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The Advanced Microgrid
Integration and Interoperability

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Abstract

This white paper focuses on "advanced microgrids," but sections do, out of necessity, reference today's commercially available systems and installations in order to clearly distinguish the differences and advances. Advanced microgrids have been identified as being a necessary part of the modern electrical grid through a two DOE microgrid workshops,[1,2] the National Institute of Standards and Technology,[3] Smart Grid Interoperability Panel and other related sources.

With their grid-interconnectivity advantages, advanced microgrids will improve system[4] energy efficiency and reliability and provide enabling technologies for grid-independence to end-user sites. One popular definition that has been evolved and is used in multiple references is that a microgrid is 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. Further, an advanced microgrid can then be loosely defined as a dynamic microgrid.

The value of microgrids to protect the nation's electrical grid from power outages is becoming increasingly important in the face of the increased frequency and intensity of events caused by severe weather. Advanced microgrids will serve to mitigate power

1 "DOE Microgrid Workshop Report," Office of Electricity Delivery and Energy Reliability Smart Grid R&D Program, http://energy.gov/oe/downloads/microgrid-workshop-report-august-2011, Aug 2011.

2 "DOE Microgrid Workshop Report," Office of Electricity Delivery and Energy Reliability Smart Grid R&D Program, http://energy.gov/oe/downloads/2012-doe-microgrid-workshop-summary-report-september-2012, Sep 2012.

3 SGIP webpage for applicable Smart Grid Interconnections, http://www.sgip.org/#sthash.6Gcyft6W.dpbs.

4 "DOE Microgrid Workshop Report," Office of Electricity Delivery and Energy Reliability Smart Grid R&D Program, http://energy.gov/oe/downloads/2012-doe-microgrid-workshop-summary-report-september-2012, Sep 2012.

disruption economic impacts.[5] Advanced microgrids will contain all the essential elements of a large-scale grid, such as the ability to (a) balance electrical demand with sources, (b) schedule the dispatch of resources, and (c) preserve grid reliability (both adequacy and security). In addition to these basic features, an advanced microgrid will also be able to interact with, connect to, and disconnect from another grid.

An advanced microgrid is aptly named “micro” in the sense that a power rating of 1 MW (plus or minus one order of magnitude) is approximately a million times smaller than the U.S. power grid’s peak load of 1 TW. Some of the complexities required for a large grid such as complicated market operation systems, state estimation systems, complex resource commitment, and dispatch algorithms will be simplified. New advanced microgrids will enable the user the flexibility to securely manage the reliability and resiliency of the system and connected loads. By shifting resources and partitioning the systems in different configurations, a system-survival resiliency essentially is created. System owners can then optimally use system resources to address threats and potential consequences, and even respond to short-time-frame priority changes that may occur. Whether the primary driver for establishing a microgrid is cost saving, surety, or reliability, benefits will accrue to the system owner.

Acknowledgments

The authors wish to acknowledge the many experts that provided guidance and information for this document. The members NIST and the Smart Grid Interoperability Panel and its subgroups provided up-to-date and valuable information related to their proactive work on architectures of smart grid interoperability, required standards and codes, microgrid architecture, and testing. National laboratory experts provided guidance and are continuing work to develop critical tools to enable advanced microgrid developments and evaluate value added to installations of the future. Members of industry and utilities shared their experiences with installations that are already providing highly reliable microgrids for critical loads and for economic benefits to the owner. Thanks also to Lisa Sena-Henderson of Sandia National Laboratories for creating many of the graphics for the document. This project was funded by the US Department of Energy Office of Electricity Delivery and Energy Reliability Smart Grid R&D Program.

5 Executive Office of the President, “Economic Benefits of Increasing Electric Grid Resilience to Weather Outages,” Aug 2013.

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Acronyms and Abbreviations

ASHRAE	American Society of Heating, Refrigerating, & Air-Conditioning Engineers
BACnet	Building Automation and Control Networks®
CERTS	Consortium of Electric Reliability Solutions
CHP	combined heat and power
CIP	critical infrastructure protection
DER	distributed energy resource
DER-CAM	Distributed Energy Resources Customer Adoption Model
DEWG	Domain Expert Working Group
DG	distributed generation
DNP3	distributed network protocol
DOE OE	U.S. DOE Office of Electricity Delivery and Energy Reliability
DR	distributed resource
DRGS	Distributed Renewables, Generators, and Storage
DSL	digital subscriber line
DSO	distribution system operator
EMS	energy-management system
EPS	electric power system
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronic Engineers
ISO	International Organization for Standardization
LVRT	low-voltage ride through
MO	market operator
μEMS	microgrid energy-management system
NERC	North American Electric Reliability Corporation
NIST	National Institute of Standards and Technology
NREL	National Renewable Energy Laboratory
PCC	point of common coupling
PG&E	Pacific Gas & Electric
PMU	phasor measurement unit
PRM	Performance Reliability Model
PV	photovoltaic(s)
QF	(FERC-jurisdictional) qualifying facility
QOS	quality of service
R&D	research and development
RTO	Regional Transmission Operators
SCADA	supervisory control and data acquisition
SEGIS	Solar Energy Grid Integration Systems
SEL	Schweitzer Engineering Laboratories
SGIP	Smart Grid Interoperability Panel
SPIDERS	Smart Power Infrastructure Demonstration for Energy Reliability and Security
T&D	transmission and distribution
TMO	Technology Management Optimization
UPS	uninterrupted power supply
VAR	Volt-Ampere reactive
VLAN	virtual local-area network

Executive Summary

This white paper is organized to provide a synopsis of many elements of microgrid component technologies and system configurations that can subsequently be used for an "advanced microgrid" development activity. The paper is written as a compilation of microgrid status, advanced microgrid goals and requirements, new challenges and opportunities, tools for designs, and tools to strengthen infrastructure and standards activities. It is written to complement workshop reports and information provided by The United Stated Department of Energy Office of Electricity Delivery and Energy Reliability Smart Grid R&D Program and other microgrid conference proceedings.

The introduction and background section provides reviews at an overview level but reveal today's critical needs such as improved resiliency of our nation's electric grid. It includes some of the developments leading up to today's microgrid status and progresses to the needs for moving forward from a disparity of microgrid ideas, designs, purposes, and control methodologies. Two DOE workshops have provided industry input and prioritizations for the needs of an advanced microgrid. Other important interoperability activities such as the Smart Grid Interoperability Panel being directed by the National Institute for Standards and Technology are described.

An indispensable term attached to the description of the functions of advanced microgrids is "automatic." Today's microgrid installations exhibit some automatic functions such as automatic disconnect and reconnect as part of the built-in controls. Automatic load shedding is another. Many new functionality requirements, now on the horizon, will be required to be compatible with interconnects of the future smart grid. A second indispensable descriptive word is "interoperability." Challenges and opportunities are discussed in the introduction to point out anticipated impacts and value added for a reliable and stable power supply through the nation's electric grid that will be coupled with an aggregation of microgrids. The interconnectivity and new functionalities will work together to improve the grid's power quality, reliability, and resilience, while reducing overall cost. Standards will be a huge part of bringing the technologies and interconnect requirements up to speed.

The reader is reminded that much basic technology does exist today, but some products are often not well matched and much of existing technology deserves improvements in reliability, two-way communications, and standardization. A resulting scenario will be new or improved products such as sensors, communications equipment, controllers, and eventually advanced microgrids that do not lock out new ideas or the ability to interconnect with others of slightly different design. Today's developments toward an advanced microgrid are already moving forward but sometimes in a disparate manner.

Deploying advanced microgrid systems will include various forms of energy storage, depending upon system drivers. A microgrid designed to provide critical power during and after disruptive events such as storms will use energy storage or will maintain its own spinning reserve. There will be many tradeoffs. An advanced microgrid designed to improve the economics of a building will likely use batteries as energy storage and will cycle power to and from the grid to benefit system economics. Advanced microgrids with economic drivers may use time-of-day pricing or peak-demand charges to determine when and whether energy is returned to or drawn from the grid. It is likely there will be no two identical advance microgrids in the near-term because the drivers will vary, but it is necessary to establish the infrastructure to handle them all.

This paper provides a vision section that bundles the informations and concepts provided in the paper and that when aggregated shape the vision for an advanced microgrid system. The vision creates an image of a viable advanced microgrid model that integrates features crucial to achieving high-value microgrid system applications interconnected with the utility grid and additional microgrids. Advanced hardware, intelligent inverters, smart controllers, and compatible communications will be the enabling technologies mix to maximize economics and operational benefits of advanced microgrid systems. Advanced and secure communication interfaces and smart controls will increase the value of the energy provided by these advanced microgrid systems. The reliability, resilience, and interoperable electrical service for conventional and advanced microgrid customers is vastly improved over results of today's installed microgrids.

The objectives and scope of advanced microgrid development goals are expanded beyond today's microgrid deployments within this white paper. Discussion focuses on systems that are less than several megawatts but much larger systems will evolve from expansion of the scalable systems and by using many of the basics being developed. The flow of the paper advances from operations mode descriptions, such as interconnected and islanded modes with controls, through dispatched, scheduled, and autonomous operation. The system-architecture discussion addresses the microgrid functionalities, the applications of energy storage, and controls in a detailed overview. A detailed discussion on tools, reliability, and communications provides valuable insights into many options for advanced microgrid developments and designs.

The list of advanced microgrid impacts is extensive and is covered through discussions, definitions, opportunities, and challenges. The many new goals and applications evolving for microgrids are considered in the discussions of impacts and desired results.

Standards and codes play an essential role in moving forward for both the smart grid and compatible advanced microgrids. The status of standards and codes, methodologies being employed to move standards forward to enable advanced microgrid interoperability with the more intelligent electrical grid, and the discussion of domestic and international activities provides a snapshot of the essential work. It must be noted that microgrid and smart-grid components and systems are evolving quickly and fast-tracks for standards will be needed.

1. Introduction and Background

Microgrid concepts and definitions are in flux as their benefits in terms of integrating renewables, cost savings, and grid reliability and resilience are acknowledged. Early microgrid definitions have expanded from their islanded generation and load support to include utility support, and managing generation and load as a part of a more resilient electric power system (EPS). Along with broadened definitions, the scale of microgrids is changing from <1 MW to 2–10 MW, and 60–100 MW in coming years. Many of these changed concepts and definitions will be developed and will become essential parts of new "advanced microgrids" interconnected to smart utility grids or other microgrids.

The U.S. government has recognized the need for increased surety and resilience of the nation's electric grid in order to reach goals for energy independence since the publishing of the Energy Independence and Security Act of 2007.[6] This white paper provides an overview of critical elements of and pathways to the successful pervasive implementation of innovative advanced microgrid systems that can play important roles in future distributed electrical independence. Well-designed microgrids have been in existence for over a decade and they have proven their worth in several installations when natural disasters or grid disruptions occurred. This paper will use some of the existing installations and technology information (use cases) as a base from which advanced microgrids with intelligence, automation, secure communications, and added resilience for the utility can be developed.

The U.S. DOE Office of Electricity Delivery and Energy Reliability (OE) has designated the research and development (R&D) of next-generation microgrids systems a high priority. The DOE's OE has allocated funding for microgrid R&D to meet its 2020 goals "to develop commercial-scale microgrid systems (capacity <10 MW) capable of reducing outage time of required loads by >98% at a cost comparable to nonintegrated baseline solutions (uninterrupted power supply [UPS] plus diesel genset), while reducing emissions by >20% and improving system energy efficiencies by >20%, by 2020."

The DOE Advanced Microgrid Program is aimed at using technology advances and developing or using models that accurately depict functionalities, performance, systems compatibilities, protection methodology, and ultimately deploying hardware. Deployed systems will be designed to maximize economic benefits for grid interconnectivity and islanded performance and to optimize energy profiles and efficiencies.

A major goal for advanced microgrid systems is to develop promising new solutions to integrating advanced microgrids capable of operating in parallel with the utility distribution system and transitioning seamlessly to an autonomous power system complete with its controls, protection, and operating algorithms. It is expected that advanced microgrids will be fielded in a wide variety of electrical environments ranging from substations to building-integrated systems.

[6] The Energy Independence and Security Act of 2007, http://www1.eere.energy.gov/femp/regulations/eisa.html.

One huge opportunity for growth and innovation is implementing innovative controls with new microgrid technologies to prioritize critical loads, while taking into account the sum of all connected energy sources. The resulting determinations will lead to an expanded understanding of the advanced microgrid's ability to provide appropriate voltage regulation, frequency stability, and power characteristics whether grid connected or as an islanded system. R&D for certain new hardware, including sensors, components, innovative inverters, controllers, energy-management systems (EMSs), and advanced energy-storage systems will be required.

Applying new components to advanced microgrids will entail a suite of advanced controls, operational methodologies and protocols, and appropriate secure communications. The standards and codes that specify operational requirements, protocols, and safety must continue to be developed and approved in an accelerated and timely manner. Timely testing to validate the viability, functionality, consistency, reliability, compatibility, and interoperability with utility grids, other microgrid systems, and in islanded states will be necessary.

It is expected that new functionalities associated with smart-grid interoperability and fielded-system testing will serve to accelerate the advanced microgrid systems into the intelligent, distributed electric grid and smart-grid applications. The advances in microgrid technologies will also accelerate the continuing evolutionary processes forward in an expeditious but focused manner.

In order for a microgrid to continue operating after a transition to an islanded mode, it has to include a compatible form of on-site power generation and/or energy storage. Without either, or both, a microgrid could not function properly. The distributed generation (DG) and energy storage become the foundation for the localized islanded smart-grid network. Other critical components include energy storage and a compatible microgrid control mechanism.

Many energy resources will be used in advanced microgrids. Conventional rotating machine technologies using renewable and fossil fuel combined with solar, wind, micro-hydro, and others will be universally compatible. Other designs will use combined heat and power (CHP) technology. It is estimated that a total of 518 MW of CHP capacity will be deployed in microgrids this year.[7] This technology lends itself to most forms of microgrid deployments today and will continue to hold the edge by 2018 (with an estimated 1,897 MW, representing more than $7 billion in annual revenues). Given that CHP can be a base load electricity resource that also provides thermal energy, today's microgrid CHP capacity is the largest of any DG option besides diesel generators.

Benefits of advanced microgrids include:

- Supporting the existing grid infrastructure by adding resilience to the grid infrastructure, locally compensating for the variable supply of renewable energy, and supplying ancillary services such as Volt-Ampere reactive (VAR) support and voltage regulation to sections of the bulk power system.

[7] Executive Office of the President, "Economic Benefits of Increasing Electric Grid Resilience to Weather Outages," http://energy.gov/oe/articles/white-house-council-economic-advisers-and-energy-department-release-new-report, Aug 2013.

- Meeting end-user needs by ensuring UPS 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.
- Enabling grid modernization and interoperability of multiple smart-grid interconnections and technologies.
- Enhancing the integration of distributed and renewable energy resources that help to reduce carbon emissions, peak load congestion, and line losses by locating generation near demand.

In addition to the intended benefits, new innovations for advanced microgrids can be applied to provide secure and advanced automated or dispatched controls for today's legacy electric grid. The advanced microgrid will initiate changes to the grid that will contain nearly self-healing sectors in the event of natural disasters or other massive grid failures. The advanced microgrid systems will use new communications methods that have integrated security and surety for immunity from outside events or adversaries.

A list of the objectives for the DOE Advanced Microgrid Program includes:

- Improves the resilience of the nation's electric distribution infrastructure
- Operates in and seamless transition between "islanded" and "grid parallel" modes
- Provides interconnection and interoperability for smart grids
- Provides cybersecurity for performance and data
- Supports power quality enhancements for connected loads
- Provides two-way communications (frequency, verification, data latency)
- Provides data management and system predictions
- Provides Volt/VAR/frequency controls and support for interconnectivity and island
- Enables dynamic local feeder reconfiguration
- Improves reliability for critical loads
- Provides outage management (i.e., number, duration, and extent)
- Balances distributed and central control
- Enables price-driven demand response
- Reduces peak loads for the interconnected grid
- Integrates with intermittent and variable output renewables
- Defers generation, transmission, and distribution investments

Numerous major disruptions in electrical service shown in Figure 1 clearly indicates the need to develop advanced microgrid systems as a component of overall increased electric grid resilience.[8] Because of this report and similar reports the US DOE's Smart Grid R&D Program directions show microgrids to be a key building block for a smart grid. A significant number of R&D needs and challenges have been identified for microgrids.[9]

[8] Executive office of the President, "Economic Benefits of Increasing Electric Grid Resilience to Weather Outages," http://energy.gov/oe/articles/white-house-council-economic-advisers-and-energy-department-release-new-report, Aug 2013.

[9] Smith, M., and Ton, D., "Key Connections: The U.S. Department of Energy's Microgrid Initiative," *IEEE Power and Energy Magazine*, **11**(4), July 2013.

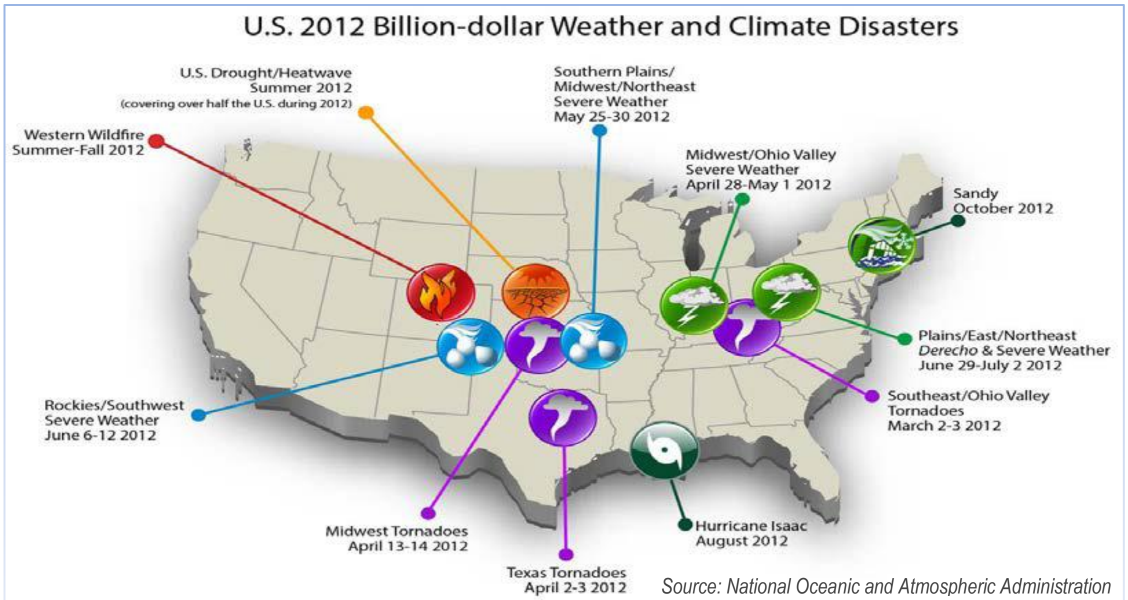

Figure 1. Increasing numbers of natural disasters in the U.S.

Consequently, the United Stated Department of Energy Smart Grid R&D program, the DOE OE Advanced Microgrid Program is addressing the need for a new and complete commercially available advanced and innovative microgrid system capable of reducing outage time of critical loads by >98% at a cost comparable to nonintegrated baseline solutions for a backup system.

A roadmap looking forward to developing dynamic microgrids that accommodate different sources of energy, are self-sustaining –for short times and up to extended periods of operation, exhibit advanced self-healing capabilities and provide optimal management of energy demand and supply has been presented by at Brookhaven National Laboratories.[10] The anticipated evolution path is depicted in Figure 2.

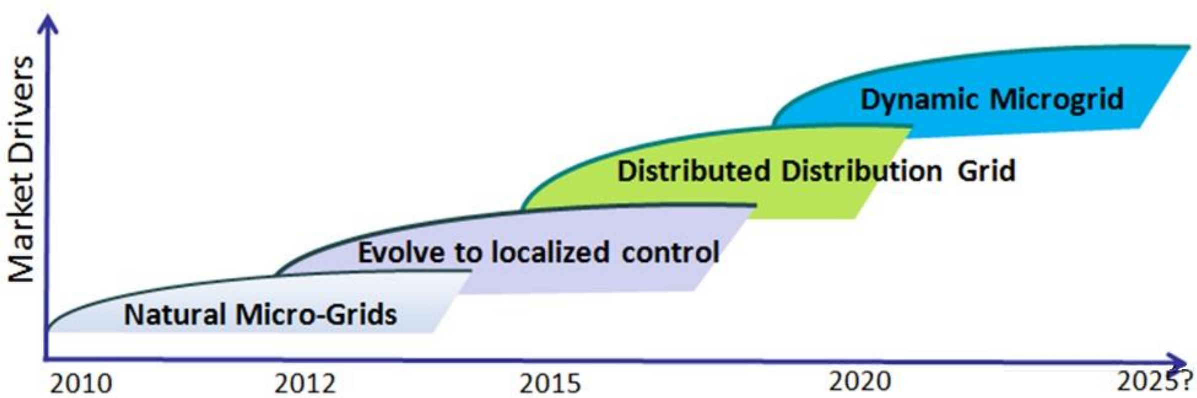

Figure 2. Roadmap to evolving to the dynamic microgrid.

[10] Villaran, Michael, Beyond the Classic Microgrid, Government & Military Smart Grids & Microgrids Symposium, Washington, DC, October 25, 2013

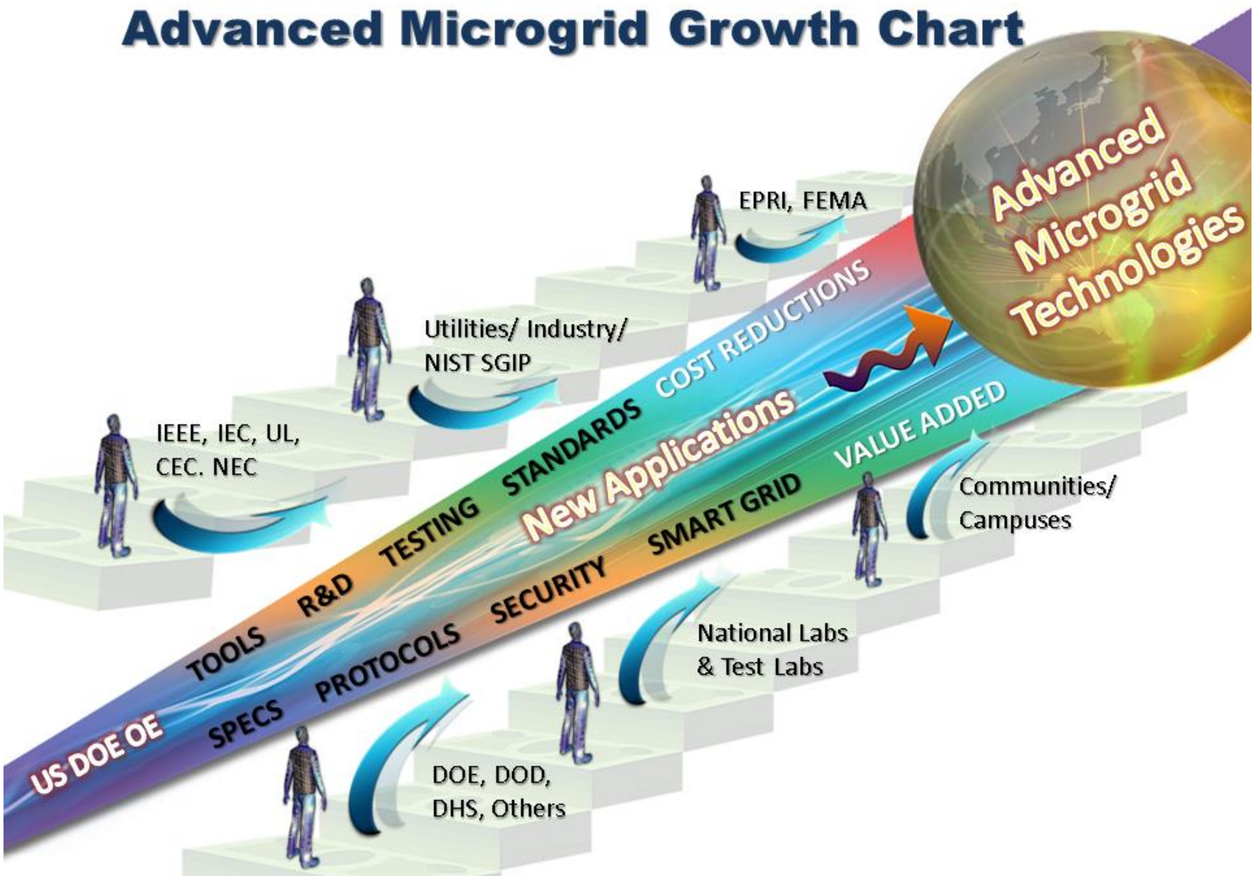

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Figure 3. Advanced microgrid growth showing contributors and essential technologies.

2. Vision—Concept for Advanced Microgrids

Figure 3 shows an illustrated pathway vision toward developing advanced microgrid systems with a depiction of both the primary needs and the participants. All of this work requires a well-coordinated team of experts in applying advanced technologies, funding, cost share, system logistics, system/component testing, standards, codes, and in facilitating interconnectivity with stakeholders and customers.

A viable advanced microgrid model that integrates the following features will be crucial to achieving high-value applications of microgrid systems interconnected with the utility grid and additional microgrids. Advanced hardware, intelligent inverters, smart controllers, and compatible communications will be the enabling technology mix used to maximize a microgrid system's economic and operational benefits. Advanced communication interfaces and smart controls will increase the value of the energy provided by these advanced microgrid systems. The reliability, resilience, and interoperable electrical service for conventional and advanced microgrid customers will be vastly improved over results of today's installed microgrids.

The term “DR islanded systems” sometimes referred to as microgrids, is used for electrical power systems that:

- have distributed resources (DRs) and load,
- have the ability to disconnect from and parallel with the area EPS,
- include the local EPS and may include portions of the area EPS, and
- can be intentionally islanded.

DR islanded systems can be either local EPS islands or are larger EPS islands.

The defining characteristics/features of an advanced microgrid:

1) Geographically delimited or enclosed
2) Connected to the main utility grid at one point of common coupling (PCC)
3) Fed from a single substation
4) Can automatically transition to/from and operate islanded
   a) Operates in a synchronized and/or current-sourced mode when utility-interconnected
   b) Is compatible with system protection devices and coordination
5) Includes DR, but generator agnostic and according to needs of customer with
   a) renewables (inverter interfaced),
   b) fossil fuel based (rotating equipment generators), and/or
   c) integrated energy storage
6) Includes an EMS with
   a) controls for power exchanges, generation, load, storage, and demand response and
   b) load-management controls to balance supply and demand quickly
7) Includes power and information exchanges that take place on both sides and across the PCC in real time

3. Advanced Microgrid Objectives

The main objectives of the DOE Advanced Microgrid Program is to develop and better enable the technologies needed to increase the ranges and applications of energy-efficient advanced microgrids. They are capable of maintaining or improving the power quality, reliability, and resilience of the utility grid during times of interoperability. These objectives go beyond technical advances and include system modeling for continued evolution of microgrids. Advanced microgrids will improve the nation’s energy infrastructure resilience, provide value added that improves electric power quality, enables assurance of power to critical loads, creates avenues for personal security, and supports emergency services. Spinoff devices and secure communication will be beneficiaries for other applications such as more intelligent grid infrastructure, smarter loads that will be considered part of the smart grid infrastructure, building energy management, and optimized demand-side management.

Essential components to be employed will include state-of-the-art, highly integrated components, innovative controlling devices, advanced intelligent inverters, and compatible balance-of-system elements for all-sector energy applications. Advanced integrated inverters and controllers will also incorporate building energy-management functions with improved compatibilities with today’s building energy management. They will also communicate with new utility energy portals. New advanced microgrids will employ products equipped for compatibility with the legacy grid of one-way power flow, intermediate evolving grids, and the future grid of a two-way power flow. DRs such as solar, wind, advanced demand-response systems, and optimized energy storage will be employed in fielded advanced microgrid systems.

Figure 4 shows a pictorial diagram illustration of a microgrid with several examples of interconnectivity. The new advanced microgrid systems will use similar, but more complex interconnectivity, security, and combinations of renewable energy resources.

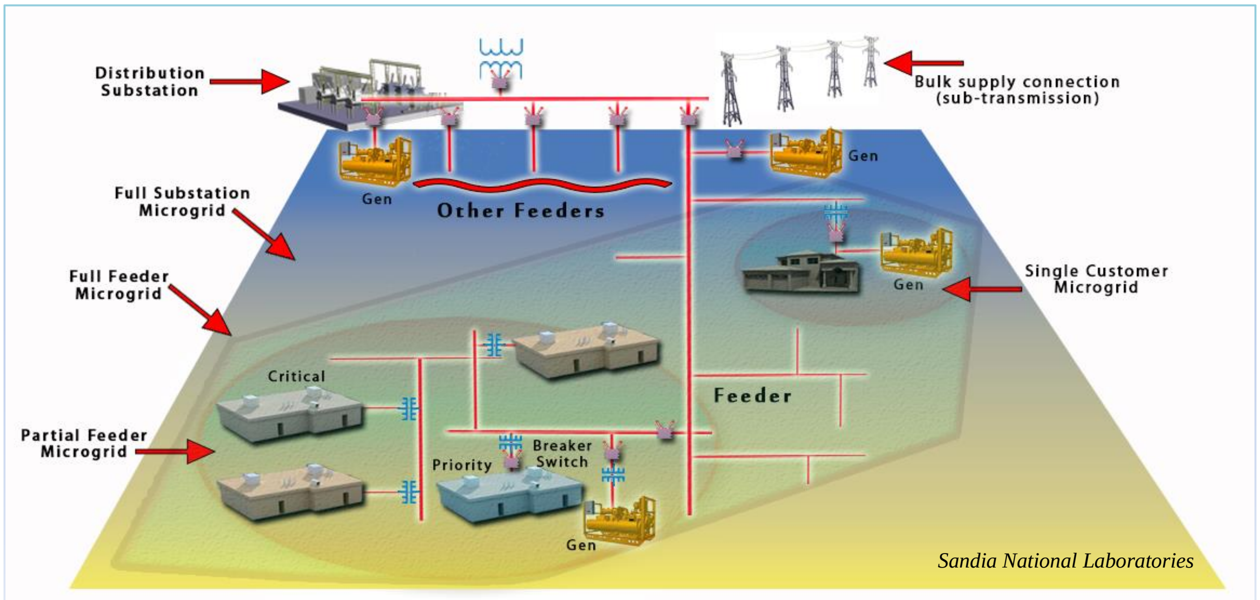

Figure 4. Microgrid categories and examples of interconnectivity.

4. Advanced Microgrid Program Scope

The scope of the Advanced Microgrid Program is to improve the reliability and increase the value of large, innovative microgrids (initially up to 10 MW capacity). The Advanced Microgrid Program will leapfrog current communications technology through advanced and secure communications. It will use adaptive logic to optimize a system's energy resources and the energy storage, and develop new interfaces for advanced autonomous operation (islanded operation) with seamless interconnectivity with the national electric grid. The new proven products and processes will increase the value of advanced microgrids interconnected with today's one-way electrical distribution infrastructure and tomorrow's two-way smart grid and other microgrid systems.

The newly designed inverters and controllers will interact with EMSs and provide demand response for the interconnected grid and islanded loads. Optimized energy storage and the electric-utility infrastructure will work together as a DG and energy storage system while increasing the utility grid's overall reliability and resilience.

Table 1. Important Advanced Microgrid Contributing Elements

Name	***Type***	***Element Description***
Area EPS	System	The EPS that normally supplies the microgrid through their PCC.
EMS	System	EMS acting at the interface between loads and the microgrid. It communicates with smart devices and to the outside with the microgrid control center. It aggregates the services of the smart devices and provides further services to the microgrid. Furthermore, it can implement some level of intelligence to fulfill the services.
Grid Control Center	System	Control center from which the grid is operated. All required supervision and control functions are carried out here.
Market Operator (MO)	System	The system that procures energy and ancillary services and ensures reliability for the area EPS. The MO may be part of the area EPS or may be a separate entity.
Microgrid Control Center	System	The control system comprising different microgrid operator subsystems that ensures the control & management tasks of the microgrid and the aggregation of supply and demand.
Microgrid Controller	System	A control system able to dispatch the microgrid assets, e.g., opening/closing switches, changing control reference points, changing generation/consumption levels, etc. Other than the microgrid functions specifically referenced below, this use case does not specify the objective of any of the microgrid controller functions. This use case does not specify how the control signals are transferred or implemented in the microgrid assets.
Consumer	Person/ Org	A consumer of electricity, e.g., a private house, business building, large industrial/manufac-turing industry or transportation system. The consumer acts as a customer. The consumer may operate smart appliances (an electric load with some intelligence to control it) that are flexible in demand.
DER Owner	Person/ Org	The distributed energy resource (DER) owner (or DG owner) operates a DER (or DG) that is connected to the microgrid.
Service Provider	Person/ Org	The service provider provides different kinds of services to the microgrid operator to support him in the operation of the microgrid, e.g., weather forecasts or energy market analysis.
Storage Owner	Person/ Org	Provider of storage capacity for storing and delivering energy.
Aggregator	Org	Market participant that purchases/sells electricity products on behalf of two or more consumers/generators/DERs. In a small microgrid, the microgrid operator could act also as aggregator. In a large microgrid, the aggregator might be a legal entity and the microgrid operator contracts with this entity.
Grid Operator	Org	The grid operator is the operator of the grid to which the microgrid has a connection point. The term "grid operations" refers to the undertakings of operating, building, maintaining, and planning electric power transmission and distribution (T&D) networks.
Microgrid Operator	Org	The microgrid operator acts as system operator in the microgrid and is responsible for operating, maintaining, and, if necessary, developing the microgrid's distribution system. In some use cases, e.g., running the microgrid in an islanding mode, the microgrid should take over the roles of the energy retailer and/or the aggregator to ensure system stability.
Retailer	Org	Entity selling electrical energy to consumers. Could also be a grid user who has a grid connection and access contract with the transmission system operator or distribution system operator (DSO)
DER Unit	Device	DER including DG (small photovoltaics [PV], wind, etc.) connected to the microgrid. The device provides some degree of intelligence to facilitate monitoring and control.
Network Smart	Device	An intelligent electrical device in the microgrid that can be supervised and controlled (e.g., sensors, circuit breakers, or switches)
Storage Unit	Device	A storage unit provides an electricity reserve to the microgrid. The device provides some degree of intelligence to facilitate monitoring and control.

Table basics provided by James Reilly, Lead, NIST Smart Grid Interoperability Panel, Subgroup C - microgrids

This program emphasizes the development and ultimate demonstration of viable and complete advanced microgrid systems in the 10 MW power-capacity range. The broad technical requirements of advanced microgrids reveal a new level of architecture complexity for microgrid systems and certainly the need for coordination of close collaborations and teaming.

Table 1 shows the elements that are most likely to be contributors to research, designs, and deployment for the microgrids. Colors are used to identify the different element categories. This list includes a collection of elements (sometimes referred to as actors) described as contributors in case studies by the Smart Grid Interoperability Panel (SGIP) headed by the National Institute of Standards and Technology (NIST).[11]

Table 2 outlines the ranges of probable advanced microgrid early market applications.

Table 2. Today's DOE Microgrid Program Applications—Power Categories

Commercial	Greater than 50 kW, three-phase and functionally expandable
Community/Campus	1–10 MW may be modular or single rating
Utility Scale	>10 MW possibly using multiple interconnected microgrids

Future advanced microgrid systems present many opportunities and potential applications. It is an area of vigorous and likely exponential growth with a wide variety of applications and interconnections with utility grids. Although current technology is being installed today with early automated functionalities for supplying power to critical loads, the advanced microgrid systems will be the favored technologies that interconnected utilities will demand as higher DER and renewable energy generation penetration results in the need for a virtual system of advanced microgrids and a more complex intelligent electric distribution infrastructure. Figure 5 shows a projected growth for installations over the next five years.[12]

[11] Executive office of the President, "Economic Benefits of Increasing Electric Grid Resilience to Weather Outages," http://energy.gov/oe/articles/white-house-council-economic-advisers-and-energy-department-release-new-report, Aug 2013.

[12] Asmus, Peter, "Moving Microgrids into the Mainstream," Contributor, Chart from Pike Research, http://www.forbes.com/sites/pikeresearch/2012/10/17/moving-microgrids-into-the-mainstream/.

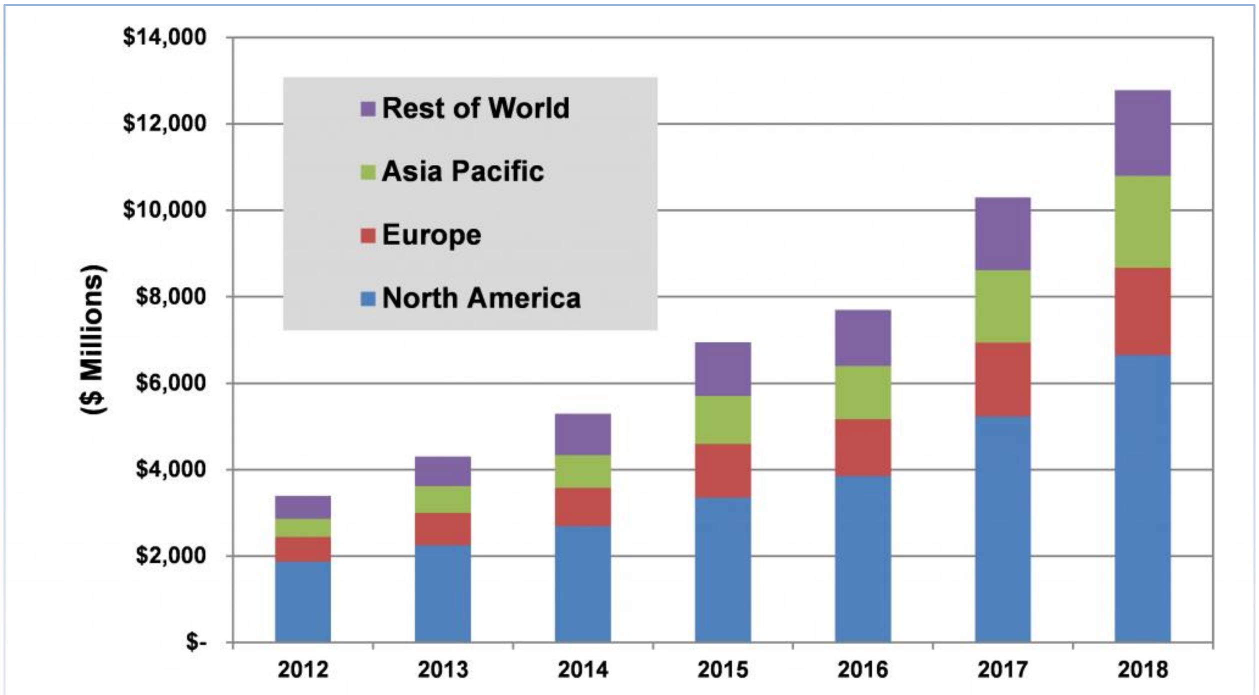

Figure 5. Projected worldwide microgrid market (2012–2018). Source: Pike Research (Forbes.com)

5. Advanced Microgrid Operational Modes

5.1 Interconnected and Islanded Operation

An advanced, interconnected microgrid system must meet all of the operational and interconnection requirements that utility electric grids must meet. Advanced microgrid systems will provide high-quality power to their loads with safety protections, synchronization, harmonic distortion limits, voltage limits, support for devices requiring VARs, surge capabilities, and protection-device coordination. The PCC is typically where the standards and codes in effect today apply. New rules to cover the anti-islanding that have been in place for over a decade are being changed. The IEEE1547 Recommended Practice is commonly applied today, but there is a new recommended practice on the way (IEEE1547a) and the revised IEEE1547.4 has provisions for allowing islanding. Results of the evolution of the microgrid concept have been captured in the latest version of IEEE1547.4. Seamless transfers from grid-interactive to islanded modes will become commonplace. Advanced microgrids will be required to meet the new IEEE1547a as its new interconnection standard once it is published in the U.S. Other standards are also likely to provide requirements for microgrid components and systems as harmonization of international and domestic standards evolves. Regardless, R&D for advanced microgrid systems must be broad-base in order to meet today's interconnect standards, but also to support utility value propositions, such as the supply of fault current, that may yet to be reflected in current standards.

5.2 Dispatched, Scheduled, and Autonomous Microgrid Operation

Whether future advanced microgrid support will be dispatched, scheduled, or automatic will depend on many factors such as but not limited to

- power throughput capabilities of the microgrid's resident controller or inverter-controller,

- speed of detection and speed of response of all equipment,
- communications and the need for dispatch,
- reliability of all equipment,
- number and locations of microgrids on the same feeder,
- energy storage capacity and peak power delivery, and
- codes and standards requirements.

Advanced microgrid development will provide opportunities for deploying, monitoring, and exercising new advanced microgrid capabilities, advanced control algorithms, utility interconnectivity, and resulting distribution system impacts as well as the impacts on local loads that will be supplied by the microgrid in an islanded state. Automatic or dynamic utility support by advanced microgrids will need extensive testing and analysis with a majority of the interconnected systems. An advanced microgrid system connected to a utility grid where the majority of the power supplied by the primary energy system should present a benign addition to the distribution system while providing reliable backup power to the microgrid system loads.

When the smart-grid capabilities on newly developed inverters and the new controls were first demonstrated during the DOE Solar Energy Grid Integration Systems (SEGIS) program conservative approaches were the first steps taken by Pacific Gas & Electric (PG&E) and other utilities to allow for scheduled VAR support as a smart-grid function. This was generally only where the needs for distributed VAR support were predictable. Recently, however, demonstrations of dispatched and automatic support are taking place. PG&E, for instance, reported that on March 17, 2012, a total of four low-voltage ride-through (LVRT) events took place. The low-voltage condition was caused by momentary phase-to-phase faults on an adjacent 12 kV circuit that was fed from the same substation where a PV system was connected. The inverter provided power during that low-voltage event instead of dropping off line per the current IEEE1547 requirements when the support was needed.

According to the same report, a similar event occurred at the same location when an adjacent feeder experienced a short-circuit condition causing both A and B phases at the connected substation to experience a voltage sag to 50% of normal, which activated the inverter's LVRT capabilities. The protective relays on the faulted 12 kV circuit detected the short circuit and cleared the fault in ~7 cycles. The inverters successfully rode through the event and returned to normal operation upon clearance of the short-circuit condition. Schweitzer Engineering Laboratories (SEL) graphs were collected and reviewed by PG&E's Renewable Resource Development department. Figure 6 shows the voltage and current waveforms taken from the SEL relay on the substation.[13]

[13] Hionis, Anastasios and Ng, Steven, "Case Study: Advanced Energy PV Inverters Ride-Through PG&E Low Voltage Events," http://www.google.com/#fp=492a54485f563ccb&psj=1&q=PG%26E+Case+Study+260-01, 2012.

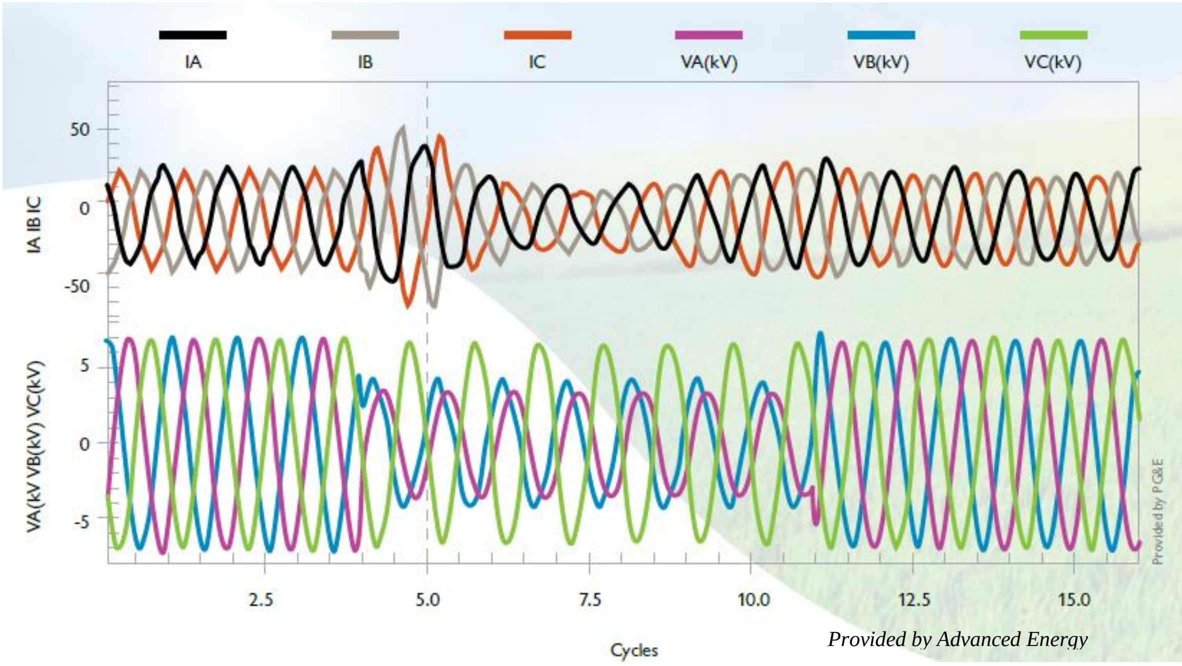

Figure 6. Voltage and current plot from the SEL relay for the voltage-sag event.

These real-time events have demonstrated the LVRT capabilities for inverters without energy storage. Extended periods of other smart-grid functionalities are probable with an advanced microgrid system. Advanced microgrids will require energy storage as well as advanced controls to autonomously transition further into an islanded state or to provide more extended periods of grid support.

5.3 Commanded Shutdown, Ramp-Up and Ramp-Down While Grid-Interconnected

Advanced microgrids, connected to a primary energy source such as a utility electricity distribution system, will have built-in algorithms and communications for shutdown, start-up, and curtailment. Each of these functionalities may also be commanded when the stability or voltage regulation of a section of distribution line is in danger of drifting out of specification because a load/distribution mismatch. Adequate communications methods will be necessary for these conditions.

Commanded shutdown that overrides normal shutdown processes will not be as likely, but if intermittent renewable energy sources such as PV are linked into the system there may be a need for curtailment, commanded startup slew rates, and energy-storage interactions.

5.4 Black Start In an Islanded State

A critical requirement of an advanced microgrid comes into play when reconnection to loads occurs in the islanded state especially after the microgrid has been inoperable but loads are still connected. This connection of the microgrid to the loads in the islanded state is called “black start.” Where conditions on the main grid result in the microgrid being disconnected from the main utility, the advanced microgrid should transition either seamlessly or as quickly as possible and continue to operate as connected DG. During the reconnection state, the operating states of reconnecting to the load reclosing must be carefully considered as must the capability of the advanced microgrid to provide startup surges and voltage regulation.

Developing local controllers in close co-ordination with an advanced microgrid central controller must be evaluated from the dynamic-operation point of view. Testing and studies will likely need to be performed in a simulation and in real time. The black-start functionality will help assure power system operation, power supply reliability, and protection to critical loads.

The restoration procedure in an advanced microgrid is somewhat similar to the approach adopted for medium-sized power systems. Several sources within the advanced microgrid must have black-start capabilities. A stand-by power supply and a monitoring and control scheme will likely be embedded in the microgrid control center, but autonomous inverter functions may suffice. Black-start functionalities within advanced microgrids will need minor changes in available standards such as IEEE 519 for harmonics and voltage, with time-dependent or load-dependent specifications called out for microgrids.[14] Load shedding may be an alternative method to assure an advanced microgrid power supply that meets today's interconnection standards requirements.

6. Advanced Microgrid System Architecture

6.1 System Architecture

New concepts in architecture, controls, and energy-storage application will continue to be a necessary investment. To fully realize the environmental advantages of advanced renewable generation resources discussed earlier in this report, power systems will continue to be pushed to higher penetration levels of renewable sources. The impact of resource balance is broad and complex. Systems will effectively be operating with stochastic sources and loads making power balance, transient performance, and stability much more complex objectives to achieve. Many solutions may be envisioned to solve this challenge—ranging from source-side management with high-bandwidth generators, to energy storage, or demand-side management. The burden of compensating for this new variability may also be placed in the controls/communication subsystems with migration from centralized designs to highly distributed structures.

A critical challenge that new concepts must address is the optimal mix of power flow. Sixty Hz AC has the historical investments within the U.S., however DC systems have advantages with regard to increasing system efficiency by reducing the number of power conversions between the system and non-60-Hz sources or energy storage. Networked hybrid designs may prove to be the optimal configuration for efficiency and performance. Understanding the optimal mix to create more efficient and resilient systems of the future is important to guide the investments being made today. Research at the National Renewable Energy Laboratory (NREL), the Consortium of Electric Reliability Solutions **(**CERTS), Sandia National Laboratories (the secure, scalable microgrid test bed shown in Figure 7), and other institutions around the world are developing technologies to address the challenges associated with high-penetration of renewable resources. Both the Institute of Electrical

[14] "IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems," Persistent Link, http://ieeexplore.ieee.org/servlet/opac?punumber=2227.

and Electronic Engineers (IEEE) and sections of DoD are recognizing the potential value of DC and hybrid systems through the formation of standards committees and investments in long-term research. International efforts are harmonized with efforts such as the extension of the DRGS SGIP Architecture shown in Figure 8.

Figure 7. Sandia National Laboratories' secure, scalable microgrid test bed: a flexible platform for collective microgrid research, development and validations.

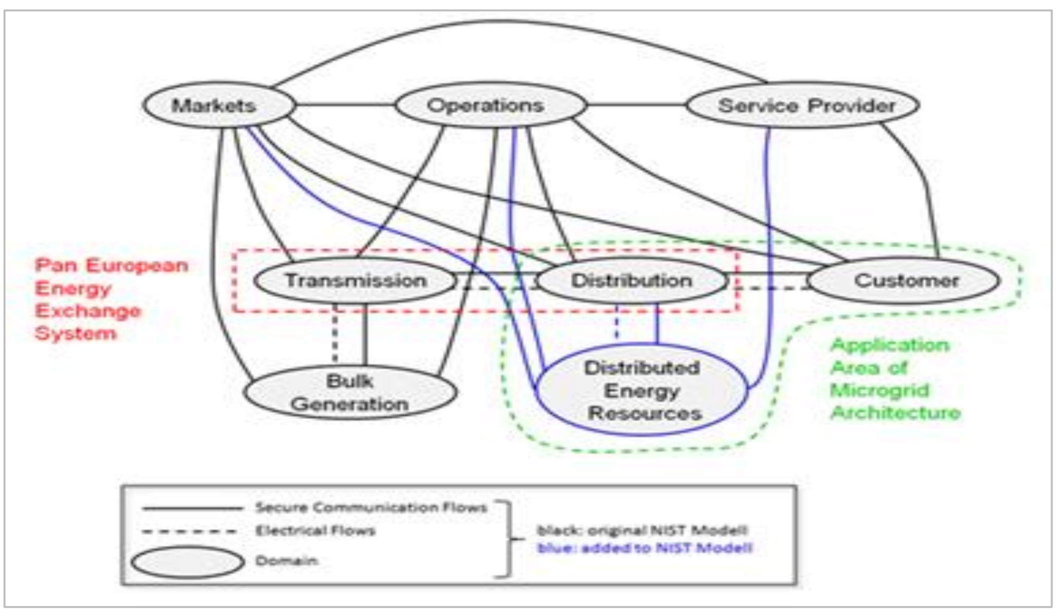

Figure 8. European extension of the DRGS SGIP architecture

6.2 Microgrid Control and Operation

Microgrid controls and operational functions are being described within the SGIP as part of the Distributed Renewables, Generators, and Storage (DRGS) Domain Expert Working Group (DEWG)

Subgroup C - Microgrids and Hierarchical Distributed Control in terms of its functions have been described as follows[15].

Function 1. Frequency control
- *F1.1 Islanding mode*
- *F1.2 ACE control and connected mode (like AGC)*
- *F1.3 Frequency smoothing*
- *F1.4 Frequency ride-through*
- *F1.5 Emergency load-shedding*
- *F1.6 Steady state control*
- *F1.7 Transient control*

Function 2. Volt/VAR control
- *F2.1. Grid-connected Volt/VAR control*
- *F2.2. Islanding Volt/VAR control*

Function 3. Grid-connected-to-islanding transition
- *F3.1 Intentional islanding transition*
- *F3.2 Unintentional islanding transition*

Function 4. Islanding-to-grid-connected transition

Function 5. Energy management
- *F5.1. Grid-connected energy management*
- *F5.2. Islanding energy management*

Function 6. Protection

Function 7. Ancillary services (grid-connected)
- *F6.1. Real-power-related ancillary services*
- *F6.2. Reactive-power-related ancillary services*

Function 8. Black start

Function 9. User interface and data management

7. Advanced Microgrid Technical Challenges

7.1 Operations and Control

The advanced microgrid presents major challenges from the point of view of its reliable operation and control from the main control principles (e.g., droop control, model predictive control, multiple-agent systems with cooperative controls) to microgrid energy-management systems (μEMSs). Future advanced microgrid systems will trend to coordinated, networked microgrid operations based on varying ownership models (utility-owned, non-utility-owned, virtual, and their combinations). The trends are currently being better defined across the industry.[16] Microgrid control strategies can be classified into three levels: primary, secondary, and tertiary, where primary and secondary levels are associated with microgrid operation itself, and tertiary level pertains to the coordinated operation of the microgrid and the host (macro) grid.

[15] Xu, Yan, Microgrid Control and Operation Use Cases (Outline), Oak Ridge National Laboratory, for NIST SGIP Subgroup C - Microgrids and Hierarchical Distributed Control Subgroup, Jun 11, 2013.

[16] "Trends in Microgrid Control," IEEE PES paper to be released July 2014.

A key microgrid operation element, the control function that defines the microgrid as system that can manage itself, operate autonomously, and properly connect to the main grid for the exchange of power and the supply of ancillary services is the microgrid energy-management system.

A microgrid energy-management system enables interoperability of different controllers and components needed to operate the EMS through cohesive and platform-independent interfaces. This approach allows for flexibility and customization of deployed components and control algorithms without sacrificing "plug-and-play" or limiting potential functionality.

Microgrid components and operational solutions exist in different configurations with different implementations. Regardless of whether equipment and software are commercial or custom, components should be interoperable and with interfaces that comply with functional standards defined by the μEMS.[17] State of the art control methods must be developed that pertain to different control levels from the perspective of the advanced microgrid.

The hierarchical levels of control can be categorized as primary, secondary, and tertiary.

a) *Primary control* is the level in the control hierarchy that is based exclusively on local measurements, which includes islanding detection, output control, and power sharing (and balance control).
b) *Secondary control*, the μEMS, is responsible for microgrid operation in either the grid-connected or islanded mode.
c) *Tertiary control* is the highest level of control and sets long-term and "optimal" set points depending on the host grid's requirements. Tertiary control coordinates multiple microgrids interacting with one another in the system and communicates requirements from the host grid (voltage support, frequency regulation). Tertiary control is considered as part of the host grid, not the microgrid itself.

Figure 9 depicts the hierarchical levels of control that will be applied to advanced microgrids.

[17] *Microgrid Control*, Dr. Geza Joos, McGill University, Canada October 2013.

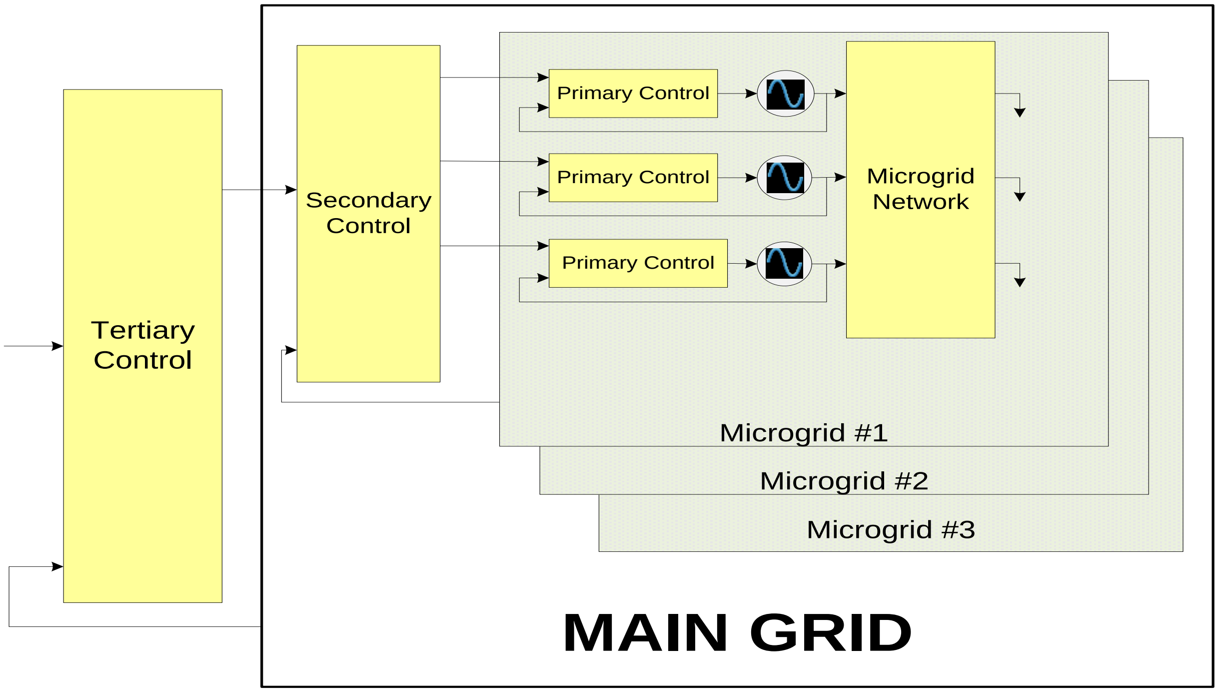

Figure 9. Hierarchical control levels in networked microgrids (to be released Q1 2014).

7.2 Energy Storage

Advanced microgrids will not exist without an energy-storage element (e.g., fossil fuel, flywheels, batteries, capacitor banks, pumped hydro, as well as other forms). An advanced microgrid's required reliability and resiliency will help drive energy storage cost. These requirement demand further R&D of design and analysis approaches to optimize energy storage selection and placement within a microgrid to minimize capital cost and operational cost of such systems. The need for energy storage in low-inertia power systems also drives the need for more advanced control schemes, potentially distributed in nature, to ensure that appropriate response times support a stable system. System efficiency targets will continue to drive minimizing how many power conversions occur in advanced microgrids. These must take into account conversions from DC sources and storage to AC power flow. Long-term investments in microgrid technologies must continue to target DC and hybrid (AC/DC) architectures to fully optimize the system efficiencies.

7.3 Component Designs and Compatibility

Advanced microgrids will almost always use inverters and controllers to interface with the EMS or other coupled microgrids. Inverters can provide many functions that enable smart-grid interoperability. The SEGIS program was a proactive DOE-sponsored initiative to design smarter PV systems with inverters and controllers that provided functionality for more intelligent PV and other DERs. The SEGIS initiative provided demonstrations of these "value added functions" as part of its final deliverables to demonstrate the advanced functionalities to the distribution grid.[18] The existing standards did not allow most of the new functionalities—functionalities that are now seen as stabilizing features and energy-saving additions to a utility distribution grid with DR

[18] Bower, W., "Solar Energy Grid Integration Systems (SEGIS)-Adding Functionality While Maintaining Reliability and Economics," SPIE Conference; San Diego, CA; Aug 22, 2011.

interconnections. SEGIS feature adoption is becoming more common with scheduled and dispatched commands for the features being used now but with rapid changes toward dynamic and autonomous functionalities being considered and soon required for PV and other DR interconnections.

The SEGIS interconnectivity pathways developed over the three-year program are illustrated in Figure 10.

Figure 10. SEGIS interconnectivity advances applied to inverters.

Important smart-grid interoperability functions developed and demonstrated during the SEGIS and follow-on programs that are now available for advanced microgrid systems and the necessary interconnectivity include:

- PV systems integration and economic optimization
- DC bus for multiple-source energy supply
- VAR support (scheduled, dispatched, and dynamic)
- LVRT functions
- System performance predictions
- Source intermittency mitigation
- Integrated communications for measurement devices, sensors, inverters, controllers, and EMSs
- Applications for phasor measurement units (PMUs)
- Mesh network, power line communications, and wireless communications alternatives
- Data collection and advanced analysis
- Anti-islanding and intentional islanding controls

- Power output slew rates and curtailment
- Microgrid enablement (islanded state with black start)
- Building EMSs
- Performance/economic optimizations
  - Utility support (value added)
  - System optimization (economics)
- System monitoring and data analysis
- Modeling

7.4 Analytical Tools

As advanced microgrids evolve in complexity, analytical tools for field projects, technologies, control strategies, and assessing cost/benefits will be necessary. Some of the analytical tools include

GridLAB-D

A power-system simulation tool that provides valuable information to users who design and operate electric power T&D systems and to utilities that wish to take advantage of the latest smart-grid technology. GridLAB-D was developed by Pacific Northwest National Laboratory and is in the public domain.

Distributed Energy Resources Customer Adoption Model (DER-CAM)

DER-CAM was developed by Lawrence Berkley National Laboratory and its functionalities and scope include:

- Available routines to minimize annual energy costs, CO_2 emissions, or multiple objectives of providing services at building microgrid level (typically buildings with 250–2000 kW peak) but can be applied elsewhere
- Results with technology-neutral and pure-optimal results with highly variable run time
- Designation by Berkeley Lab and collaborations in the U.S., Germany, Spain, Belgium, Japan, and Australia over ~10 years. Commercialization by Software-as-a-Service is currently under license

Performance Reliability Model (PRM)

- Under development by Sandia National Laboratories
- Restricted access

Technology Management Optimization (TMO)

- Under development by Sandia National Laboratories
- Restricted access

7.5 Reliability

The North American Electric Reliability Corporation (NERC), which the Federal Energy Regulatory Commission (FERC) has certified as the nation's electric reliability organization, has developed critical infrastructure protection (CIP) cybersecurity reliability standards. On January 18, 2008, FERC issued Order No. 706, the final rule approving CIP reliability standards, while concurrently directing NERC to develop significant modifications to address specific concerns.[19] Work continues, with reliability being a high priority, on developments related to developing smart-grid and microgrid strategies.

One reliability aspect of microgrid applications is related to (a) components integrated into the microgrid systems, (b) components related to interoperability with the utility grid, and (c) whether the microgrid's functionality is compatible with current infrastructures. Those reliabilities are typically assessed as mean-time-between failures (in hours) and must be assesses during a system's (such as a microgrid's) design.

The reliability of the power being delivered to critical loads is another aspect of reliability. An understandable grid-reliability measure is the number of outage minutes per year. Self-healing features are one method for adding resilience to established electric grid infrastructure.[20] Advanced microgrids are another method to improve critical-load power reliability. The microgrid basically can be considered a redundant energy source when a viable electric grid is available.

7.6 Communications

Communication will be a critical function for advanced microgrid systems. Communication with the DSO will be essential to ensuring safe, reliable operation as system numbers and penetration increase. Additional communication functions will be critical to optimizing system value. Advanced microgrids will need to use protocols based on new system standards in order to be broadly applicable. Greater market penetration will be more attainable when communications capabilities compatible with other standards, such as the pertinent International Electrotechnical Commission (IEC) standards, are developed. Providing secure communications between system monitor and control functions spread out over long distances back to a centrally located supervisory control and data acquisition (SCADA) -type administrative control site will increase acceptability. Dedicated virtual private networks can be implemented to specify security features and separate different user traffic over a SCADA network.

Because microgrids lack the inertia of an interconnected power system, having a good understanding of what is happening at any point is critical. Microgrid operating conditions can change very quickly with incremental load or generation. PMUs are able to directly measure the state throughout the microgrid (with near-real-time updates up to 60×/second), thus providing needed visibility of the actual operating conditions. Also, this can be useful for control the microgrid system as well (PMU measurements are used in a control system that keeps the system operating in a safe region).

7.6.1 Distributed Measurements.

PMUs provide distributed measurements throughout the microgrid that can be useful for understanding system operation or tuning system components or for providing additional information in post-event analysis. Because PMU functionality is available in protective relays, voltage regulators, reclosers, and meters, PMU measurements are readily available across the microgrid.

[19] http://www.ferc.gov/industries/electric/indus-act/reliability/cybersecurity.asp.

[20] Amin, Massoud, "Toward Self-healing Energy Infrastructure Systems," *IEEE Computer Applications in Power*, Jan 2001.

7.6.2 Synchronization.

PMUs are ideal for measuring voltage magnitude, angles, frequency, and slip between any two portions of the electric system. This could be the islanded microgrid and the rest of the interconnected power system, or this could be portions of the system within the microgrid (e.g., a generator looped line feeder). One big benefit of using PMU measurements for resynchronizing is that no portion of the system must be “turned off” to resynchronize the microgrid to the utility connection.

Synchrophasor measurements can help operators quickly identify islanded portions of the system (monitor frequency of the various PMUs).

7.6.3 Metering

With PMUs spread around the microgrid, the user can effectively see where power is flowing, where the loads are, where the generation is, how large the load is, etc. Because users have access to voltage and current phasors, they can see real and reactive power flows within the microgrid.

7.6.4 Anti-Islanding and Islanding Control

The inverters in today’s DR systems monitor grid parameters and disconnect when those parameters fall outside the ranges established in IEEE1547. As the number of interconnected inverters increases, as noted above, a more interactive method is needed to ensure that inverters will disconnect when required, but will also ride through variations in utility operating parameters likely caused by high demand. Communication of the need to disconnect must be fast (less than one second) and certain (always occurs when connection to the utility is lost). The distance over which this information must travel is potentially long, but the amount of information required is small.

7.6.5 Internal Communication

Communication within the system is critical to controlling loads and storage to optimize system value while maintaining system safety. Distance over which data must travel will generally be modest, unless the site is a large commercial system or microgrid. In addition to ensuring safe, efficient system operation, a system that is connected under time-of-day and/or demand rate structures will be trying to balance the available energy from the solar generating system, other connected DG sources, and storage with variations in loads and utility pricing. While solar output can change rapidly with cloud passages and loads can change with the flick of a switch, utility demand charges are usually assessed over a 15–30 minute period, so the system has time to respond. However, in the event of off-grid operation, the system must act quickly to prevent load from exceeding maximum system capability (maximum inverter rating and/or available solar plus storage system discharge capability) at any given time. If the system is not permitted to export power, then loads, storage, or the inverter output must be controlled to avoid back feed (less than one cycle).

7.6.6 Communication Methods and Protocols

Communication types and applications in use or under consideration in some case are summarized here.

Dedicated copper wiring. Large transmission-connected generators use dedicated copper wiring for control, but the cost to connect with large numbers of individual DG systems would be very high.

Dedicated fiber-optic link. Substations and control centers are increasingly using fiber-optic links for dedicated, secure communications. Dedicated fiber-optic links provide speed and reliability that enables real-time communication with synchrophasors.

Ad hoc mesh networks. Smart, granular network topologies that use ad hoc connection methods, whereby individual devices discover others within range to form a cooperative mesh communication network capable of establishing a massive infrastructure with end-to-end routing links.

Continuous-carrier power line communications carriers. Used by some utilities for automated meter reading systems. The power line communications carrier signal is lost if the connection to the utility is lost, so this signal could be effective for inverter anti-islanding control. Drawbacks are high cost, low bandwidth, and high power demand.

Broadband-over-power-line. This approach takes advantage of existing power-line infrastructure to communicate data, but this technology has faced technical issues, including interference with other radio spectrum users and interference from loads. Some systems have gone to digital multiple-carrier modulation scheme to mitigate radio interference issues.

Ethernet. Provides communications within buildings, but must be connected to a wide-area-network technology, such as cable television. Wide-area networks do not have sufficient reliability to support protection functions.

Wireless local area network (IEEE802.11). Used inside and outside of buildings to provide short-distance wireless data.

Wireless interoperability for microwave access (IEEE802.16). Provides longer range wireless access.

Wireless metropolitan area networks (IEEE802.16d). This is a standards-based technology enabling the delivery of last mile wireless broadband access as an alternative to cable and DSL (digital subscriber line). It is often used in urban environments to transmit 2 km without line-of-sight antenna configurations and up to 10 km with unobstructed path.

Personal area networks (e.g., IEEE802.1). Provides short-distance (few meters) wireless communications.

BACnet. Developed under the auspices of the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), BACnet® is an American national standard, a European standard, a national standard in more than 30 countries, and an International Organization for Standardization (ISO) global standard.[21] Further, the protocol is supported and maintained by ASHRAE Standing Standard Project Committee ANSI/CEA-709.1-B establishes another standard for control networking. It provides one of the data link/physical layers of BACnet®.

Leased telco links. These are point-to-point communications links via leased lines that may also include microwave-relay links and two-way radio.

[21] BACnet® is a registered ASHRAE trademark. The website is dedicated to providing the latest information on BACnet, "A Data Communication Protocol for Building Automation and Control Networks," http://www.bacnet.org/.

Shared-fiber VLAN/QOS. Virtual local-area networks (VLANs) provide a secure method to communicate using mutually isolated, optically coupled devices. The packets of information can only pass between them via one or more dedicated routers. This also provides for a new layer of quality of service (QOS).

Other. A variety of other technologies are available, including conventional telephone landlines, cellular telephone, spread-spectrum radios, and pagers. Some utilities have used wireless technology to dispatch customer loads, e.g., Nevada Power's Cool Share program.

7.6.7 Communication for System Optimization

As communication techniques and information flow in advanced microgrids evolves, the opportunity for further system performance optimization must be considered. Research that enhances the holistic microgrid design and analysis, taking into account the communication flow, will become a more significant focus of system design. Tools and design approaches that effectively allow tradeoffs between information flow and component performance will continue to be developed.

7.6.8 External Communication

Increased microgrid applicability will be enabled for widespread use both by more than 3,000 utilities in the U.S. as well as military bases, campuses, industry, and others in need of a guaranteed power supplies. To optimize system value, it must respond to external data, such as utility rate structures, real-time pricing, secure dispatch signals, and weather forecasts. Security is important for both dispatch and anti-islanding signals because a cyber-attack resulting in the simultaneous disconnect of a number of microgrids representing significant penetration of a portion of the grid could overwhelm the utility's reserve capacity, causing an outage. Relative to islanding control, the speed with which data must be transferred is lower, depending on the need, as follows:

- **Spinning reserve (replacing lost capacity).** Signal sent ~1/second. Thermal generation units providing spinning reserve achieve full output in a few minutes. Hydroelectric units respond more quickly.
- **Frequency and area regulation (maintaining frequency control).** Signal sent every few seconds. Response time is over several minutes.
- **Voltage regulation**. Line voltage provides signal. Very fast (subcycle) response, e.g., using droop algorithms is possible. Central dispatch is slower (few cycles).
- **Peak shaving (demand response).** Signal can be built into peak-demand rate structures or real-time pricing, which may be updated at intervals of 1–60 minutes, depending on the utility. Some utilities also dispatch loads to shave peak demand.
- **Back feed control.** Some systems, especially large commercial systems, may be restricted from exporting power to the utility. Often, these systems are sized so that the system output never exceeds load, but in the event it does or if the system is larger and uses storage to absorb excess power, then the response must be faster than the reverse-power relay, which is typically subcycle.

8. List of Advanced Microgrid Development Impact Areas

This section provides and extensive list of impact topics that either enable, or in some cases, are barriers to expansion of advanced microgrids. Concerns and problems are discussed as are the advantages of developing solutions and pathways for each impact area.

8.1 Regulatory Rules and Regulations

Some of the important concerns and problems identified through microgrid case studies and interviews include establishing best practices for (a) consistent methodologies for determining and measuring microgrid benefits; (b) engaging customers; (c) cybersecurity methods and protocols; (d) interoperability standards; and (e) microgrid communications and control systems, including for autonomous operations. Some of the policy concerns identified include how best to

a) implement dynamic pricing;
b) refine interconnection policies;
c) adjust retail rate designs and refine rates for partial-requirements service;
d) establish utility DER investment policies;
e) develop retail-market participation rules;
f) provide utilities with appropriate regulatory incentives;
g) coordinate microgrid policies with other policies intended to promote DG, electric vehicles, and other distributed resources; and
h) achieve consistent regulatory policies across multiple utility-service territories, including multiple-state, regional, and conceivably national policies.

Thus, it appears that policies flexible enough to allow experiments, demonstrations, and pilot projects to continue and expand, and adjustable enough to accept changes, over time, as more is learned are needed.

As DRs capture a larger role in utility systems, the impacts on utility revenues and earnings will vary substantially depending on the existing market and tariff structures. Increasing importance will be associated with the ability to model utility costs and revenues based on variable rate and tariff structures. Legitimate concerns and difficult issues are embedded in these barriers, including (a) how reliability of service is to be assured, (b) who is ultimately responsible for assuring it, and (c) what are fair prices both for distributed generators to receive for off- or on-peak electricity generated and how to pay for their share of the fixed costs of any grid in which they participate.

Rate structures for both full- and partial-requirements service need to be reviewed to ensure that price signals reflect, as accurately as practical, the time and geographic properties that affect costs and account for the benefits (e.g., reliability, diversity, avoided generation, T&D costs, etc.) that are conferred to the utility grid by advanced microgrid systems. The need for electricity rates that reward demand-side management are needed along with reduced rates for non-firm standby service. Note that several states already offer reduced standby charges for “DER customers that can provide physical assurance that the system will not exceed a specified load during peak periods.” In many ways, state public utility regulations will ultimately determine the details about whether, how, and where microgrids can be built, what customers they can serve, what services they can provide, and thus what benefits advanced microgrids can produce.

8.2 Advanced Microgrid System Adoption

Except for a few states, smart-grid programs with microgrids are generally limited in scope, due in part to today's utility aversion to adopting the new technologies and in part to market risks.[22] With the economy slowly recovering from a recession, electricity demand is unpredictable, fuel prices are variable, and environmental policies are uncertain. This combination of factors presents sufficient risk for public utilities to *not* consider new investments. Legislation at both the state and federal levels, which requires smart-grid resource consideration that would benefit from advanced microgrids and creates innovative financing methods, may be necessary to encourage technology development. Other considerations, such as consumer awareness, siting and permitting processes, reliability parameters, and cybersecurity concerns also impede deployment.

8.3 Consumer Awareness

Lack of awareness of smart-grid developments and advantages of advanced microgrid technologies will impede their deployment.[23] Additionally, without policies that motivate utilities, homebuilders, and others to implement these technologies, deployment may remain stagnant. State commissions and legislatures should consider whether to encourage or require the use of innovations that can help consumers understand their energy use and enable informed decisions in new applications that can balance the energy picture. Innovative financial mechanisms could mitigate consumer risks and enable consumers to obtain the capital necessary for investment in advanced microgrid technologies.

8.4 Customer Rights

Unless the customers own the facilities or are tenants of advanced microgrid owners, then an advanced microgrid in New York may need to be in compliance with the state's Home Energy Fair Practices Act. Also, if the microgrid opts for standby service during peak demand periods, the standby fees may have to be paid by customers. Advanced microgrid owners should have a clear expectation of evolving local and state rules and associated fees.

8.5 System Siting and Permitting for Interconnection

A consumer who wishes to install an advanced microgrid system faces regulatory and environmental obstacles to obtain all of the necessary siting and permitting approvals. Approvals often include multiple rounds of approval across multiple organizations. A similar situation applies for an industrial customer installing a grid-connected, advanced CHP system or a microgrid at its manufacturing plant. Addressing this process will be a key factor in encouraging smart-grid and microgrid deployment. The complexity and multitude of siting and permitting requirements for potential owners creates a significant time and cost barrier to implementation. FERC released a notice of proposed rulemaking on reforms to its small generator interconnection agreements and procedures. This rulemaking is an attempt to ease the interconnection process for all generators under 20 MW that interconnect under its jurisdiction with a fast-track process for resources less than 2 MW. It addresses the issues involved for public utility transmission providers and their

[22] U.S. Energy Information Administration, "Smart Grid Legislative and Regulatory Policies and Case Studies," December 2011.

[23] Black and Veatch, "2011 Strategic Directions Survey Results," http://bv.com/docs/reports-studies/2011-Electric-Utility-Survey-Results.pdf, 2011.

customers.[24] Similar efforts by states and local jurisdictions will be helpful in easing the interconnection process for advanced microgrids connected to intelligent grid infrastructure.

8.6 Reliability Parameters

Better component and system reliability parameters are necessary to fully address a resilient electric-grid infrastructure. As evidenced by Hurricane Sandy in 2012, there is an immediate and increasing need to develop more effective national standardized metrics and policies for grid reliability and resilience. Along with the improved reliability standard, new infrastructure investment must be identified and prioritized. Despite current reliability metrics indicating high levels of reliability in New York City during and after the storm, much of the city was without power. Existing reliability metrics do not provide sufficient and complete insight into operational risk that may exist under disaster conditions. Federal and state governments are working to evaluate electric-grid improvements to ensure continued electricity access during such disasters. New resilience metrics at the federal and state levels will provide the necessary incentive to promote improvements, in which smart-grid technologies and advanced microgrid systems will play a critical role.

8.7 Cybersecurity

With advanced metering and control deployment, larger data volumes must be handled, while at the same time safeguarding privacy and addressing critical cybersecurity concerns. Threats to security are vitally important for consumers, developers, and utilities when deploying smart-grid resources and advanced microgrids. A large New Jersey utility, for example, does not yet permit wireless controls on its system, limiting a number of innovative smart-grid technologies that could play a role in addressing its needs and those of its customers. Policy which enables validation of cybersecurity methods in communications and data handling would ensure the rights of users are protected and appropriate safeguards are in place across the electric grid. As of 2011, three states had made significant strides in establishing such policies, while 12 more had rulemakings in consideration. This leaves the majority of states, and the federal government, yet to make progress on addressing cybersecurity issues.[25]

8.8 Market Access for Electric Power

In addition to advanced technologies being a limiting factor for deployment, the lack of electricity market access for microgrid technologies, at both the wholesale and retail levels, and the regulations and policies in place that restrict this access also present a barrier to the deployment of microgrids interconnected with a smart grid. New policy is needed to ensure that these technologies are able to provide services and to be compensated for this provision. For example, only 11 states have adopted advanced retail metering plans, where most others are still in the study phase.[26] This restricts microgrid resources, dynamic control of interconnected loads, and the dispatch of electricity services to the distribution environment.

[24] Federal Energy Regulatory Commission, “Small Generator Interconnection Agreements and Procedures, Notice of Proposed Rulemaking,” 142 FERC 61,049, January 17, 2013.

[25] U.S. Energy Information Administration, “Smart Grid Legislative and Regulatory Policies and Case Studies,” December 2011.

[26] Ibid.

Markets herein are defined as any avenue through which resources can participate in the electricity system, whether at the wholesale or retail levels. It also includes technology markets, for example, markets for microgrids, DG, and control systems. Policies that restrict electricity market access present an obstacle to microgrid technology market development: if the products are unable to participate on the electric system, the incentive for their production and cost reductions through research and economies of scale are limited.

8.9 Retail Participation

Policies currently in place restrict the retail market participation of microgrids connected to smart grids by limiting their use for a number of functions. Retail wheeling, for example, is not allowed.[27] A retail customer who has a microgrid, or just DG installed, cannot contract with nearby customers to trade power. He or she must instead sell any excess power directly to the utility. This presents higher costs to the customer as they receive lower rates for that energy relative to its purchase in the retail market and is a disadvantage to ratepayers because wheeling through a microgrid system may be a means of reducing the need for distribution capital investments. Other rules also present retail restrictions. For example, an Illinois rule prohibits multiple-tenant building owners from installing and aggregating smart meters to secure competitive rates and operate as an aggregate system.[28] The same rule is easily construed to include microgrids. Considering that retail customer participation will be essential to the microgrid connection with the smart grid by enabling increased energy efficiency and demand response, addressing these restrictions will be important.

8.10 Ownership

Deciding who owns the electricity generating equipment and wires for linking the loads can have a huge impact on how a microgrid functions. Mechanisms to allow sharing among one or more customers, as an electric cooperative, as a corporation, or as a nonprofit association will be needed. Questions such as “how much input will the end-users have on their microgrid’s operation?” and “what are the consequences if a customer wants to leave the microgrid entirely?” will need solutions.

8.11 Ownership Rate Structure

How will a microgrid be regulated? Depending on the size, structure, and ownership model, the microgrid can be exempt from most federal and state regulation if it meets the standards as a FERC-jurisdictional qualifying facility (QF). The benefits of QF status include avoiding burdensome regulations regarding rate setting, finances, construction, and operation.

8.12 Franchise Rights

Installing wires over public-access streets can trigger franchise-rights litigation. A nonutility installing facilities and distributing electricity over public streets will get the attention of the local utility that has a franchise in the street to construct power lines. Not only must a microgrid avoid infringing on a utility’s franchise rights, but it also has to work with the local utility to avoid having to go through lengthy and expensive litigation just to prove that it’s not doing so. This may require

[27] McDermott, Karl A., “The Regulatory Dilemma: Getting Over the Fear of Price,” *The Electricity Journal*, **25**(9), 6–13 November 2012. http://dx.doi.org/10.1016/j.tej.2012.10.011.

[28] Kelly, J.; Rouse, G.; and Nechas, R., “Illinois Electricity System Guiding Principles and Policy Framework,” Galvin Electricity Initiative, July 2010.

contracting with the utility to pay for using the wires that cross public streets to avoid franchise issues.

8.13 Wholesale Market Access

Energy storage is a microgrid technology that can be categorized under FERC policy as a regulated transmission or distribution asset, which is allowed a fixed rate of return, or as a deregulated generation asset, which can participate in wholesale market operations. However, the commission does not make its policy clear on whether a single asset can provide both regulated and deregulated service and requires any such consideration to be decided on a case by case basis.[29] This restricts market access for energy storage and other smart-grid technologies. It is present in all Independent System Operator/Regional Transmission Operators (ISO/RTO) market regions. In non-ISO/RTO regions, a vertically integrated utility can use its assets for any purpose and recover all value that the asset provides.[30] In this case, state utility regulators must ensure that smart-grid or microgrid technologies, such as energy storage or demand response, are considered as alternatives to other generation, transmission, and distribution investments.

The lack of ancillary service markets for inertial response, governor response, black start, and voltage regulation in most regions, also presents a barrier to deploying microgrid resources in ISO/RTO markets. Currently, on-line spinning generation provides inertial response, but does not get paid for this service. The advanced microgrid can function as a spinning reserve with total-energy and peak-power limitations when compared to the utility grid and fall under the same rules. As generation from microgrids increase, there will be a need to ensure access to inertia from nontraditional resources. Dynamic resources, such as energy storage or advanced inverters, are capable of providing this service, but as there is no market compensation, there is no incentive for their use.[31] Similarly, bundling reliability services in a transmission utility's open-access transmission tariff may restrict deploying resources which provide individual, or a subset of, reliability services.[32]

8.15 Transmission and Distribution Market Access

The separation between planning and operations at the generation, transmission, and distribution level is no longer sustainable as new technologies will have to be considered under both planning and operational realms and across the different system boundaries. This separation limits identifying the need for smart-grid resources that will use advanced microgrid systems. As these resources enter the system, policies will be needed that establish new operating methods that take new technologies' capabilities into account.

FERC Order 1000 establishes regional planning coordination for transmission and requires considering "nonwire" resources to meet needs. This is an important first step in opening up the

[29] Federal Energy Regulatory Commission, "Notice of Proposed Rulemaking: Third-Party Provision of Ancillary Services; Accounting and Financial Reporting for New Electric Storage Technologies," 139 FERC 61,245, June 22, 2012.

[30] Hayashi, Paul M., Goo, James Yeoung-Jia, and Chamberlain, Wm. Clif, "Vertical Economies: The Case of U.S. Electric Utility Industry, 1983-87," *Southern Economic Journal*, **63**(3), 710–725 (Jan., 1997).

[31] Morren, J., de Haan, S.W., Kling, W.L., & Ferreira, J.A. "Wind turbines emulating inertia and supporting primary frequency control." *IEEE Transactions on Power Systems*, **21**(1), 433–434, 2006.

[32] Morrison, J. A. "The clash of industry visions," *The Electricity Journal*, **18**(1), 14–30. 2005.

transmission market to smart-grid resources. However, considering that many of these technologies will reside at the distribution level, it is incumbent on regional planners to ensure that distribution resources including advanced microgrids are taken into account and considered along with bulk transmission. Transmission operation and planning must reach into the distribution level in order to exploit existing and emerging communications and smart resources. The lack of defined policy around this issue will most likely restrict the access of smart-grid technologies along with microgrid supplementary resources to long-term T&D capacity planning methods.

8.16 Value Proposition

Ensuring advanced technology applications and market access will help advanced microgrid resources become one of the technology options evaluated for investment. Appropriate economic valuations will help ensure their deployment. A few policy barriers restrict potential users from determining their full value proposition. They include the lack of externality pricing, limitations in utility revenue and retail rate models, and the lack of financing options. Policy which ensures that all benefits and costs, including social benefits and costs, are considered when infrastructure is evaluated for deployment will help to deploy technologies that meet system reliability and resilience needs at the lowest cost.

8.17 Externality Pricing

The lack of externality pricing allows the market to ignore the full cost of electricity grid resources. Carbon, for example, is not priced in the marketplace. Policies, such as renewable portfolio standards and renewable incentives, have been in place for a number of years; however, they only address generation assets, leaving out many other smart-grid and advanced microgrid technologies. Microgrids can inherently improve building control systems and demand response programs, which would have an improved value proposition with the consideration of externalities. While pricing these externalities might be a difficult process, other mechanisms would force the consideration of positive and negative externalities in the evaluation process for new resource deployment, such as energy-efficiency and clean-capacity standards.

Advanced microgrid benefits can vary widely depending on their physical location in the utility-system's distributed macrogrid and the size and scope of microgrid operations. In some cases, because consumers value the benefits microgrids can provide, owners will be willing and able to pay all or nearly all of the associated costs. In that circumstance, utility-system benefits can be highly cost-effective, irrespective of the benefits and costs to the microgrid's owners.

8.18 Utility Revenue and Rate Models

Some regulatory policies do not allow the recovery of investment in modern grid technologies. In most states, investor-owned utilities are incentivized to address system peak issues by investing in new generation facilities rather than supporting consumer-side demand response and energy-efficiency opportunities.[33] Public utilities are rewarded for increasing electricity consumption because their revenue depends on electricity sales. That scenario restricts the likelihood that they will

[33] Chu, L.Y., and Sappington, D.E., "Motivating energy suppliers to promote energy conservation," *Journal of Regulatory Economics*, 1–19, 2013.

create programs for demand response or allow grid-interactive, customer-deployed, smart-grid resources without a regulatory mandate.

Similar to utility revenue models, retail electricity rate models create a disincentive for the customer to consider deploying microgrid systems. Only 12 states have adopted dynamic pricing or have begun studies into evaluating the potential for dynamic pricing on their systems. This leaves 38 states that do not consider dynamic pricing in retail rates.[34] A policy that implements dynamic pricing could provide a price signal for deploying smart-grid resources. Representing real electricity costs to consumers, depending on the time of day and usage, might increase power system efficiency.

8.19 Financing

Policy that governs electricity system asset financing provides an advantage for traditional system resources. T&D capital resources obtain thirty or more years of financing under regulator-approved rate base, while smaller investments by ratepayers and third parties, who are likely to represent a significant proportion of microgrid asset owners, must have shorter payback periods. This creates disconnects between utilities, independent developers, and retail customers when considering new infrastructure deployment to meet electricity system needs. Policymakers must ensure that appropriate legislative incentives are in place, whether through tax credits or low-rate loan guarantees, which level the playing field with utility-owned capital investment. In addition, many utilities have generation assets that are not yet depreciated and they are not willing to leave them stranded in favor of energy-efficiency programs or microgrid technologies. Policies that allow faster depreciation of these assets' remaining book value, while replacing them with modern microgrid and smart-grid assets, could be one means of eliminating this issue.

8.20 Restrictions

Advanced microgrid technologies have the potential to significantly impact today's legacy electric grid and more importantly the future smart grid. The smart grid will emerge slowly because the current system will require considerable infrastructure investment to maintain reliability and ensure resilience as assets get older, demands on the system increase because of more variable loads and generation, and the system moves toward lower carbon emissions. A number of barriers restrict these technologies' further deployment.

- Consideration of these resources amongst alternatives when the electricity grid requires new infrastructure
- Ability of these resources to participate in electricity markets, whether wholesale generation, transmission, distribution, or retail
- Deployment value propositions

State and federal lawmakers and regulators must ensure that these policy barriers are addressed to give microgrid and smart-grid technologies fair consideration for deployment.

[34] U.S. Energy Information Administration, "Smart Grid Legislative and Regulatory Policies and Case Studies," December 2011.

8.21 Grid Resilience

The U.S. electric grid is vulnerable to natural disasters, severe weather, and acts of sabotage. The recent report prepared by the President's Council of Economic Advisers and the U.S. Department of Energy's Office of Electricity Delivery and Energy Reliability, with assistance from the White House Office of Science and Technology estimates "the average annual cost of power outages caused by severe weather to be between $18 billion and $33 billion per year.[35] In a year with record-breaking storms, the cost can be much higher. For example, weather-related outages cost the economy between $40 billion and $75 billion in 2008, the year of Hurricane Ike." Although it is not a certainty, costs related to loss of electric power are expected to rise because of climate change.

From this report and a host of others, it is evident that a more resilient electric grid must become a high priority in reconfiguring and updating the nation's electric power distribution and transmission. Evolution of smart-grid technology designed to increase resilience will result in reduced outage time and even prevent the loss of electric power to critical loads in cities and critical infrastructure. Smart-grid improvements will also enhance national security. The emerging smart grid and the components of advanced microgrids must, however, be protected against cyber attacks and maintain adequate autonomy to keep critical loads energized.

Advanced microgrids with energy storage are cited in this paper to "achieve a good match between generation and load." An advanced microgrid with economically and functionally optimized energy storage will provide voltage and frequency regulation to maintain desired electric grid balance between loads and generated power in many distribution-system sectors. Renewable energy supported by alternative resources and energy storage is already supporting a high penetration of intermittent renewable energy in some grid sectors. An advanced microgrid will have a built-in ability to separate and isolate itself from the utility seamlessly with little or no disruption to the loads within the microgrid. The separation can occur as a result of scheduled, dispatched, or autonomous commands. An advanced microgrid can then be dispatched or automatically reconnected to an electric grid when conditions return to normal. Advanced microgrids will automatically synchronize to primary power sources before reconnecting to the restored grid. Technologies including advanced and secure communication and controls, building controls, DG, and inverters already are commercially available, but even more advanced functionality will be needed for advanced microgrid systems. CHP systems have demonstrated their potential by maintaining power and heat at several institutions following Superstorm Sandy.[36] Resilience is increasingly important as climate change increases severe weather's frequency and intensity. Greenhouse gas emissions are elevating air and water temperatures around the world. Scientific research predicts more severe hurricanes, winter storms, heat waves, floods, and other extreme weather events as being among the changes in climate induced by anthropogenic greenhouse gas emissions.

[35] Executive office of the President, "Economic Benefits of Increasing Electric Grid Resilience to Weather Outages," http://energy.gov/oe/articles/white-house-council-economic-advisers-and-energy-department-release-new-report, Aug 2013.

[36] "CHP Kept Schools, Hospitals Running Amid Hurricane Sandy," http://www.ase.org/efficiencynews/chp-kept-schools-hospitals-running-amid-hurricane-sandy, Dec. 11, 2012.

8.22 Regulatory Barriers[37]

At the present time, the distribution grid utilities have taken small steps toward implementing microgrids. Incumbent utilities are still developing a business case for the recovery of costs associated with establishing (a) "microgrid-readiness" and (b) a tariff structure for the electric service microgrids provide. One of the arguments against incumbent utility microgrid development is the potential ratepayer cost impact due to the need to upgrade and retrofit the existing distribution grid to allow for high DG and energy storage levels. There is no clear regulatory directive to develop microgrids. There may be other regulatory barriers, such as interconnect rules.

Another barrier may be the close integration, enabled by microgrids, of electricity supply and thermal energy supply that natural gas presently provides. Microgrids with DG high levels can make use of small-scale CHP technology ("micro-CHP") to deliver both electricity and heating or cooling services for buildings. However, presently the electric distribution grid and the natural gas distribution grid are entirely distinct entities, with entirely distinct regulatory structures and metering and billing systems.

A third barrier may be the lack of a third-party electricity supplier than can address an integrated microgrid-based electrical/thermal/transportation energy supply.

There are also problems with developing a tariff and rate structure for microgrids that would (a) enable the distribution operator to recover costs and (b) allow a retail supply of microgrid-based generation and storage services. Without a retail electricity market, using wholesale-connected DG as part of a utility supply does not necessarily allow microgrid customers to enjoy the economic benefits of optimized local DG. A new tariff would have to be developed that would allow microgrid customers to be treated differently from a rate standpoint than the standard bundled utility customer. This tariff and rate structure will have to be integrated with other policy goals for real-time pricing, as well as accounting for revenue streams potentially created by microgrid operations.

9. "Advanced Microgrid" Considerations for Systems

9.1 Approaches to Deploying Microgrid Applications

Microgrids integrated with renewable energy sources such as solar and wind can enable many new applications for the renewables. Using renewable energy usually requires energy storage or spinning reserve to manage power intermittency. Microgrids also use other sources, such as reciprocating-engine-driven generators, turbines, fuel cells, micro-hydro generators, and energy storage from a wide variety of methods.

Early microgrid installations have successfully provided power for essential loads where continuous power for loads is absolutely necessary. Those early microgrid installations successfully met design goals, but opportunities and challenges still exist for improving the economics, communication, and overall marketability. The microgrid installation driver is usually power reliability and consistency to critical loads, but a few designs are being driven by system-owner economics.

[37] Confidential working paper – permission required for quotations.

Advanced microgrids will provide new functionalities and features that will focus on the reliability of continuous power to loads, optimization for economics, or both. Security and safety will be necessary considerations for new designs. Advanced microgrids will provide the ability to perform value-added functionalities for the system owner and the interconnected electric utility.

9.2 Today's Microgrid Installations

Three examples of installed and successful microgrids are presented in this section. The drivers for the installations were reliability of power with security, economics, and reliability with load-shedding priorities. The first example is the Smart Power Infrastructure Demonstration for Energy Reliability and Security (SPIDERS) microgrid now operating at two military bases. The goal for SPIDERS microgrid technology is to provide secure control of on-base generation.[38]

The first SPIDERS microgrid was implemented at Joint Base Pearl Harbor Hickam in Honolulu, and took advantage of several existing generation assets, including a 146 kW PV power system, and up to 50 kW of wind power. The second installation, at Fort Carson, is much larger and more complex; it integrates 2 MW of existing solar power, several large diesel generators, and electric vehicles. Large-scale electric energy storage is also implemented to ensure microgrid stability and to reduce PV intermittency effects on the system. Advanced microgrids will meet the needs of a wide range of applications in commercial, industrial, and institutional settings. Larger advanced microgrid applications will include communities ranging from neighborhoods to small towns. Another largely untapped application is the "off-grid" area of the world where one billion-plus people live without regular access to electricity. These "off-grid" areas are currently served (if at all) by diesel generators or similar small-scale electricity generating equipment. The driver for these systems was reliability of power to existing loads with additional security that required two-way communications.

A second example of a successful reliability driven microgrid is the White Oak Microgrid installed at the White Oak Federal Research Center in Silver Spring, Md. The microgrid system designed by Honeywell ensured that critical operations such as research labs, global data centers, and communications networks would be able to stay online and function despite conditions around White Oak, the new headquarters of the U.S. Food and Drug Administration.[39] The system is a net exporter of power to the local utility via integrated renewable PV and local electricity generation that supports the microgrid. It has had an uptime of greater than 99.999% since installation, providing power to critical loads with some load shedding. The system has automatically islanded more than 70 times in the last 2.5 years and has never been interrupted due to weather disturbances.

The third example is a microgrid installed with an economics driver—the Princeton Microgrid, installed on the Princeton University Campus in New Jersey. It has real-time cost reduction controls and is providing the campus with energy cost savings.[40] During Hurricane Sandy, Princeton was able to switch off the grid and power part of the campus with about 11 MW of local generation, according

[38] Sandia National Laboratories, "SPIDERS microgrid project secures military installations," Sandia Labs News Release, https://share.sandia.gov/news/resources/news_releases/spiders/, February 22, 2012.

[39] http://www.honeywellnow.com/2011/09/28/honeywell-provides-energy-security-to-help-fda-headquarters-weather-recent-earthquake-and-hurricane/#ixzz2kYCmMOzJ.

[40] http://www.technologyreview.com/view/507106/microgrids-keep-power-flowing-through-sandy-outages/.

to a report in the *Daily Princetonian*. The system provides smart capabilities such as automatic load shedding and black start in the islanded mode.

These examples show proof of concept and point to an advanced microgrid's overall advantages. The new structure will provide more viable platforms for large entities to reduce energy cost, improve grid reliability, and even generate revenue through energy sales during peak demand periods. Additionally, advanced microgrids will efficiently and effectively provide "off-grid" regions with regular access to electricity as well as "keep the lights on" for critical applications in times of crisis.

Figure 11 depicts the many opportunities for advanced microgrid systems interconnecting with a myriad of energy sources and loads that may be critical loads or that provide a balance for the overall electrical grid or for stand-alone applications.

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Figure 11. Depiction of possible energy sources and interconnects for microgrids.

10. Standards and Codes for Advanced Microgrids

U.S. interconnection standards and requirements for DG are currently dominated by the family of IEEE1547 standards, recommended practices, and guides.[41] These documents have 5-year effective lifetimes when published before 2012, but now have 10-year lifetimes. Amendments and corrections can be balloted within the 10-year period and revisions can be partial or complete. The documents are updated through volunteer efforts from stakeholders that serve on Standards Coordinating Committee 21 (SCC 21). Efforts are now underway to update several of the documents to keep up with the evolving needs to interconnect DR and microgrids with smart grids labeled as EPSs (electric

[41] Basso, Thomas S., Member, IEEE, and DeBlasio, Richard, Senior Member, IEEE, "IEEE 1547 Series of Standards: Interconnection Issues," *IEEE Transactions on Power Electronics*, **19**(5), September 2004.

power systems). The IEEE1547 process is an important and critical effort in that the Energy Policy Act of 2005 states: *"ADOPTION OF STANDARDS.—Section 111(d) of the Public Utility Regulatory Policies Act of 1978 (16 U.S.C. 2621(d)) is amended by adding at the end the following…"*

10.1 Interconnection

Each electric utility shall make available, upon request, interconnection service to any consumer that the electric utility serves. For purposes of this paragraph, the term 'interconnection service' means service to an electric energy consumer under which an on-site generating facility on the consumer's premises shall be connected to the local distribution facilities. Interconnection services shall be offered based upon the standards developed by the IEEE. The IEEE 1547 for Interconnecting DRs with EPSs may be amended from time to time. In addition, agreements and procedures shall be established whereby the services are offered shall promote current best practices of interconnection for DG, including but not limited to practices stipulated in model codes adopted by associations of state regulatory agencies. All such agreements and procedures shall be just and reasonable, and not unduly discriminatory or preferential.

Table 3 lists the IEEE standards and the titles with most applying to interconnected microgrids. Most of these standards are being revised or will need revisions as the advanced microgrids and interconnects with the smart grid become reality.

A new IEEE 1547a is a temporary amendment for IEEE 1547 and was on a fast track to support the exceptional growth of DR and eventually advanced microgrid systems.[42] It was approved in December 2013. The focus of the IEEE 1547a Amendment is limited to establishing updates to voltage regulation, response to area EPS abnormal conditions of voltage and frequency. Other changes to IEEE 1547 may be made if deemed absolutely necessary in response to the updates that are established under preceding topics of the amendment. The approval of this new amendment provides the critical pathway for interconnectivity of microgrids with new smart grid functionalities such as VAr support and low voltage ride-through.

Also for microgrid systems the recent acceptance of IEEE 1547.4 for design, operation and integration of DR islanded systems now provides interconnect requirements for microgrids, renewable energy providers and distributed generation.[43]

[42] "P1547a - IEEE Draft Standard for Interconnecting Distributed Resources with Electric Power Systems - Amendment 1," http://standards.ieee.org/develop/project/1547a.html.

[43] "IEEE1547.4 Guide for Design, Operation, and Integration of Distributed Resource Island Systems with Electric Power Systems," http://grouper.ieee.org/groups/scc21/1547.4/1547.4_index.html.

Table 3. Advanced Microgrid-Relevant IEEE Standards Description and Status

IEEE Standard	Title and short description
1547-2003	IEEE Standard for Interconnecting Distributed Resources with Electric Power Sources
1547.4-2011	IEEE1547.4 Guide for Design, Operation, and Integration of Distributed Resource Islanded Systems with Electric Power Systems
1547.7	IEEE P1547.7 Draft Guide to Conducting Distribution Impact Studies for Distributed Resource Interconnection (Approved Sept 2013)
P1547.8	IEEE P1547.8/D5.0 Draft Recommended Practice for Establishing Methods and Procedures that Provide Supplemental Support for Implementation Strategies for Expanded Use of IEEE 1547 (Clause 8- Recommended Practice for DR Islanded Systems) Status: Ballot ready draft due 2Q2014
P1547a – Amendment 1	IEEE1547a Standard for Interconnecting Distributed Resources with Electric Power Sources – Amendment 1 (The amendment limited to address three topics for change 1) voltage regulation, 2) voltage ride-through, and 3) frequency ride-through.) Status: P1547a/D2 ballot achieved 91 % affirmation; recirculation Dec 2013)
1547 Revision	PAR December 2013; Working group Jan 2014

Other standards that are likely to apply to advanced microgrid systems and their components are being developed. The IEEE 2030 Smart Grid Interoperability Series of Standards is one example.[44] Developing this set of standards stems from the Energy Independence and Security Act of 2007. It calls for developing protocols and standards to increase smart-grid equipment/system flexibility of use. Under Section 1305 of the act, this interoperability framework "shall be flexible, uniform, and technology neutral" and "align policy, business, and technology approaches in a manner that would enable all electrical resources, including demand-side resources, to contribute to an efficient, reliable electricity network." Other standards, led by the IEEE 2030 series as a framework are moving forward at this time.

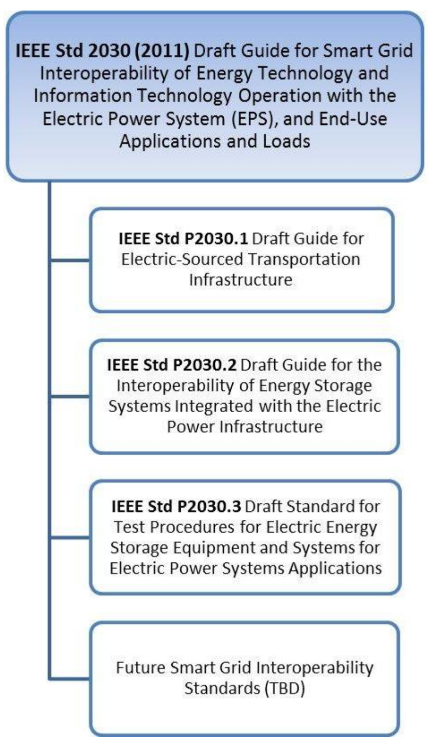

Figure 12. The IEEE 2030 suite of standards and guides for smart grids.

[44] "2030 Smart Grid Interoperability Series of Standards," http://grouper.ieee.org/groups/scc21/dr_shared/2030/.

Microgrids will often be connected to or in close proximity to utility substations. DNP3 (distributed network protocol) is a set of communications protocols used between components in process-automation systems.[45] Its main use is in utilities such as electricity and water companies. Usage in other industries is not common. It was developed for communications between various types of data acquisition and control equipment. It plays a crucial role in SCADA systems, where it is used by SCADA master stations (aka control centers), remote terminal units, and intelligent electronic devices. It is primarily used for communications between a master station and remote terminal units or intelligent electronic devices. The inter-control center communications protocol (a part of IEC 60870-6) is used for inter-master station communications.

The DNP3 protocol was designed to be very reliable, but it was not designed to be secure from attacks by hackers and other malevolent forces that could potentially wish to disrupt control systems to disable critical infrastructure. Because smart-grid applications generally assume access by third parties to the same physical networks and underlying infrastructure of the grid, much work has been done to add secure authentication features to the DNP3 protocol. The DNP3 protocol is now compliant with IEC 62351-5.

10.2 Microcontrollers

The reason for establishing a standard for microgrid controllers is to enable interoperability of components through cohesive and platform-independent interfaces. This approach will allow for flexibility and customization of components and control algorithms to be deployed without sacrificing “plug-and-play” or limiting potential functionality. This is important for both the µEMS as well as for achieving transient performance, system stability, and regulation requirements (voltage, current, etc.). Technical challenges associated with these controllers will include computational power necessary to react to the stochastic nature of some renewable sources and to perform more advanced control and optimization calculations.

Communications and interfaces to these microcontrollers will drive a hardened security approach. This becomes more complex as Internet-type interfaces are introduced requiring a secure cyber connection.

Establishing standards that define the appropriate security level and microcontroller testing will need to consider the risks associated with particular microgrids and the impact of a compromised system. These considerations should be weighed against the cost of implementing the necessary levels of security. Further, software (commercial or custom) and components should be interoperable and with interfaces that comply with functional standards.

[45] “Overview of the DNP3 Protocol,” http://www.dnp.org/pages/aboutdefault.aspx.

10.3 Code Requirements

Codes are typically requirements for installing components and systems and are designed for personnel safety and fire prevention. Microgrids installed in the United States will be subject to some of the requirements of national, state, and local codes. Codes that may apply include:

- *National Electrical Code*, NFPA 70 (with the applicable edition determined by local adoption or legislation)[46]
- *National Electrical Safety Code*, American National Standards Institute (ANSI) Standard C2[47]
- State and local electrical codes
- International Building Code

10.4 The NIST Interoperability Framework

Although NIST does not write standards, it has been mandated to coordinate and collaborate on standards for interoperability or DG with the evolving smart grid. NIST organized a number of groups and events to achieve the goal of an interoperable smart grid. These groups include SGIP (the Smart Grid Interoperability Panel) along with its committees and working groups. Outputs include the NIST Framework and Roadmap for Smart Grid Interoperability Standards.[48] Guidelines for Smart Grid Cyber Security, NIST Interagency Report 7628 (Aug. 2010) are also available to the public. Various documents related to new or modified standards are produced by Priority Action Plan working groups. These materials along with descriptions of the various groups, their memberships, tasks, and timelines can all be accessed at http://collaborate.nist.gov/twiki-sggrid/bin/view/SmartGrid/WebHome.

10.5 Other Standards

Other standards will apply to microgrid systems but are too numerous to discuss in this paper. Examples of other standards include but are not limited to:

- IEEE and ANSI standards for batteries and battery installations
- ANSI and American Society for Testing and Materials standards for construction and protection from elements like surges
- IEEE and ANSI standards for the numerous components utilized in microgrid systems
- International standards from the IEC
- Underwriters Laboratories and ANSI standards for certification for safety of and performance of components

10.6 Special Cases

Special cases for requirements for installations and operations will continue to apply in localities where no local codes or national codes applied due to local circumstances or the requirements of local utilities, or where environment or operations circumstances dictate modifications or different standards. Examples include special state exemptions for localities such as Hawaiian Islands or parts of Alaska.

[46] "*National Electrical Code*, NFPA70," Published by the National Fire Protection Association, Batterymarch, MA.

[47] *National Electrical Safety Code, 2012 Edition*, Published by the NFPA, Batterymarch, MA.

[48] http://www.nist.gov/public_affairs/releases/upload/smartgrid_interoperability_final.pdf.

10.7 Smart Grid Interoperability Panel

The SGIP is a public private partnership, supported by NIST. Its primary responsibility is to identify standards and gaps in standards with respect to interoperability. FERC has spoken out on the critical need for interoperability within the energy grid and has called SGIP "the best vehicle for developing smart-grid interoperability standards." SGIP has established committees and working groups to address smart grid and interoperability issues.[49] The Distributed Renewables, Generators and Storage Domain Expert Working Group, in particular Subgroup C - Microgrids and Hierarchical Distributed Control, is proactively working on issues related to advanced microgrids.

11. Summary

Advanced microgrids will indisputably become a significant player in maintaining and improving the quality, reliability, and resilience of the nation's electricity grid in the future. Several of today's microgrids are already providing some of the services, features, and functionalities that will be required of an advanced microgrid. New advanced microgrids will have interoperability capabilities in widely varying degrees but interoperability will be necessary as the electricity grid gains intelligence. The drivers for advanced microgrids will be more complex that today's reliability and economic drivers for microgrid installations, but the two the two key drivers will remain either for the owner or the utility infrastructure. Reliability, resilience, longevity, electricity grid support, critical-load power will remain the most important metrics. The number of variables to be addressed in the near future is large but manageable and affordable. There will likely standard advanced microgrid configurations that bracket interoperability protocol, communications optimization, and prioritization but custom designs will likely prevail for several years. There are many methods for employing communications in advanced microgrids and likely new methods will evolve. An advanced microgrid development program tied with learning from installations will sort out the winners and losers. It is already clear that two-way communications coupled with internal communications and some microgrid system autonomy will reduce the communications complexity. New and evolving standards and codes are emerging today but there is much to be addressed with solutions that do not lock in or lock out sectors that can successfully transform systems into advanced microgrids. This paper provides a compilation of today's hardware, materials, and methodologies along with goals and visions for advanced microgrids. The challenges and opportunities are presented; all that remains is applying the ingenuity and expertise to bring advanced microgrids to future installations that are ready for even more improvements for the owners and the interoperable utilities.

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