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The DOE acknowledges the support provided by the organizations represented on the workshop planning committees in developing the process and sessions for the two Microgrid Workshops discussed in this article. This article's content is based on the workshop session discussions, with session summary descriptions taken from the report-out presentations by individual teams during the closing plenary. Contributions to this article by all workshop participants are duly acknowledged.
The Microgrid Workshops were sponsored by the DOE Office of Electricity Delivery and Energy Reliability. The workshops were hosted by the University of California – San Diego and by the Illinois Institute of Technology in Chicago.

The U.S. Department of Energy's Microgrid Initiative

The DOE Smart Grid R&D Program considers microgrids as a key building block for a Smart Grid and has established microgrid R&D as a key focus area. A significant number of R&D needs and challenges have been identified for microgrids during two workshops, with input from more than 170 experts and practitioners representing a broad group of stakeholders.

Dan T. Ton and Merrill A. Smith

I. Introduction

Microgrids have been identified as a key component of the Smart Grid for improving power reliability and quality, increasing system energy efficiency, and providing the possibility of grid-independence to individual end-user sites. The DOE defines the microgrid as ''a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island-mode.''[1] Many other organizations define microgrids with very similar definitions, including the concept of a system of multiple loads and generation, and of islanding from the grid. The benefits of microgrids include:

- Enabling grid modernization and integration of multiple Smart Grid technologies.
- Enhancing the integration of distributed and renewable energy sources that help to reduce peak load and reduce losses by locating generation near demand.

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- Meeting end-user needs by ensuring energy supply for critical loads, controlling power quality and reliability at the local level, and promoting customer participation through demand-side management and community involvement in electricity supply.
- Supporting the macrogrid by handling sensitive loads and the variability of renewables locally and supplying ancillary services to the bulk power system.

Within the U.S. Department of Energy (DOE) Office of Electricity Delivery and Energy Reliability (OE), the Smart Grid R&D Program was established to accelerate the deployment and integration of advanced communication, control, and information technologies that are needed to modernize the nation's electric delivery network. This modernization includes preparing America's electric infrastructure to meet the challenges of our 21st century economy. The Smart Grid R&D Program has two goals: (1) to dynamically optimize grid operations and resources for a robust, flexible, and secure ''plug-and-play'' electric grid, and (2) to fully integrate demand response and consumer participation into grid resource planning and operations. The microgrid initiative satisfies the first goal of dynamic optimization of distribution grid operations as well as an emphasis on distribution automation. Toward this end, the initiative has established its 2020 microgrid performance targets on costs, reliability, system energy efficiencies, and emissions.[2]

DOE microgrid performance targets 2020	To develop commercial scale microgrid systems (capacity $<$10 MW) capable of reducing outage time of required loads by $>$98% at a cost comparable to non-integrated baseline solutions (uninterrupted power supply [UPS] plus diesel genset), while reducing emissions by $>$20% and improving system energy efficiencies by $>$20%, by 2020.

This article provides an overview of ongoing microgrid projects being undertaken by DOE and its Smart Grid R&D Program and a process of engaging microgrid stakeholders to jointly identify the remaining R&D gap areas and develop an R&D plan to address the gap areas.

II. Ongoing Microgrid Projects

The bulk of DOE microgrid R&D efforts to date have been focusing on demonstration activities to meet niche application needs, such as the needs for meeting peak load reduction, renewable energy mandates and directives, and energy surety and reliability at some critical facilities including military installations. These ongoing microgrid demonstration projects consist of lab- and field-scale R&D test beds, renewable and distributed systems integration (RDSI) projects for peak load reduction, select Smart Grid Demonstration Program (SGDP) projects as part of DOE's implementation of grid modernization under the American Recovery and Reinvestment Act of 2009 (ARRA), and assessment and demonstration projects jointly supported by the Department of Defense (DoD) and DOE. These and other ongoing microgrid development and deployment projects are shown in **Figure 1**, including those projects funded under the DoD Environmental Security Technology Certification Program (ESTCP) Installation Energy Test Bed initiative. The DOE projects shown in Figure 1 are summarized below and elsewhere.[3]

Nine RDSI projects were selected in 2008 via a competitive DOE solicitation. The primary goals of these projects are to (1) demonstrate at least 15 percent peak demand reduction on the distribution feeder or substation level through integrating distributed energy resources (DER), and (2) demonstrate microgrids that can operate in both grid parallel and islanded modes. The application of technologies in an integrated fashion has the potential to allow more power to

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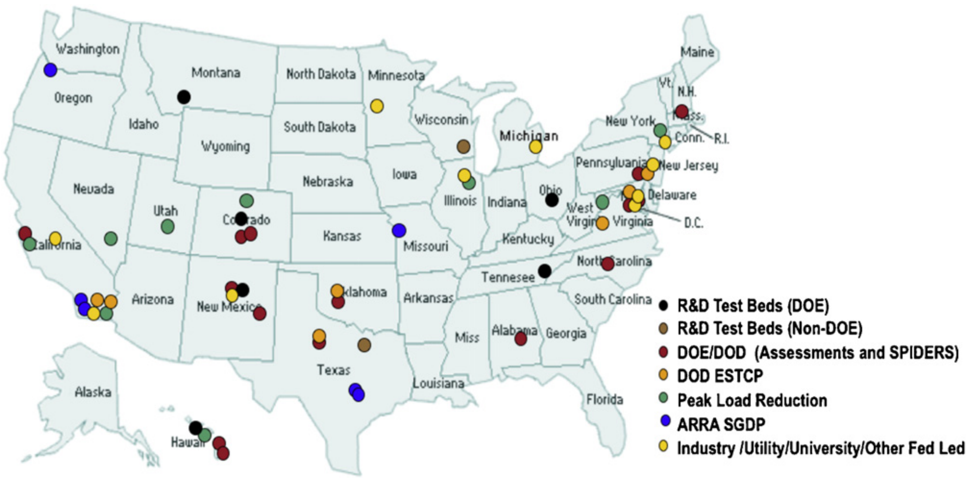

Figure 1: Select Microgrid Assessment and Demonstration Projects in the U.S.

be delivered through existing infrastructure, thereby deferring transmission and distribution investment, and to increase the reliability of the grid by adding elements that make it more stable and reconfigurable. Other potential benefits include addressing vulnerabilities in critical infrastructure, managing peak loads, lowering emissions, using fuel resources more efficiently, and helping customers manage energy costs. These RDSI projects are progressing toward achieving the goal of at least 15 percent peak demand reduction, and some have already successfully demonstrated 15 percent or more in reductions. The total value of the RDSI program will exceed $100 million, with approximately $55 million from the DOE over five years and the rest through participant cost share.

There is also a significant effort by national laboratories on microgrid designs, analysis, and demonstrations at test facilities and military bases. Lawrence Berkeley National Laboratory (LBNL) is teaming with American Electric Power (AEP), the University of Wisconsin, and Sandia National Laboratories (SNL) to apply Consortium for Electric Reliability Technology Solutions (CERTS) microgrid concepts in AEP's Dolan Technology Center-Walnut Station Test Facility in Groveport, Ohio. CERTS microgrid concepts are also being applied in field demonstrations by the Sacramento Municipal Utility District, Chevron Energy Solutions (RDSI project) shown in Figure 2, and the DoD at Fort Sill and Maxwell Air Force Base. LBNL has also developed the Distributed Energy Resources Customer Adoption Model (DER-CAM), which is an economic model to predict and optimize the capacity and minimize the cost of operating distributed generation in microgrids.

SNL is working on the Energy Surety Microgrid (ESM) methodology, which uses cost and performance data from military bases to develop approaches for implementing high reliability microgrids and to assist in planning for and analysis of potential risks in future military and commercial projects. To date, 14 military bases have received assessments and/or conceptual designs using the Sandia ESM methodology. In addition, Sandia has developed a set of valuable lessons learned that combined with their design methodology provide a blueprint for future ESM microgrid implementation. Building on the ESM work, the DOE is supporting SNL, Oak Ridge National Laboratory (ORNL), Idaho National Laboratory, National Renewable Energy Laboratory (NREL), and Pacific Northwest National Laboratory (PNNL) to work with the DoD to conduct the Smart Power Infrastructure Demonstration for Energy Reliability and Security (SPIDERS) at Pearl Harbor-Hickam Air Force Base, Hawaii; Fort Carson, Colo.; and Camp Smith, Hawaii. A key element of

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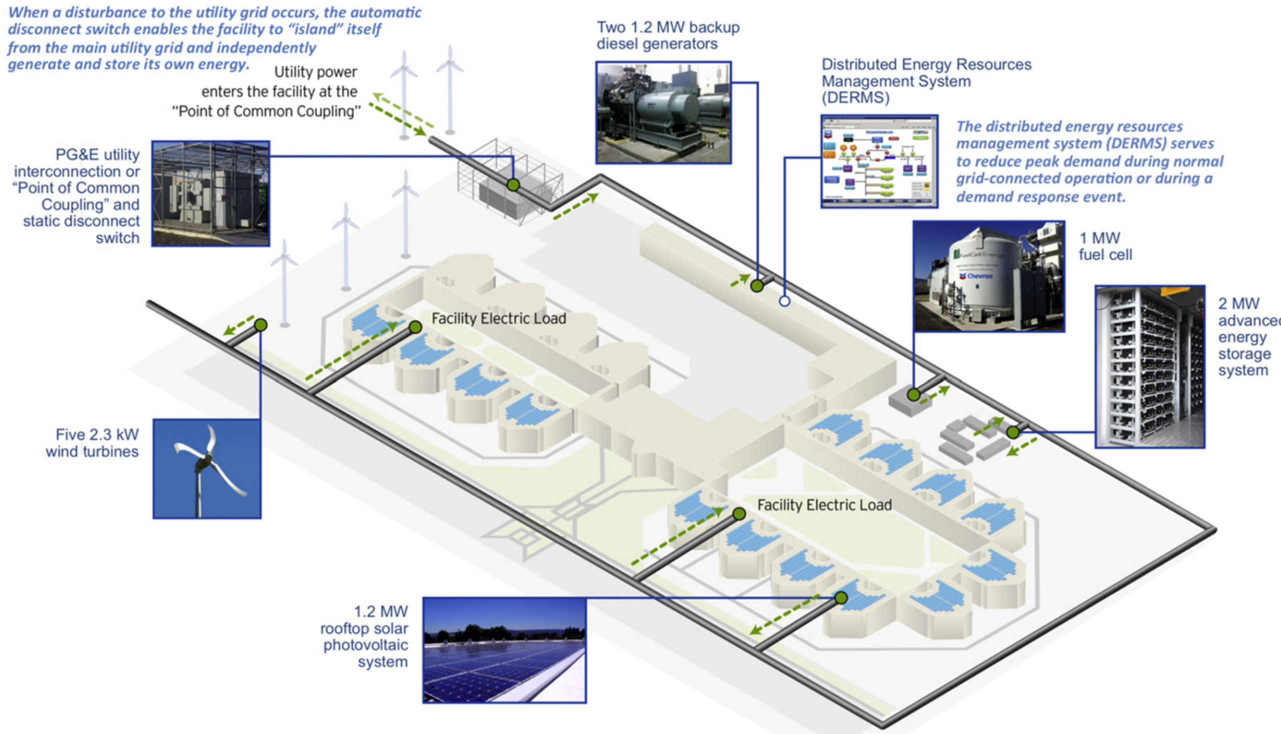

Figure 2: Chevron Energy Solutions' Project at the Santa Rita Jail in Dublin, Calif., to Demonstrate Commercial Application of a CERTS Microgrid

SPIDERS is standardization of the design approach, contracting, installation, security, and operation of these microgrids to support future applications.

Additional work at the National Laboratories also supports the microgrid effort. At ORNL, the Distributed Energy Communications & Controls Laboratory is developing controls for inverter-based DER to provide local voltage, power, and power quality support for the campus distribution system. On the simulation side, PNNL has been developing GridLAB-D as a distribution system simulation tool that integrates grid operations at several levels, including microgrids.

Under the ARRA, the SGDP has awarded 16 Smart Grid regional demonstration projects for demonstrating emerging Smart Grid technologies and alternative architectures to validate business models and address regulatory/scalability issues. Among them, several projects are conducting demonstrations involving combinations of integrating uses of renewable energy resources, distributed generation, energy storage, demand-side management, and charging schemes for plug-in electric vehicles. These projects include: Energy Internet Demonstration by Pecan Street Project Inc. in Texas; Pacific Northwest Smart Grid Demonstration by Battelle Memorial Institute including Portland General Electric's High Reliability Zone (microgrid); Green Impact Zone SmartGrid Demonstration by Kansas City Power and Light in Missouri; and Smart Grid Regional Demonstration by Los Angeles Department of Water and Power in California.[4] The total value of these four projects is over $372 million, including the ARRA funding of $183M.

In addition to meeting individual niche applications, the demonstrations above also field-prove capabilities of current technologies and unveil lessons learned, challenges, and needed but unmet capabilities. Clearly, current technologies will not be enough to meet the 2020 performance targets established by the DOE for microgrids. As a continuing effort to engage stakeholders on jointly planning and implementing RD&D activities, the Smart Grid R&D Program convened two Microgrid

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Workshops, one in 2011 and the other in 2012, to seek stakeholder input on identifying key R&D areas and performance baselines, targets, and actionable plans. This input is being incorporated into the 2012 edition of the Smart Grid Research and Development Multi-Year Program Plan to guide current and future DOE R&D efforts in microgrids.

III. Microgrid Workshops

The DOE held the first Microgrid Workshop on Aug. 30–31, 2011, in San Diego, and the follow-on workshop on July 30–31, 2012, in Chicago. The purpose of the first workshop was to convene experts and practitioners to assist the DOE in identifying and prioritizing R&D areas in the field of microgrids. The second workshop was held in response to path-forward discussions that called for sharing lessons learned and best practices for system integration from existing projects in the U.S. (including military microgrids) and internationally. In addition, the purpose of the second workshop was to delve more deeply into R&D topics gathered from the first workshop and subsequently determine system integration gap areas and functional requirements.

A similar process was followed to plan, organize, and conduct both workshops. Workshop planning committees were assembled to develop the process and sessions. The first workshop committee comprised representatives from four national laboratories and a consulting company; the second workshop committee comprised representatives from four national labs, three universities, and two consulting companies. The committee members provided nominations of experts and practitioners to the DOE for invitation to the workshops. Registration reached 73 and 100 people for the first and second workshop respectively, representing vendors, utilities, national laboratories, universities, research institutes, and end users. The technical topic sessions were conducted by having committee members facilitate or lead session discussions; for the first workshop, an industry representative was paired with a committee member to co-lead the discussions in each session.

IV. 2011 Workshop: Sessions and Major Findings

The workshop planning committee identified major cost components and subcomponents for microgrids based on their field experience (**Table 1**). The italicized subcomponents shown in Table 1 were further identified as areas having potential for significant cost reduction from the

Table 1: Major Cost Components and Subcomponents for Microgrids, as Identified by Workshop Planning Committee (percentages in parentheses are estimates of costs).

Energy resources (30–40%)	Switchgear protection and transformers (20%)	Smart grid communications and controls (10–20%)	Site engineering (30%)	Operations and markets
Energy storage; controllable loads; distributed generation; renewable generation; combined heat and power	*Switchgear utility interconnection* (including low-cost switches, interconnection study, protection schemes [programmable relays], and protection studies)	*Standards and protocols; control algorithms and software* (integration with energy management system [EMS], prime movers, utilities); real-time signals (openADR); local SCADA access; power electronics (*smart inverters*, DC bus [typically on the battery])	A&E *(modeling and analysis); system integration, testing, and validation*	O&M; market (utility) acceptance

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Smart Grid R&D Program efforts. Two parallel tracks were organized on the first day to address the potential cost reduction areas identified. One track focused on *microgrid components*, with separate sessions on switch technologies, control and protection technologies, and inverters/converters. The other track focused on *microgrid systems*, with separate sessions on standards and protocols, system design and economic analysis tools, and system integration. The second day of this workshop consisted of a combined session in which the selected industry representatives summarized their sub-sessions to the entire group. These report-out presentations consisted of priority R&D areas and performance baselines, targets, and actionable plans.

Conclusions from the breakout session discussions and the report-out presentations from the workshop are documented in the DOE Microgrid Workshop Report.[5] Following are the key R&D areas identified for each session to achieve the above-stated DOE 2020 targets for microgrids.

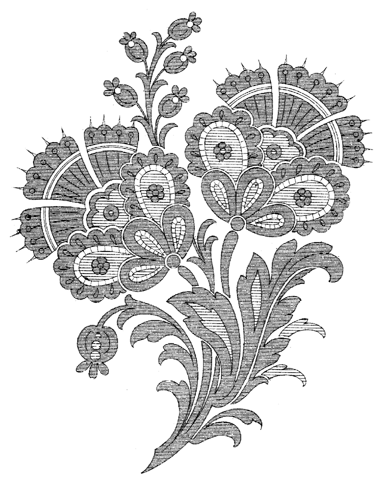
A. R&D areas relating to microgrid components

Switch technologies

- **Legacy grid-connection technologies to enable connect/disconnect from grid:** Achieve functionality without designating specific technologies. Focus on integration of functions and generation sources, long-term maintainability, and reliability.
- **Requirements based on customer and utility needs:** Collect information on end-user needs and determine functions for a myriad of applications.

Control and protection technologies

- **Best practices and specifications for protection and controls; information models:**



Conduct pilots with the DOE/DoD to develop use cases and provide guidelines for multiple approaches. Leverage what works at transmission level to distribution level.
- **Reliable, low-cost protection:** Use a layered approach, with the first level being protection of components for fast and local decisions, the second level being control for system stability (load reconfiguration), and the third level being optimization.
- **Switches to handle full fault:** Develop fault current limiting devices at the point of connection to the grid.

Inverters/converters

- **Topologies and control algorithms for multiple inverters to operate in a microgrid:** Define functionalities needed for combining multiple power sources. Develop control and methods for coordinated operation of multiple, smaller distributed inverters (<100 kW).
- **Advanced power electronics technologies:** Design topologies for reduction in volume, cost, and weight of passive components using switch and magnetic technologies for higher efficiency. Develop multi-functional power conditioning systems including transformer function, DC circuits, and multiple types of generators.

B. R&D areas relating to microgrid systems

Standards and protocols

- **Universal microgrid communications and control standards:** Define an end-to-end communications and control standard that links distributed generation, loads, and utility connections with standardized component capabilities that are consistent with applicable cyber security standards.
- **Microgrid protection, coordination, and safety:** Modify existing anti-islanding DER techniques to operate correctly in microgrid operations, and develop new unintentional islanding techniques to handle

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more DER in the microgrid. Define acceptable anti-islanding requirements for microgrids that export power. Develop new protection and coordination methods to handle faults and abnormal conditions when grid-connected and inside microgrids. Coordinate disturbance response with utility.

System design and economic analysis tools

- **Microgrid multi-objective optimization framework:** Develop a multi-objective (based on quantitative metrics) optimization framework over time (dynamic programming). Develop microgrid-specific design tools and build a library of solutions and tools by 2020.
- **Design an operations optimization methodology with uncertainty:** Uncertainty includes financial risk and return; design should be risk-resilient. Perform a ''stress test'' of preliminary operational design against various external factors that threaten system operation.

System integration

- **Common integration framework:** Develop a common framework for cyber security/control/physical architectures. Vertically integrate information management systems.

The workshop concluded with a path-forward discussion, during which workshop participants suggested the following next steps:

- Effective reporting and sharing of lessons learned and best practices on existing microgrid initiatives and projects, including those at the military sites.
- Integration of the R&D areas identified across all technical sessions in this workshop for pursuit to better address some common, crosscutting elements (standards, control, protection coordination, security, etc.).
- Follow-up on and increased collaboration among existing microgrid projects for knowledge sharing.

V. Workshop 2: Sessions and Major Findings

The first day of the July 2012 workshop began with an international panel session, during which representatives from Europe, Japan, South Korea, and the U.S. provided an overview of microgrid development activities in their respective countries or regions. This was followed by presentations of lessons learned and best practices from the following microgrid projects: Santa Rita Jail (industrial), Twenty nine Palms (military), Sandia National Laboratory (open architecture), Illinois Institute of Technology (university), microgrid lab demonstrations and pilots (Europe), and Sendai (Japan). A working list of system integration issues, identified by the workshop planning committee and categorized into ''Planning and Design'' and ''Operations and Control'' tracks, was then presented for input from the audience, based on their experience and the presentations on lessons learned and best practices. This brainstorming session resulted in a total of six breakout sessions focusing on 12 R&D topics for discussions on the second day. For each R&D topic, session participants discussed framing of the topic; current technology status; needs and challenges; R&D scope; and R&D metrics.

Significant microgrid development activities were presented in the opening International Panel. In Europe, eight pilot microgrids, shown in Figure 3, were presented that enable the experimental validation of various microgrid architectures, control strategies, and protection algorithms. These pilots are being conducted by a consortium comprising manufacturers, power distribution utilities, and research teams from 12 European countries, as part of the EU MORE MICROGRIDs project that is co-funded by the European

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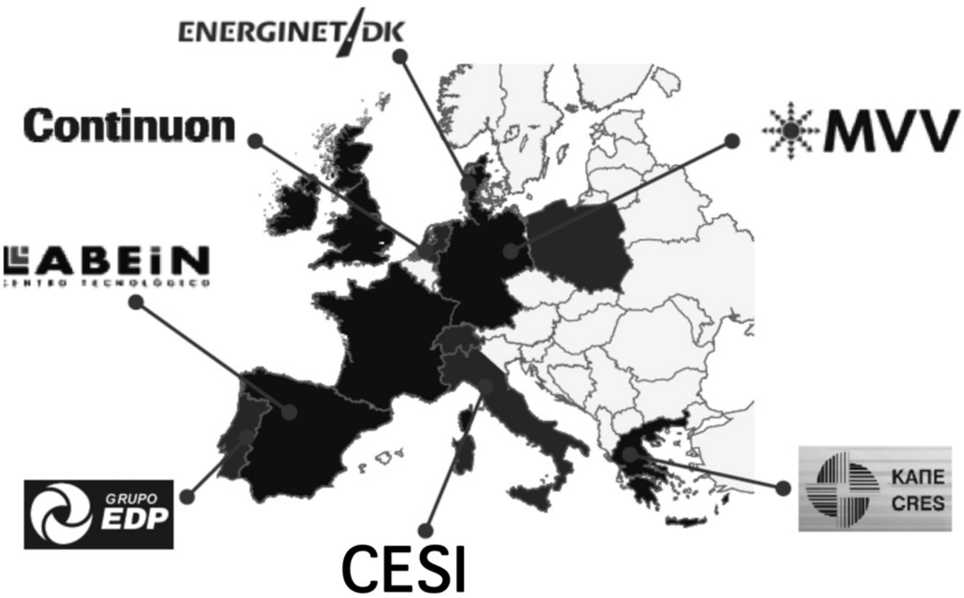

Figure 3: Eight Pilot Microgrids as Part of the EU MORE MICROGRIDS Project

Commission's sixth framework program (FP6) for research and technological development. These pilots aim at, among other objectives, conducting field trials to test control technologies on actual microgrids and are quantifying microgrid effects on power system operation and planning.

Japan presented their microgrid demonstration projects, as shown in Table 2. In South Korea, the leading research groups in microgrids include Korea Electrotechnology Research Institute (KERI), Korea Electric Power Research Institute (KEPRI), Myong Ji University (MJU) and Korea Maritime University (KMU). Several microgrid projects are being undertaken in Korea by these research groups, as well as a joint project with the Illinois Institute of Technology in the U.S. to develop a local area monitoring system for microgrids.

A. R&D topic session breakouts

Following are the key R&D topics identified by workshop participants as high priority for DOE microgrid R&D. These topics are presented with a brief scope description below, without prioritization, under two tracks: ''Planning and Design'' and ''Operations and Control.''

B. R&D topics relating to microgrid planning and design

System architecture development

- **Definition of microgrid applications, interfaces, and services.** Define the following: an ideal microgrid architecture, use cases, and interfaces to reference existing standards (interconnection versus communication versus information).
- **Open architectures that promote flexibility, scalability and security.** Develop interoperable distributed controls and flexible architecture to facilitate different applications.

Modeling and analysis

- **Performance optimization methods and uncertainty in the modeling and design process.** Develop a standard set of collaborative tools that addresses uncertainty, have a more holistic approach (to integrated energy systems, communications, vehicles, combined heat and power systems, etc.), and broadly assesses value streams; validate the tools on both domestic and international systems.

Power system design

- **DC Power.** Establish codes and standards for DC applications in residential, commercial, and industrial settings; develop standard design methodologies and software tools; develop DC system control

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Table 2: Microgrid Demonstration Projects by Japan.

Project name	Scale	Project	Control system	Element
Aichi Microgrid FY 2003–2007	1,200 kW	NEDO	Balancing (by 10 min)	PV, NAS Battery, Fuel Cell, Smart Metering, PMU (Phasor Measurement Unit)
Hachinohe Microgrid FY 2003–2007	600 kW	NEDO	Balancing (6 min moving average), power quality	Wind, PV, LA Battery, Gas Engine, Smart Metering, PMU
Kyotango Microgrid FY 2003–2007	650 kW	NEDO	Balancing (by 5 min)	Wind, PV, LA Battery, Methane Fermentation, Fuel Cell, Smart Metering
Sendai Power Quality Management FY 2004–2007	950 kW	NEDO	Balancing	PV, LA Battery, Capacitor, City gas, Fuel Cell, Smart Metering
Shimizu Construction Company FY 2006–	600 kW	Private own	Balancing	PV, Ni-MH Battery, City Gas, Smart Metering
Miyako Island Microgrid FY 2009–2013	50 MW	Utility (Okinawa EPC)	Balancing, power quality	Wind, PV, NAS Battery, SCiBT, Gas Turbine and Thermal
Higashida Co-generation (Kita-Kyushu Project) FY 2010–	33 MW	Steel company	Balancing, power quality	Wind, PV, Li-ion battery, Fuel Cell, EV, Smart Metering
New Mexico – Los Alamos FY 2010–2013	5 MW	Distribution utility (+NEDO)	Balancing	PV, NAS Battery, LA Battery, Smart Metering
New Mexico – Albuquerque FY 2010–2013	300 kW	Building owner (+NEDO)	Ancillary service, balancing	PV, LA Battery, City Gas, Fuel Cell, Smart Metering

algorithms; implement a push-and-pull strategy for DC microgrids, and develop advanced power electronics (lower cost, higher function and reliability).

- **Microgrid Integration.** Develop the following: a resource guide (handbook) of available products, costs, installation methods, valuation methods, etc.; standard and observable models to be used in modeling and analysis; standard analysis methods and software models; surety design methods and metrics for reliability and security; and advanced power electronics and advanced controls.

C. R&D topics relating to microgrid operations and control

Steady state control and coordination

- **Internal services within a microgrid.** Develop a standard set of hardware and software that supports the communication protocols and cybersecurity standards already developed to allow DER to plug and play; develop three-phase estimators based on phasor measurement units (PMUs) and compatible instrumentation for run time control; develop a better understanding of methods of decoupling frequency and voltage; and demonstrate a system that can synchronize and reconnect a microgrid under all edge conditions (high PV penetration) for all classes of microgrids.
- **Interaction of microgrid with utility or other microgrids.** Evaluate microgrids against other existing utility mitigation tools and schemes; evaluate potential effects of multiple microgrids on the stability of the grid and potential regulatory policies, economic incentives, and control schemes that could be used to mitigate the negative effects; develop tools for distribution to manage

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microgrids and their resources in cooperation with other distribution resources (assets) in ''RDO'' (regional distribution operator); and develop a technical, operational, and economic model to demonstrate the value of microgrids to utilities through simulation and case studies.

Transient state control and protection

- **Transient state control and protection.** Define impact of types of communication and identify requirements; develop three-phase unbalanced dynamic stability analysis models and a reference study for transient stability analysis of microgrids; develop technically mature, commercially available autonomous transition control and protection concept and products that meet the defined capabilities; and validate standard microgrid component models for protection and transient studies.

Operational optimization

- **Operational optimization of a single microgrid.** Develop real-time (RT) and near-RT controls that incorporate optimization; evaluate various optimization techniques as applied to microgrid operations; and develop methodology for comparing microgrid baseline to optimized microgrid operations for potential input into business case analysis.
- **Operational optimization of multiple microgrids.** Develop RT and near-RT controls that incorporate optimization between multiple microgrids; develop methods to negotiate objectives and optimizations between multiple microgrids (between different microgrid integrators); evaluate various optimization techniques as applied to multiple microgrid operations; and develop methodology for comparing multiple microgrid baseline to optimized microgrid operations for potential input into business case analysis.

The workshop report will summarize conclusions from the breakout session discussions and report-out

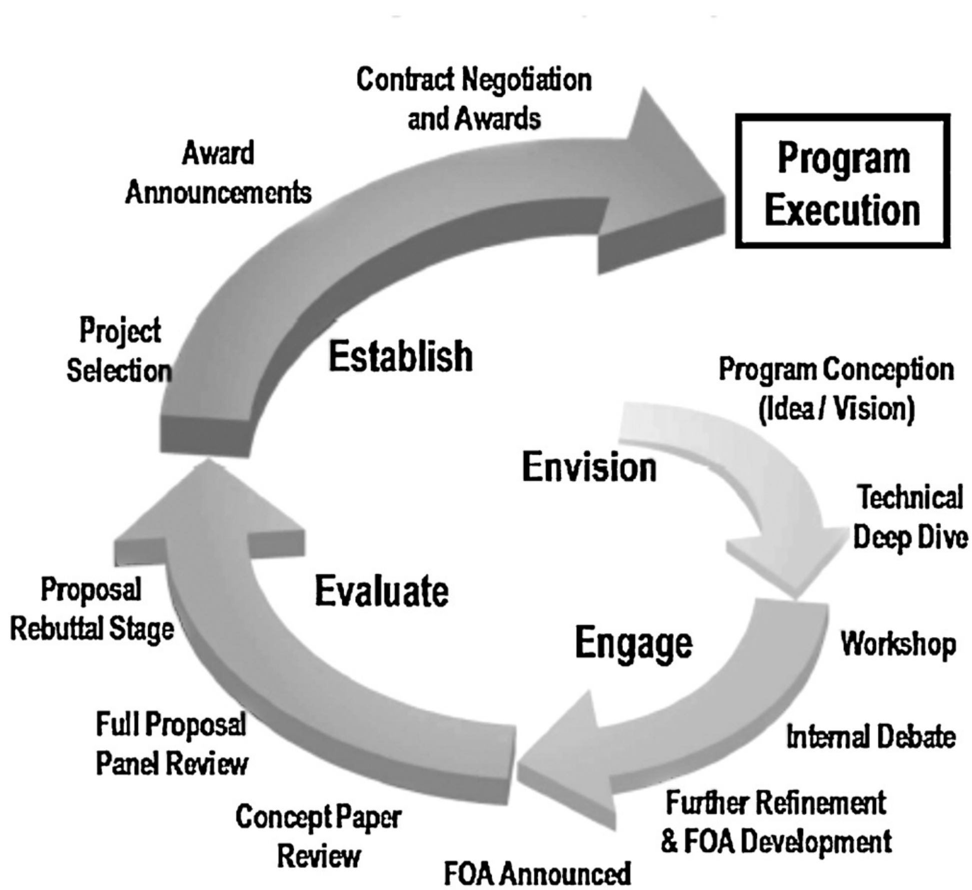

Figure 4: Microgrid Initiative Development Process by the DOE Smart Grid R&D Program

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presentations. Once completed, the report will be published on the DOE Web site for access by all interested parties. Meanwhile, all presentations made at the July 2012 workshop can be downloaded through Web links embedded in the workshop program agenda.[6]

VI. Conclusions and Path Forward

The DOE Smart Grid R&D Program considers microgrids as a key building block for a Smart Grid and has established microgrid R&D as a key focus area. A significant number of R&D needs and challenges have been identified for microgrids during the two workshops, with input from more than 170 experts and practitioners representing a broad group of stakeholders in the U.S. and other countries such as Europe, Japan, Korea, and Canada. R&D scope to address the identified needs and challenges has been outlined at the two workshops. Also, evident from workshop discussions and presentations are the technical, economical, societal, and environmental benefits that can result from successful development and deployment of microgrids.

Engaging stakeholders in workshops to seek input on R&D needs as described above is a key part of the R&D management process shown in **Figure 4** and practiced by the Smart Grid R&D Program. After gathering input, the Program will further refine R&D requirements to plan and develop a competitive funding opportunity announcement (FOA), subject to available funds from annual appropriations. The DOE Microgrid R&D initiative is following the process in Figure 4, from conception through R&D execution.■

Endnotes:

1. Definition developed by the Microgrid Exchange Group, which is comprised of an ad hoc group of individuals working on microgrid deployment and research.

2. U.S. Department of Energy, Smart Grid Research & Development Multi-Year Program Plan: 2010–2014, Sept. 2011 Update in Draft (at http://events.energetics.com/SmartGridPeerReview2012/pdfs/SG_MYPP_2011.pdf).

3. D.T. Ton, W.M. Wang and W.-T.P. Wang, *Smart Grid R&D by the U.S. Department of Energy to Optimize Distribution Grid Operations*, Proceedings of 2011 IEEE Power & Energy Society General Meeting at Michigan, Detroit, July 24–28, 2011.

4. Information on the SGDP projects is available at http://www.smartgrid.gov/recovery_act/project_information?keys=&project%5B%5D=2.

5. U.S. Dept. of Energy, DOE Microgrid Workshop Report, Aug. 30–31, 2011, at http://energy.gov/sites/prod/files/Microgrid%20Workshop%20Report%20August%202011.pdf.

6. The workshop program agenda with embedded presentation links is available at http://e2rg.com/events/agenda/.

A significant number of R&D needs and challenges have been identified for microgrids.

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