/the-demand-to-grid-lab-testing-and-demonstrating-smart-grid-and-customer-technolo; also facility for low energy experiments/microgrids http://der.lbl.gov/microgrid-concept
Los Alamos Demonstration Smart Grid project; **Los Alamos Department of Public Utilities (DPU),** Los Alamos, NM	Joint projects to demonstrate smart technologies which are difficult to test in Japan. Creates a residential microgrid including: a 1 megawatt photovoltaic solar array at the former landfill on East Jemez Road (another 1 MW to be built later); a large scale battery storage system; a demonstration smart home in Los Alamos equipped with photovoltaics, a battery, a home energy management system, and smart equipment and appliances for optimized power consumption, and smart meters.
Smart Grid Regional Demonstration Program (Smart Grid LA); **Los Angeles Department of Water and Power** (LADWP), Los Angeles, CA	Deploys/tests new technologies, such as automated switches, monitors, controllers, and meters that relay information to each other through a near-real-time communications network. Test bed sites will investigate a full range of user environments: residential, commercial, light industrial, and institutional. Electric Vehicle (EV) Integration into the LADWP Grid: demonstrate aspects such as smart charging and battery aggregation; renewables and EV battery integration; an operational microgrid; demonstration of a ride/car share program at LADWP; and EV test bed sites at USC and UCLA. USC offers a unique testbed for simulating a Smart Grid within a small city – creating a microgrid. Over 50,000 sensors monitor USC electricity usage and equipment status in near real time for enhanced information collection and power management by facilities.

Testbed/Host Organization	Description
Energy Systems Integration Facility (ESIF); **National Renewable Energy Laboratory** (NREL), Golden, CO	Scale-up of promising clean energy technologies -- from solar modules and wind turbines to electric vehicles and efficient, interactive home appliances, and testing how they interact with each other and the grid at utility-scale. Houses 15 experimental laboratories and several outdoor test beds, including an interactive hardware-in-the-loop system to test products at full power and real grid load levels. Grid related facilities include the Distributed Energy Resources Test Facility (DERTF) and NWTC - Grid Integration Testing. Includes microgrid testing with Sacramento Municipal Utility District (SMUD).
JUMPSmartMaui; **New Energy and Industrial Technology Development Organization** (NEDO) (Japan), Kihei, HI	Energy partners from Japan and the United States have collaborated on a multi-million dollar Smart Grid demonstration project – JUMPSmartMaui. The JUMPSmart Maui project aims at improving integration of variable renewable energy resources, such as solar and wind power, and preparing the electric system for widespread adoption of all-electric vehicles. Volunteers to test 1) 200 current and future owners of the Nissan LEAF throughout Maui; 2) 40 households in Kihei based on their interest and specific renewable energy criteria.
ORNL Microgrid Testbed, Distributed Energy Communications and Controls (DECC) Laboratory; **ORNL**, Oak Ridge, TN	Offers a unique test bed for testing distributed energy resources, responsive loads, smart inverter and microgrid controls, communications and protection. Advanced smart grid sensors; PEV integration; microgrids. Connected to and is part of the ORNL campus distribution system
PG&E Emerging Technology Program; **Pacific Gas and Electric Emerging Technology Laboratory**, **Applied Technology Services**, San Ramon, CA	Assesses potential of a smart electric grid to limit the scope and duration of user outages on local circuits; aim is to get "intelligent" switches to open and close automatically to reroute electricity while protecting sensitive equipment from damage caused by short-circuits. Electronic circuit maps are created via computer systems that spot potential circuit problems before any human operator. Testing of home energy devices such as SmartMeters, electric vehicle chargers, wireless Home Area Networks, home energy displays, smart thermostats, and related equipment. http://www.pgecurrents.com/2012/11/06/the-smart-grid-takes-shape-at-pge%E2%80%99s-san-ramon-technology-center/
Electricity Infrastructure Operations Center (EIOC); **Pacific Northwest National Laboratory** (PNNL), Richland, WA	Unique platform for researching, developing and deploying technologies to better manage and control the grid. Researchers work with real data--running scenarios to determine how to increase capacity and improve reliability models, and testing new technology without the cost and risk of disrupting the system. Fully functional energy system control room with computing, networking, and analysis capabilities focused on bringing the control of the electric power grid from minutes to seconds.
The Distributed Generation and Smart Grid Test-Bed; **Rensselaer Polytechnic University**, Troy, NY	Developing a power grid test bed to better understand the effects wind, solar, and fuel cell power sources contribute to the grid under a high degree of distributive generation device penetration. Testbed will lend itself to modular device modifications to evaluate and study new smart grid technologies.
Distributed Energy Technologies Laboratory (DETL); **Sandia National Laboratory** (SNL), Albuquerque, NM	Research on generation, storage, and load management at the component and systems levels; examines advanced materials, controls, and communications to achieve reliable, low-carbon electric infrastructure. 480V, 3-phase microgrid with interconnections to the utility grid and to various distributed energy resources including PV inverters, microturbines, fuel cells, reciprocating engine-generators, and electrical energy storage systems.
UCI Microgrid; **Southern California Edison (SCE) and University of California** (UCI), Irvine, Irvine, CA	UCI Microgrid served by SCE through the UCI Substation which steps down voltage from 66kV to 12kV using two 15 MVA transformers, encompasses ten 12kV circuits, includes more than 1 MW of solar power, is served by a 19MW natural gas fired combined cycle plant, incorporates centralized chilling including one of the largest thermal energy storage tanks in the country (4.5 million gallons/60,000 ton-hours). Serves more > 30,000 people and encompasses a wide array of building types (residential, office, research, classroom), transportation options (automobiles, buses, shared-cars, bicycles), and a wide array of distributed energy resources.
Smart Wire Grid Demonstration Project; **Tennessee Valley Authority** (TVA), Knoxville, TN	Installation of 99 Smart Wire units covering 17 tower spans on a 161-kV transmission line near Knoxville, Tenn. Units convert the existing transmission system to a smart asset that can bring extensive monitoring capability; regulate power flow; and effectively shift overloads to underused portions of the network. Will demonstrate ways to carry more power, reduce overloads, support renewable generation, lower maintenance costs, and defer line upgrades.

Testbed/Host Organization	Description
Irvine Smart Grid Demonstration Project (ISGD); **University of California**, Irvine, Irvine, CA	End-to-end demonstration of advanced smart grid technologies; tests all interlocking pieces of the end-to-end smart grid. Demonstration will take place on a new SCE feeder circuit that intersects the UC Irvine campus and provides a living laboratory. Encompasses two smart 12 kV primary circuits and a host of smart grid technologies installed from residences on the secondary circuits to energy storage alternatives on both the secondary and primary circuits, to synchrophasors throughout the Western Electric Coordinating Council (the "Western Grid").
Smart Grid Energy Research Center (SMERC); **University of California**, Los Angeles	Performs research, creates innovations, and, demonstrates advanced wireless/ communications, Internet and sense-and-control technologies to enable the development of the smart grid. Current topics include automated demand response, electric vehicle integration (G2V and V2G), microgrids, distributed and renewable integration, and cybersecurity.
University of Illinois Smart Grid Testbed; **University of Illinois**, Urban-Champaign, IL	Testbed spanning the grid system, including generation, power system modeling, RTDS, transmission/ distribution, relays, substation computers, PMUs, PDCs, EMS, advanced metering, meter platforms, energy monitoring, and home automation.
Duke Energy Smart Grid Laboratory; **University of North Carolina** at Charlotte, Charlotte, NC	Serves as testbed to simulate power grid in real-time (order of 5-10 micro-seconds step-times) and can interact with devices and other systems for communication, interoperability, control, testing, model validation, system integration, static and dynamic analysis. It is a test bed for: Large-scale real-time G-T&D simulations, Integration of plug-in hybrid vehicles and DR, Protective relay testing, HiL Controls (HVDC, SVC, FACTS, Exciters), Phasor measurement-based techniques, and Model validation and wide area control.
CURENT Center Hardware Test Bed; **University of Tennessee**, Knoxville, TN	Includes CURENT Hardware Testbed, CURENT Large-scale System Testbed, FNET monitoring and visualization lab, and general power systems and power electronics lab facilities. Develops power monitoring hardware and server software for nationwide power frequency dynamics monitoring network, and conducts power systems research and hardware testing. http://curent.utk.edu/contact-us/facilities/university-of-tennessee/
Pecan Street Testbed; **University of Texas and Pecan Street Inc.**, Austin, TX	World's first independently researched network of power meters and collects data from more than 450 homes participating in its smart grid. UT Austin Pike Powers Laboratory works with Pecan Street Inc to test/analyze home-industry-related systems generating massive amounts of data. Supercomputers at UT Austin pro 90 million unique current and voltage reads daily. http://www.engr.utexas.edu/features/pecan-street-igert-fellows
Power Systems Energy Research Center (PSERC); **Arizona State**, with **U. of Wisconsin,** multiple university partners	Power systems, complex systems, PMU data analysis, computing, control theory, power electronics, operations research, non-linear systems, economics, industrial organization and public policy. Partners with organizations that provide integrated energy services, transmission and distribution services, power system planning, control and oversight, market management services, and public policy. http://www.pserc.wisc.edu/home/index.aspx
SmartGridCity; **Xcel Energy**, Boulder, CO	SmartGridCity is a technology pilot that allows Xcel Energy to explore smart-grid tools in a real-world setting. As part of SmartGridCity, Xcel Energy has successfully installed approximately 23,000 automated smart electric meters in Boulder as part of a new era in electricity grid management. Current status/success is unclear

Appendix B. Acronyms/Abbreviations

ADR	automated demand response
AMI	advanced metering infrastructure
BOS	balance of system
BPA	Bonneville Power Administration
BMS	Building Management System
CES	community energy storage
CPS	cyber-physical systems
DDS	direct digital synthesis
DE	distributed energy
DEMS	Distribution Energy Management System
DG	distributed generation
DHS	U.S. Department of Homeland Security
DLC	direct load control
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
DR	demand response
DRGS	distributed renewables, generators and storage
DRMS	demand response management systems
EE	energy efficiency
EISA	Energy Independence and Security Act
EM&V	evaluation, measurement, and verification
EMS	energy management systems
EPRI	Electric Power Research Institute
ETS	electric thermal storage
EV	electric vehicle
FACTS	flexible alternating current transmission system
FERC	Federal Energy Regulatory Commission
FDRI	fault diagnosis, isolation, and recovery
GENI	Global Environment for Networking Innovation
GIS	geographic information system
GPS	global positioning system
HAN	Home Area Network
HEMS	home energy management systems
HVDC	high voltage direct current
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
ISO	independent system operator
IPV6	Internet Protocol V.6
IP	Internet Protocol
IT	information technology
IVVC	integrated Volt-VAR control
kW	kilowatt
kWh	kilowatt-hour
LBNL	Lawrence Berkeley National Laboratory
LC	load control
M&V	measurement and verification
MVDC	medium voltage direct current
MDMS	meter data management system

NEMA	National Electrical Manufacturers Association
NERC	North American Electric Reliability Corporation
NIST	National Institute of Standards and Technology
NREL	National Renewable Energy Laboratory
PDC	power distribution center
PDU	Phasor Data Unit
PEV	Plug-in Electric Vehicle
PLC	power line carrier
PMUs	phasor measurement units
PNNL	Pacific Northwest National Laboratory
PV	photovoltaic
RD&D	research, development, and demonstration
RAS	remedial action schemes
ROI	return of investment
RTDS	real-time digital simulator
RTO	regional transmission operators
RTU	remote terminal unit
SCADA	supervisory control and data acquisition
SCMS	superconducting magnetic energy storage
SG	Smart Grid
SGIP	Smart Grid Interoperability Panel
SPIDERS	Smart Power Infrastructure Demonstration for Energy Reliability and Security
TB	testbed
T&D	transmission and distribution
VAR	volt-amp-reactive
WAM	wide area monitoring
WAMPAC	wide area monitoring protection and control