Applied Energy 228 (2018) 1656–1668

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

A review of microgrid development in the United States – A decade of progress on policies, demonstrations, controls, and software tools

Wei Feng[a,*], Ming Jin[a,b], Xu Liu[a], Yi Bao[a,c], Chris Marnay[a], Cheng Yao[d], Jiancheng Yu[d]

[a] *Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA*
[b] *University of California Berkeley, Berkeley, CA 94720, USA*
[c] *Wuhan University, Wuhan, Hubei Province 430072, China*
[d] *Tianjin Electric Power Co., Tianjin 200001, China*

HIGHLIGHTS

- Conduct comprehensive literature review of U.S. microgrid development in the recent decade.
- Discuss U.S. progress on microgrid policies, demonstration projects, control methods, and software tools.
- Summarize key successful experience of U.S. microgrid development.

ARTICLE INFO

Keywords:
Microgrids
Self-generation
Resilience
Combined heat and power
Research and development
Renewable energy

ABSTRACT

Microgrids have become increasingly popular in the United States. Supported by favorable federal and local policies, microgrid projects can provide greater energy stability and resilience within a project site or community. This paper reviews major federal, state, and utility-level policies driving microgrid development in the United States. Representative U.S. demonstration projects are selected and their technical characteristics and non-technical features are introduced. The paper discusses trends in the technology development of microgrid systems as well as microgrid control methods and interactions within the electricity market. Software tools for microgrid design, planning, and performance analysis are illustrated with each tool's core capability. Finally, the paper summarizes the successes and lessons learned during the recent expansion of the U.S. microgrid industry that may serve as a reference for other countries developing their own microgrid industries.

1. Introduction and background

Microgrids have become increasingly popular in the United States. About 34% of the world's microgrid projects are located in the United States and North America area – drivers for this fast growth could include the country's aging electricity megagrid and end-use customers' increasing desire for greater security and reliability [1]. In the past decade, the U.S. government and industry have established supporting policies, demonstration projects, control systems research, and the development of software tools. This paper reviews U.S. efforts on microgrid development from early 2000 up to now, summarizing successful experience.

Noticeably, besides North America, microgrid projects are expanding rapidly in the rest parts of the world, especially in Asia Pacific region, which takes about 40% of the world total microgrid capacity. Various policies drive microgrid development in different countries and regions. In the EU, microgrid development is accompanied with comprehensive R&D efforts supported by a series of EU's Framework Programs (FPs) [2]. Demonstration projects are developed starting in FP 5 to now with focuses on island and remote microgrid system, utility scale multi-microgrid, control and operation. In Asia, Japan is a leader in microgrid research. New Energy and Industrial Technology Development Organization (NEDO) has funded many microgrid research and demonstrations around the world [3]. The goals of these demonstrations are often related with alternative new energy solution, new technologies, and controls for better reliability and resilience. Japan's demonstration projects show excellent performance under disasters, particularly the successful operation Sendai Microgrid after the "311 Great Easter Japan Sumani" [4,5]. China started its microgrid development through the 12th Five Year Plan (FYP, from 2011 to 2015). The primary goal is to find a distributed clean energy way which can relieve China's dependence on centralized coal power, reduce low emission,

---

* Corresponding author.
E-mail address: weifeng@lbl.gov (W. Feng).

https://doi.org/10.1016/j.apenergy.2018.06.096
Received 21 April 2018; Received in revised form 12 June 2018; Accepted 20 June 2018
0306-2619/ © 2018 Elsevier Ltd. All rights reserved.

and improve air quality. Chinese central government targeted to build 30 microgrid demonstration projects in the 12th FYP and this work is further extended to the 13th FYP (from 2016 to 2020). In order to support the national development projects, microgrids are further defined as three types – island, remote and city microgrids, with each type including recommendations of energy system configuration applicable in China [6,7].

The definition of a microgrid depends on perspectives: the distributed energy resources point of view differs from the control perspective [3,8,9]. The U.S. Department of Energy (DOE) provides the following definition of a microgrid [10]:

> *"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. A remote microgrid is a variation of a microgrid that operates in islanded conditions."*

Similarly, a microgrid definition is given by The International Council on Large Electrical Systems (CIGRE) [11]:

> *Microgrids are electricity distribution systems containing loads and distributed energy resources (such as distributed generators, storage devices, or controllable loads,) that can be operated in a controlled, coordinated way either while connected to the main power network or while islanded.*

Both definitions point out that microgrids have important characteristics. First, a microgrid is an integration of distributed energy resources and loads; second, a microgrid system must be a controllable entity that can operate in either grid-connected or island mode. These two definitions are limiting: not all projects can operate in either grid-connected or island mode. Other definitions of microgrids [12] focus on the distributed generation and end-use load sides and not on grid-connected or islanding operating modes. However, in order to eliminate confusion regarding island microgrids, U.S. DOE later added a sentence to their definition to include island microgrids as a variation of a microgrid.

Of the many demonstration projects developed in the United States, low natural gas price is a primary driver for early demonstrations [13]. For regions where electricity prices are relatively high, projects make use of the spark spread of distributed natural gas power generation. The use of renewable and clean energy is another driver for U.S. microgrid development. Many microgrid projects have set up high targets for renewables and low-carbon footprints. Also, high renewable penetration has become one goal in federal and local government support. The distributed energy resources that microgrids host are valuable assets in the electricity market. Participating electricity market ancillary services provide additional values and motivations for microgrid development [14]. More recently, system-level reliability and resilience have become key drivers for microgrid construction. Hurricanes on the U.S. East Coast have drawn public attention to the pressing need for improved power system reliability. Microgrids are recognized as a way to strengthen power system reliability and increase local resilience.

To support the microgrid demonstration projects described previously, U.S. federal, state, and local policies play a vital role. Support for microgrids comes from research and development (R&D) programs at federal and state levels, software and tools, grants and funding support to incentivize demonstration projects, and tax and financial incentives for the installation of distributed energy [3,8,9,12]. Such programs are often complimented by local utilities that value the interconnection of microgrids with the utility grid as well as possible ancillary services that microgrids can provide [15].

Control systems are essential to ensure that microgrids coordinate distributed energy resources effectively [16]. The U.S. DOE has identified several core areas for microgrid controls: (1) frequency control, (2) Volt/volt-ampere-reactive control, (3) grid-connected-to-islanding transition, (4) islanding-to-grid-connected transition, (5) energy management, (6) protection, (7) ancillary service, (8) black start, and (9) user interface and data management [17]. In line with DOE's microgrid control requirements, standards and protocols have been developed to maintain a microgrid system's stability and improve resilience. The Consortium for Electric Reliability Technology Solutions (CERTS) provides a way to control distributed resources in an aggregated fashion to main local power and heating/cooling reliability and security needs [18]. Through the CERC definition, many widely used control approaches are adopted including real and reactive power control [9], voltage regulation through droop [19], fast-load tracking and storage [20], frequency droop for power-sharing [21], and others. Besides fundamental control methods, control systems in microgrids often exhibit hierarchical structures made up of two or three levels of controllers [22–24]. High-level controllers are often involved in microgrid decision-making, including economic operations and interactions with the megagrid for demand response [25]. Recent development in microgrid stability and resilience is often associated with control systems and methods, especially during critical events (such as blackouts) to ensure that microgrids continue to operate in island mode when the grid is down [26].

Software tools are developed as a key part of microgrid research. Most tools developed focus on design and planning, as well as operation, with focus of distributed energy resources technologies integration [27–29]. Most tools can accommodate renewable technologies such as wind, photovoltaics, storage technologies, and dynamic matching energy generation and storage with energy loads. Some tools are developed with greater focus on technologies performance; others focus on the system's economic performance, minimizing system investment and operation costs. More recently, software tools have tended to focus on combining cost with reliability.

This paper first reviews the federal, state, and local level policies in the United States that drive microgrid development (Section 2). Demonstration projects developed under different level of policy are evaluated in Section 3. Then, technologies and control system commonly found in U.S. microgrid demonstration projects are elaborated in Section 4. Finally, software tools that support microgrid design and operation are reviewed based on their technical capacities in Section 5.

2. Overview of U.S. Microgrid policies and development

2.1. Federal level activity

Federal policy efforts promote the research and development of microgrids, aiming to provide more reliable, flexible, efficient, resilient, affordable, and secure power systems. The Office of Electricity Delivery and Energy Reliability (OE) within the U.S. DOE is the core organization in supporting microgrid R&D activities. Over the last decade, DOE has funded a broad portfolio of activities in microgrid design and economic analysis tools, system testing, and demonstration programs, many of which are in conjunction with the U.S. Department of Defense (DOD) [30].

OE's first major program, the Renewable and Distributed Systems Integration (RDSI) program, began in 2008 [31]. The nine projects initiated in 2008 are shown in green in Fig. 1.[1] Projects totaling \$100 M, typically with 50–50 DOE - co-funder financing, were primarily intended to achieve a minimum of 15% peak-load reduction, which is generally required by an RDSI program [31]. Two California projects, Santa Rita Jail and Borrego Springs, received subsequent California Energy Commission (CEC) funding, became exceptional microgrid examples, and are still operating [30,32]. They are described in more detail below (Section 3). Another two RDSI projects, the Fort

---

[1] Other funded projects in later years can be found at the official website: https://www.smartgrid.gov/recovery_act/overview/renewable_and_distributed_systems_integration_program.html.

Collins, Colorado, demonstration of mixed distributed resources, and the Illinois Institute of Technology's never-failing perfect power prototype, are also discussed in more detail in Section 3 [33].

The Smart Power Infrastructure Demonstration for Energy Reliability and Security (SPIDERS) programs began in 2010 [34]. Jointly funded by DOE and DOD, these projects (in red[2] in Fig. 1) aim to provide highly reliable and resilient power to military bases, which are often in remote locations and are poorly served by the megagrid. The first three SPIDERS demonstrations were at Hickam Air Force Base and Camp Smith, in Hawaii and Fort Carson, Colorado, respectively (more in Section 3). Later on, microgrid principles were rapidly adopted and have been applied at many sites, effectively making them the default power system for military facilities [35].

Another major federal investment that has facilitated microgrid development in the United States is the American Recovery and Reinvestment Act of 2009 (ARRA). The approximately $4-billion ARRA smart grid program has catalyzed many projects including the RDSI Borrego Springs project and a neighboring project, the University of California Irvine campus microgrid, both described below in Section 3. Many of these projects demonstrated technologies critical to microgrids (e.g., battery storage); however, only one complete microgrid project was executed under ARRA—this was a Portland Gas and Electric project in Salem, Oregon, that was part of the Pacific Northwest Smart Grid Demonstration Project [36–38].

In order to achieve OE's goals to develop next-generation commercial-scale microgrid systems capable of reducing the outage times of required loads by $> 98\%$—to be cost-competitive to non-integrated baseline solutions, to reduce emissions, and improve system energy efficiencies—OE has moved from demonstrations towards systems integration. Systems integration is particularly focused on microgrid controllers and standards for advanced microgrids [39,40]. This pivot coincided with a desire for microgrid standardization to speed deployment, and for more sophisticated operations, as described in an influential 2014 report from Sandia National Laboratory [17]. OE funded eight microgrid controller projects covering a wide range of microgrid types and geographic areas in the United States (see Navy Yard project in Section 3 as an example).

In addition to the supporting microgrid demonstration and system integration projects described above, DOE's Loan Guarantee Program, which provides loan guarantees to accelerate the deployment of innovative clean energy technology, added $1 billion in additional loan guarantees in 2015 to fund qualified distributed energy projects (e.g., solar photovoltaics, wind, combined heat and power, and storage), pursuant to Title XVII of the Energy Policy Act of 2005 [41,42]. The U.S. federal government also provides investment tax incentives for customers installing microgrid technologies. The incentives cover a wide range of technologies from solar photovoltaics, combined heat and power, and electric vehicles. Technical assistance is also provided. For example, DOE's combined heat and power Technical Assistance Partnerships (CHP TAPs) promote and assist in transforming the market for CHP, waste-heat-to-power, and district energy technologies/concepts throughout the United States [43]. Key services of the CHP TAPs include market opportunity analyses, education and outreach, and technical assistance. A summary of these policies and associated distributed energy technologies are provided in Appendix A, Table A1.

2.2. State and local activity

While the federal programs described above were the main engine of early U.S. microgrid research and development, there has always been significant activity at the state and local levels—often arising from self-generation projects, typically at large commercial, campus, medical, or industrial sites. The driving forces in microgrid development at the state and local levels include renewable energy requirements as reflected in renewable portfolio standards (RPS) in 29 states and Washington, DC; renewable portfolio goals in eight states; and increasing concerns regarding power system resilience due to growing extreme climate events [44–46]. Approaches that states have taken to provide incentive for microgrid R&D include funding opportunities for microgrid demonstrations, tax incentives for installation of distributed energy, and innovative business models (e.g., Solar Power Purchase Agreement and the Property Assessed Clean Energy) for application of distributed energy.

The 2011–2012 period was a pivotal year in microgrid development. During the Great East Japan Earthquake in March 2011, two Japanese microgrid projects (the longstanding Sendai microgrid and the Roppongi Hills district of Tokyo project) performed magnificently, reorienting microgrid research in the area towards resilience [4]. In late October of the following year, Superstorm Sandy hit the northeastern United States. In a similar manner, some existing microgrids performed well, and state policymakers took notice, leading to a similar reorientation of research in that part of the United States [47]. Interest by state and local government in the resilience benefits of microgrids has spawned microgrid programs of varying size and complexity in all of the states affected by Sandy. The State of New York's Prize (NY Prize) program, managed by the State Energy Research and Development Administrations (NYSERDA), is the most extensive. The NY Prize is an ambitious $60-million grant program with additional leverage opportunities designed in three stages. The first, Feasibility Study stage, completed in 2016, produced 83 studies of possible microgrids to protect public facilities, especially emergency services [48]. Interestingly, New York uses a microgrid definition that reflects its resilience focus: microgrids are local energy networks that are able to separate from the larger electrical grid during extreme weather events or emergencies, providing power to individual customers and crucial public services such as hospitals, first responders, and water treatment facilities [49].

Outside of the northeast, other states have also achieved notable microgrid research and demonstration successes, notably California. The state's RPS provides a major impetus for microgrid development, which has a target of obtaining 50% of the state's electricity from eligible renewable energy resources by 2030. California state building codes also set goals for 100% zero-energy buildings by 2020 for all new residential buildings and 2030 for new commercial buildings. To achieve these goals, California has been very successful leveraging resources at the state, federal, and local utility levels to develop microgrid projects (Appendix A, Table A1).

California's microgrids grew from the CEC's Renewable Energy Secure Communities program [50]. To support California's energy and greenhouse gas policies, CEC devoted $45 million for microgrid demonstrations that provide successful and repeatable prototypes for commercially viable microgrids. Nine projects have been awarded and each of which will last 3–4 years starting in July 2018 [51].

State-level tax incentives are also available for customers that install microgrid technologies. For example, a state sales tax incentive is available to solar photovoltaic systems that are used to provide electricity to farm equipment and machinery. Financial incentives, such as solar power purchase agreements (SPPA) and property assessed clean energy (PACE), are also available to encourage distributed energy installation in residential and commercial buildings in California. SPPAs are financial agreements where a third-party developer owns, operates, and maintains the photovoltaic system on the property of a host customer who purchases the system's electric output from the solar services provider. The rate that the host customer pays to the developer is typically lower than the retail rate of the local utility. SPPAs are also widely applied in other states including Arizona, Colorado, New York, and New Jersey [52]. The PACE model is a way of financing energy efficiency or renewable energy installations on residential, commercial,

---

[2] For interpretation of color in Fig. 1, the reader is referred to the web version of this article.

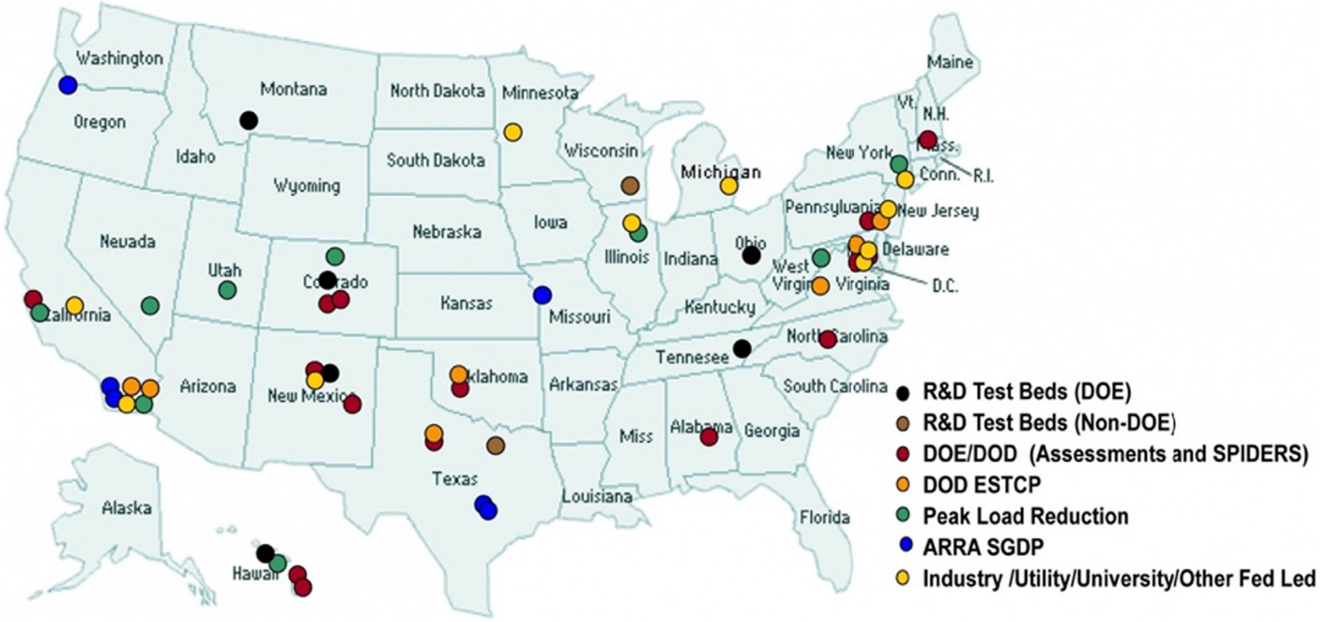

Fig. 1. Select U.S. Federal microgrid assessment and demonstration projects.
Source: OE.

and industrial properties. About 40 states in the United States have enabled PACE [53]. Table A1 in Appendix A provides some examples of PACE projects in California.

Most of California's investor-owned utilities (IOU) also provide net metering feed-in tariffs for photovoltaic solar-generated power (more details in Section 2.3). In addition, CEC is developing a state-level microgrid roadmap through research and demonstration [54]. The goals of this research are to develop commercial-scale demonstrations that provide a clear, repeatable configuration with measurable benefits and a higher probability of future commercial success with focuses on military bases, port areas, tribal communities, and disadvantaged communities. The demonstration emphasizes reliability and other monetary benefits.

2.3. Utilities and independent system operator (ISO) activity

Utilities have developed their own microgrids, sometimes called milligrids (e.g., Borrego Springs, which is discussed in the next section) [55]. Under their regulation regimes, IOUs provide financial incentives and rebates for some microgrid technologies, notably for small-scale renewables and batteries, or through programs like California's Self-Generation Incentive Program (SGIP) for various technologies (Appendix A, Table A1) [56].

Renewable feed-in tariffs are commonly used for the development of small-scale renewable energy projects (such as solar, wind, or biomass up to 1–3 megawatts or MW) within the service area of the utilities. For example, the renewable market adjusting tariff (ReMAT) is a feed-in tariff program for small renewable generators less than 3 MW in size, applicable in Pacific Gas & Electric, Southern California Edison, and San Diego Gas & Electric service areas [57]. The program provides a fixed-price contract to eligible projects, which will provide electricity to these three IOUs.

Another way to provide financial incentives is the net metering program, which allows a customer-generator to receive financial credit for power generated by their onsite system and can be used to offset the customer's electricity bill [58]. Net metering programs enable microgrid users to sell excess energy, although the terms vary widely across states. Open electricity markets in much of the United States interact with microgrids by encouraging demand response and ancillary services provision to the megagrid. Because of their wide spectrum of energy technologies and (often) advanced control systems, microgrids can participate in a variety of markets (e.g., ancillary services such as fast frequency response).

An example of rebate programs is the California Solar Initiative (CSI). The CSI provides cash back for California consumers with solar energy systems on existing homes, as well as existing and new commercial, industrial, government, non-profit, and agricultural properties within the service territories of the three IOUs: Pacific Gas and Electric, Southern California Edison, and San Diego Gas & Electric. CSI is administered by the IOUs and overseen by the California Public Utilities Commission (CPUC), which also provides funding to CSI [59]. Launched in 2007, CSI committed a total budget of $2.167 billion until 2016, signaling California's serious commitment to solar energy [56,59].

CPUC developed the SGIP to allow IOUs to provide incentives for qualifying distributed energy systems installed on the customer's side of the utility meter, including wind turbines, waste heat-to-power technologies, pressure reduction turbines, internal combustion engines, microturbines, gas turbines, fuel cells, and advanced energy storage systems. It was created initially in response to the electricity crisis of 2001 to reduce energy use, and then modified by the requirements of eligible technologies to focus on GHG emission reductions in 2009 [60]. Since its establishment in 2001, SGIP has been continuously administered and current budget is scheduled towards the end of 2019 [61,62]. By the end of 2015, SGIP provided more than $656 million in incentives to 1144 completed projects, representing more than 440 MW of rebated capacity (excluding solar projects) [60].

3. Microgrid case studies

As described, microgrid development and deployment have been accelerating in recent years as a result of initiatives from federal programs, institutions, and private sectors. These demonstration projects share the common objectives of verifying the microgrid benefits and

Table 1
Summary characteristics of example U.S. microgrids.

	Santa Rita Jail	UC Irvine	Borrego Springs	The Navy Yard	Fort Collins	Fort Carson	Illinois Institute of Technologies
Project purposes	Demo of CERTS; integrate DERs; use commercial technology; reduce peak loads; increase grid efficiency and security; meet critical reliability requirements	Test how MGs operate internally and how they interface with the future smart grid; deployment of advanced metering, and various pilot projects	Proof-of-concept test as how information technologies and DERs can increase utility asset utilization and reliability	State-of-the-art distribution system with competitively priced reliable power and progressive energy efficiency programs and tariffs	Integration of DERs; reduce peak loads; increase renewable penetration; deliver improved efficiency and reliability to the grid	Keep a group of central base facilities operating without grid power as an island, in the event of grid failure; demo of medium duty electric trucks	Demonstration of technological viability and island mode MG; peak on-demand (permanent) reduction capability
Gov. co-funders	Alameda County, DOE	UC Irvine	SDG&E, CEC	PIDC, DOE	DOE and other industry partners	Alameda County	IIT, DOE, and other partners
Projects	CERTS, RDSI	ARRA, SGDP	RDSI, ARRA	AM	FordZED, RDSI	SPIDERS	Perfect Power initiative, RDSI
Site	Dublin, CA	Irvine, CA	Borrego Springs, CA	Philadelphia, PA	Fort Collins, Colorado	Colorado Springs, CO	Chicago, Illinois
Capacity	4 MW	24 MW	4 MW	34 MW	45.6 MW	> 5 MW	12 MW
Generation technology	PV (1.2 MW), diesel generation (2.4 MW), molten carbonate fuel cell (1 MW)	Gas turbine (13.5 MW), PV (3.5 MW), steam turbine (5.6 MW), MCFC (300 kW)	Diesel generators (3.6 MW), PV (700 kW)	Gas/diesel turbines (9 MW), PV (2 MW), fuel cell (600 kW)	PV (345 kW), CHP (700 kW), microturbines (60 kW), fuel cells (5 kW), diesel generator (2.7 MW)	PV (2 MW), diesel generation (3 MW)	Gas turbines (8 MW), PV (1.4 MW), wind turbine (8 kW), diesel generator (4 MW)
Storage technology	Li-ion battery (2 MW/4 MWh)	Thermal storage (17,000 m^3, 211 $MWht_h$), Li-ion battery (2 MW/0.5 MWh)	Li-ion battery (1.5 MW/4.6 MWh), three community batteries (75 kW/150 kWh), six home storage (4 kW/8 kWh)	Community solar and energy storage (125 kW)	Thermal storage	5 electric vehicles providing voltage support	Flow battery (500 kWh)
Electric vehicle	NA	Eight level 2 chargers, H_2 station 180 kg/day	NA	Small demo	Plug-in hybrid electric vehicles	5 electric vehicles w/V2G capability	One “DC quick charge” station, six level-2 stations
Control system	Distributed energy resources management system	MelRoK EnergiStream, interfacing with MG model for real time data.	SCADA on all circuit breakers and capacitor banks, feeder automation	Coordinated distributed control, automated demand response	Load shedding and demand side management	SCADA w/IPERC technology as a cyber-secure management system	The Intelligent Perfect Power System Controller (IPPSC)
Connection interface with utility	Reverse power relay, seamless islanding (in < 8 ms)	69 kV to 12 kV using two 15 MVA transformers	Borrego substation 69–12 kV	Two main substations through 13.2 kV feeders, 15 MW & 19 MW	Two feeders	Bypass breakers at the automatic transfer switches to enable load sharing and parallel operation	Two substations and three 12.47 kV circuits (each rated at 7 MW)
Operation	Seamless islanding	Islanding	Manual islanding	Grid connected	Grid connected	Islanding	Islanding

reducing implementation risks, and, in general, further improving the reliability and resilience of the grid to ensure a sustainable energy future for the nation [30,63]. These goals have been pursued in several ways [63]: (1) development and demonstration of key microgrid technologies, such as distributed generation and storage, demand-side management, advanced control software, and planning/analysis toolsets; (2) demonstration of commercial-scale microgrid systems (capacity of less than 10 MW) by experimenting with a variety of business models, ownership, and partnership structures; (3) follow-up on and increased collaboration among existing microgrid projects to create shared knowledge of lessons learned and best practices. Table 1, below, depicts the landscape of existing microgrids in the United States. The table shows range in funding body and ownerships, primary functions (e.g., residential, commercial, industrial, and public utility), and technology and operation modes (e.g., grid-connected or islanded).

Funded by DOE, Alameda County, and the CEC over the past decade, the Santa Rita jail demonstrates CERTS technology, which allows the jail to disconnect from the grid seamlessly and quickly and run islanded for extended periods [32]. It also demonstrates a viable approach to further integrate renewable and clean distributed energy resources such as photovoltaics, which covers most of the cellblocks and was the largest such in the United States during its construction in spring 2002. The jail microgrid was constructed with best-suited, commercially available technology for all major components (battery storage, power conversion, and static disconnect switch). For example, the jail microgrid is equipped with a large Li-ion battery (2 MW and 4 MW-h) embedded with CERTS technology, in addition to a point of common coupling (PCC) device with reverse power relay and overcurrent protection capabilities, which allow the jail to complete seamless islanding in 8 ms or less. Lawrence Berkeley National Laboratory (Berkeley Lab's) tool DER-CAM has been used during both the design phase (e.g., to assist with the selection of a battery vendor) and the operation phase (e.g., to find optimal charge-discharge schedules minimizing its bill and meeting its other objectives). The jail has also undergone a series of efficiency improvements to further reduce consumption (e.g., the peak demand in the jail is approximately 3 MW). Under the terms of the DOE grant, the jail must contract with Pacific Gas & Electric to reduce the peak load on the local feeder by 15%. Reliability is also a major concern, particularly having enough energy to maintain full service during the break between a blackout beginning and the back-up diesel generators reaching full power, which spans typically a few minutes. Because of these multiple objectives, a complex optimization needs to be solved to also account for real-world uncertainty (e.g., neighboring feeder loads and outages). Overall, the jail microgrid is able to reduce the peak load of utility distribution feeder, increase grid efficiency and security, and meet critical customer reliability requirements.

Owned and operated by the University of California, Irvine (UCI), the campus microgrid aims at testing how microgrids operate internally as well as how they interface with the rest of the future smart grid. UCI has recently partnered with Southern California Edison to test advanced smart gridtechnologies, such as phasor measurement units to enable transmission substation-level situational awareness [64]. More than 100 advanced meters have been installed to obtain high-resolution load data, which are streamed through MelRoK's EnergiStream software to UCI's microgrid model for real-time decision making. The campus has installed eight Coulomb Technologies level 2 chargers that are open for public use. Under the Zero Emission Vehicle-Network Enabled Transport program, a fleet of 77 advanced vehicles (e.g., battery electric, plug-in hybrid, or fuel cell hybrid-powered vehicles) have been recruited for research purposes or ride sharing. The microgrid is also equipped with Demand Response (DR) capabilities, allowing it to operate as a smart power and demand response asset for the California Independent System Operator (CAISO). UCI has participated in the Better Buildings Challenge through the OE, launched in December 2011 to reduce the energy consumed across the campus by 20% by 2020. The campus has nominated 700 kW (kW) of DR so far, which has been achieved in various ways involving the steam turbine, heat recovery steam generator, chiller plant, and thermal energy storage tank. In the future, UCI also has plans to extend DR to the building level.

The Borrego Springs microgrid, supported by DOE and San Diego Gas and Electric (SDG&E), OE, and the CEC serves a community of 2800 customers and exemplifies an "unbundled utility microgrid," where distribution assets are owned by the utility, but the distributed energy resources are owned by independent power producers and customers [65]. The community is in a somewhat isolated area fed only by a single sub-transmission line. Prior to the microgrid instalment, the community already had many rooftop solar photovoltaic systems installed. The goal of the project is to provide a proof-of-concept test as to how information technologies and distributed energy resources can increase utility asset utilization and reliability. The total microgrid installed capacity is about 4 MW, mainly supported by two 1.8-MW diesel generators, a large 500-kW/1500-kWh battery at the substation, three smaller 50-kWh batteries, six 4-kW/8-kWh home energy storage units, and about 700 kW of rooftop solar photovoltaics. The project incorporates the supervisory control and data acquisition (SCADA) system on all circuit breakers and capacitor banks, feeder automation system technologies (FAST), outage management systems, and price-driven load management at the customer level. This enables SDG&E to explore the possibilities of price-driven DR via interaction with in-home storage, electric vehicles, and smart appliances using the areas installed smart meters and home area network devices. A detailed cost-benefit analysis of the project will be conducted by SDG&E using a methodology developed by the Electric Power Research Institute for the DOE, which classifies benefits into four categories: economic, reliability and power quality, environmental, and security and safety [66]. If the Borrego Springs microgrid proves to be cost-effective, then SDG&E will likely seek out future microgrid projects.

The historic Philadelphia Navy Yard base now owned and operated by the Philadelphia Industrial Development Corporation (PIDC) ranks among the largest non-municipal distribution systems in the nation in terms of area served and electricity consumption. Also, being a former federal facility, the Navy Yard is exempt from price regulation. In 2014, PIDC began an upgrade of the energy infrastructure at the Navy Yard to improve the management of power delivery. PIDC has engaged a consortium of partners, including PECO, Penn State, GE Grid Solutions, PJM, DTE Energy, and several additional private sector partners to establish the Navy Yard as a national center for emerging smart grid and distributed generation policies, practices, and technologies. The current commercial and industrial campus holds over 120 companies and three Navy activities with more than 10,000 employees [67]. The Navy Yard microgrid features 2 MW photovoltaics, 9 MW gas/diesel turbines, and 600 kW fuel cells, with coordinated distributed control and automatic DR capabilities. The microgrid is expected to undergo dynamic growth from its current capacity of 34–70 MW by 2022.

The Fort Collins Microgrid in Colorado is part of a larger DOE-funded project known as the Fort Collins Zero-Energy District (FortZED), where the district plans to create as much thermal and electrical energy locally as it uses [68]. The main goals are to develop and demonstrate a coordinated and integrated system of mixed distributed energy resources for the City of Fort Collins, to reduce peak loads by 20–30% on two distribution feeders, and to deliver improved efficiency and reliability to the grid and resource asset owners. The larger FortZED project represents about 10–15% of Fort Collins Utilities' entire distribution system, with a peak load of 45.6 MW across more than 7000 customers. Technologies in the Fort Collins microgrid include solar photovoltaics (345 kW), combined heat and power (700 kW), microturbines (60 kW), fuel cells (5 kW), thermal storage, and diesel-based backup generators (2.7 MW) typically deployed for emergency power. Through the SCADA system and building controls, it enables various heating, cooling, and ventilation rescheduling for DR. It is considered to be very innovative for a small municipally owned utility.

Fort Carson in Colorado Springs is one of several microgrid projects underway on U.S. military bases under the SPIDERS program [34]. This is a large military base with about 14,000 residents, covering 550 km^2 with additional firing ranges nearby. The microgrid project is intended to keep a group of central base facilities operating without grid power as an island in the event of grid failure. The microgrid consists of a 1-MW photovoltaic array, three diesel generators with a total power of 3 MW, and five electric vehicles with V2G capability deployed to stabilize the microgrid and provide DR and ancillary services. The base has a plan to become a net-zero facility using huge photovoltaic resources (potentially over 100 MW), as well as wind, ground-source heat pumps, biomass, and solar water heating.

Last but not least, the Illinois Institute of Technology microgrid was designed and built under the $14 million RDSI Perfect Power initiative in 2008 to be the world's first self-healing and efficient smart microgrid distribution system with enhanced reliability, new sustainable energy sources, and smart building automation technology [63]. The microgrid features a high-reliability distribution system (HRDS) design, which replaces the old radial distribution system with a new redundant looped system and incorporates automated distribution system breakers and switches to ensure power to all in the event of a failure. In addition to advanced metering infrastructure installed in every building for DR, an advanced system for sensing distribution system conditions and automatically reconfiguring the system to respond to disturbances has been installed to provide volt/volt-ampere-reactive management, service restoration, emergency response, and integration of distributed generation resources. The Illinois Institute of Technology microgrid is also equipped with an array of technologies to enhance its service capabilities such as the Intelligent Perfect Power System Controller (IPPSC) to interface, coordinate, and control the actions of building controllers, HRDS controllers, and distributed generation controllers; two retrofitted 4-MW turbines to achieve fast-start capability for peaking service and islanding; large-scale battery storage systems for daily peak load shaving, load shifting, and the integration of distributed energy resources; electric vehicle charging stations integrated with the battery systems and coordinated for DR; a wind turbine unit that demonstrates the integration of distributed small wind generation into a microgrid; and substation automation to make them compatible with the HRDS and the IPPSC.

Several key technology trends have been exhibited in these demonstration projects, with emphases on: (1) reduction in cost, volume, and weight (e.g., advanced power electronics technologies in the Illinois Institute of Technology microgrid); (2) long-term maintainability and reliability (e.g., switch technologies to enable frequent connection/disconnection from grid in UCI microgrid); (3) integration of various power resources and energy vectors (e.g., thermal and electrical co-generation in UCI, Fort Collins, and Fort Carson microgrids); (4) fault diagnosis, recovery, and protection capabilities (e.g., fault current limiting devices at PCC); (5) universal standards and protocols to enable device-to-device communication and coordination (e.g., CERTS); (6) enhancement of economics through planning, analysis, and operation optimization (e.g., DER-CAM utilized for Santa Rita Jail microgrid). These key components have been targeted in existing projects to ensure both grid-connected and islanding modes of operations [69].

Many existing microgrids face dynamic growth in energy demand in the next ten years. Philadelphia Navy Yard microgrid is one example [70]. PIDC has developed a Strategic Energy Master Plan to increase capacity, reduce demand, minimize capital investment, improve energy pricing, and reduce carbon footprint. It is a challenge that requires new business models to finance the expansion and achieve high return on investment, mutual strengthening of economic development and sustainable generation technologies, and, above all, close collaboration with a multitude of stakeholders such as utilities (PECO, DTE, PGW), owners (PIDC, U.S. Navy), developers (Liberty property trust), agencies (PUC, PJM), and institutions (PSU, Drexel). From a technology perspective, it is foreseeable that future microgrids will be a functional system with a hybrid combination of centralized/distributed power sources and multi-level control architectures that enables seamless interaction with the megagrid and enhances power reliability. On the other hand, the development and operation of microgrids also involve economic trade-off and regulatory incentives/barriers. It is important to delineate requirements based on customer and utility needs during planning, leverage experiences from business models to technology implementation, and establish guidelines and best practices for multiple approaches to achieve long-term maintainability and reliability [69].

4. Control system and methods in microgrids

4.1. CERTS definition

The goal of the CERTS program is to conduct research to improve power system reliability, test the performance of emerging technologies, and understand microgrid system economic, regulatory-institutional, and environmental influence [14]. A defining factor of CERTS requires a microgrid to be a self-controlled entity that can be operated as a single aggregated load [18]. This feature of a CERTS project is in line with microgrid definitions from DOE and CIGRE, as discussed in Section 11. CERT defines three critical functions in a microgrid structure: microsource controller, energy manager, and protection. To achieve these requirements, distributed energy resources technologies should have simple "plug-and-play" capabilities requiring little custom engineering for interconnection. To facilitate such interconnection, CERTS has included standards such as the IEEE 1547 series for interconnecting distributed resources [71]. Basic distributed energy resource control methods are included in CERTS as introduced in Section 1. CERTS also defines events in normal grid-connected mode and island mode. Microgrid testbeds are developed based on CERTS concepts [72–74]. The CERTS testbed demonstrates the integration of small energy resources into a microgrid. The testbed can perform core microgrid functions such as: seamless switch between grid-connection mode and island mode, electrical protection for fault currents, and self-controlled system voltage and frequency stability. Even though the original CERTS microgrid and testbed was established for small capacity (e.g., a few hundred kW) distributed energy resource connections, it was later successfully applied to a large-scale microgrid demonstration with a few MW distributed energy resource capacity [75].

4.2. Microgird control architecture and application

Microgrid control is a complex multi-objective problem that deals with issues from different technical areas at multiple timescales and physical levels [76]. It is responsible for providing control, regulation, and optimization services to microgrids during different modes of operation (e.g., grid-connected model, islanded mode, and the transitions between them). Functions that the microgrid control should provide are classified by IEEE p2030.7 Working Group into three categories [77]:

(1) Device-level control (a.k.a. primary control)—voltage/frequency control, local control of DG units, energy storage, loads, and fault protection.
(2) Local area control and supervisory control (a.k.a. secondary control)—load and energy management, economic dispatch in grid and

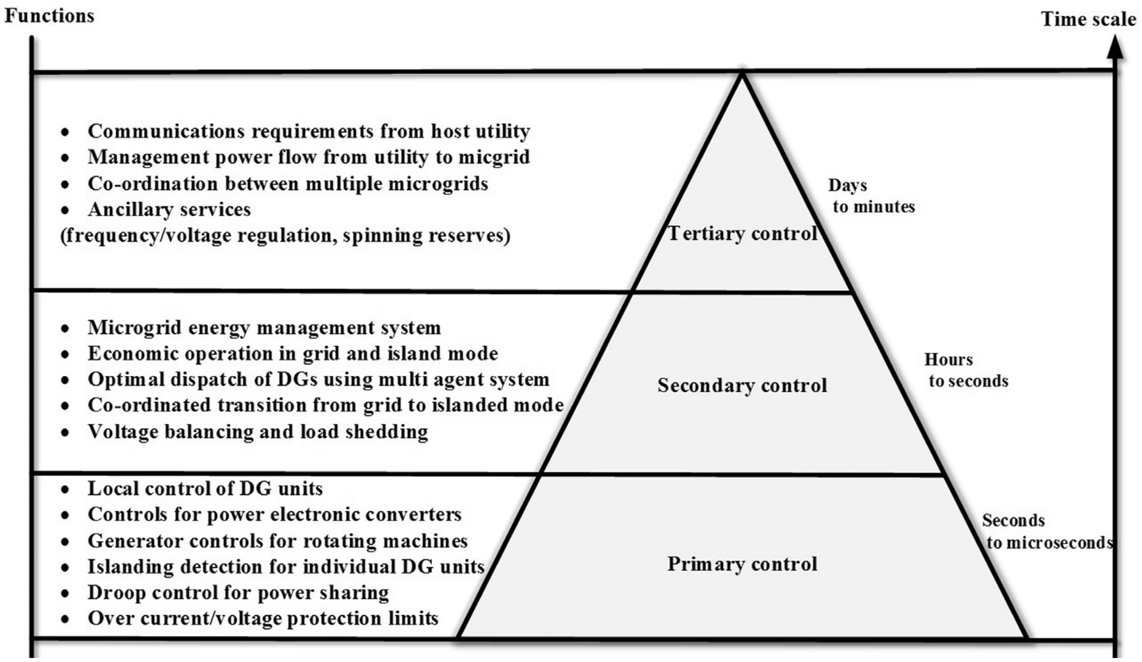

Fig. 2. Microgrid controller—time frame and action domain.

Table 2
Microgrid software comparison.

	DER-CAM/DEEP	HOMER	GridLAB-D	MDT	SGCT
Algorithm	MILP Optimization	Simulation, Optimization	Agent-based simulation	MILP Optimization, simulation, Genetic Algorithm searching	Calculation
Linear	Linear	Linear, non-linear	Linear, non-linear	Yes	Yes
Climate data	User-input	Yes	Yes	No	No
Cost	Yes	Yes	Yes	Yes	Yes
Equipment data	Some	Yes	Yes	Some	Some
Island mode	Yes	Yes	Yes	Yes	Yes
Power Quality	No	No	Yes	Yes	Yes
Thermal quality	No	No	No	No	No
Demand Response	Yes	Yes	Yes	Yes	Yes
Steady state	Yes	Yes	Steady-state & Transient	Yes	Yes
Multi-objective	Yes	Yes	No	Yes	Yes
Stochastic/Sensitivity	Yes	Yes	No	Yes	Yes

islanded mode, automatic generation control, spinning reserve, fast load shedding, and resynchronization.

(3) Grid-interactive control (a.k.a. tertiary control)—market participation, power flow from utility to microgrids, multi-microgrid coordination.

These controls have different domains of operation. Hence, a more complicated and hierarchical control structure needs to be developed to address each categorical requirements [78,79]. The relationship between different levels of control is illustrated in a hierarchical structure, as shown in Fig. 2.

The primary control at the device level acts within the micro-seconds to seconds range. Based on local measurements for control determination, it aims at stabilizing the voltage and frequency within the microgrid. Strategies in response to frequency and voltage droops are discussed extensively in the literature [23]. While the conventional droop method is simple and reliable, it has some drawbacks such as its weak transient performance. Hence, several modifications have been proposed (e.g., adjustable load sharing method [80] and adaptive droop control [81]. The flexibility of ESSs and flexible loads can also be leveraged to enhance the inertia of the MG for stability benefits [82,83].

The secondary control, such as local area control and supervisory control, typically operates in the seconds to days range and is responsible for reliable, secure, and economical operations of microgrids in both grid-connected and stand-alone modes [78]. The secondary control schemes can be categorized into centralized or decentralized structures. The key feature of the centralized secondary control is that decisions are made primarily by the microgrid operator. Presented with relevant microgrid status information, the operator schedules routing schemes and determine optimal microsource controller setpoints [84]. Using a centralized control system, the Santa Rita Jail microgrid can achieve its economic goal while meeting reliability requirements in either grid-connected or island modes [85–87]. Technologies have been developed at the National Renewable Energy Laboratory, CERTS, Sandia National Laboratory, Berkeley Lab, and other institutions to address the problems of economic dispatch and frequency/voltage regulation [88–90]. Decentralized control has become popular nowadays with its roots in multi-agent system theory [84]. The core idea is to coordinate several agents to collaborate in assigned tasks and achieve the overall system objectives [91]. A report by Sandia National Laboratory presents the application of multi-agent technology to microgrid control. Using the Sandia-developed technology, a distributed agent coalition has been prototyped [92]. The advantages of using the multi-agent system technology for MG control has been experimentally validated in the laboratory microgrid in the National Technical University of Athens [93].

Tertiary control lies in the domain of multi-microgrid collaboration and interaction with the megagrid as a cluster of entities. Core activities at this level are related to energy markets for profit pursuit (e.g., import or export energy and ancillary services). Main issues of multi-microgrid control arise from information barriers and the necessity of communication among individual entities. Some key aspects of multi-microgrid operation has been demonstrated in microgrid described in research by Madureira et al. [94] and Resende et al. [95]. Furthermore, the multi-microgrids with MV-grid-connected DG units can participate in the provision of ancillary services.

Hierarchical control architectures have been demonstrated in several microgrids. In the Illinois Institute of Technology-Bronzeville microgrid, hierarchical control architecture is used to facilitate frequency regulation. The lower-layer controllers regulate frequencies and voltages in individual microgrids, while the upper-layer controllers regulate power exchange between networked microgrids [96,97]. In the Philadelphia Navy Yard microgrid, a controller has been designed to optimize the operational cost and energy efficiency with a mix of distributed generators and storage. A hierarchal control system is planned for the future [98,99]. Schweitzer Engineering Laboratories (SEL) has developed a microgrid control system (MGCS) that includes functions such as intertie protection, local power factor control, distributed generation sharing and optimization, load shedding, load management, bidirectional power flow management, peak shaving, grid decoupling, grid auto synchronization, monitoring, and alarming [100]. The developed MGCS has been successfully installed and is in service worldwide. Furthermore, the National Renewable Energy Laboratory has selected a microgrid control system from SEL for installation in their Energy Systems Integration Facility [100].

5. Software and tools developed in U.S. Microgrid research

Software and tools are developed in the United States to support microgrid project development and operations [101]. Demonstration projects often require simulation to determine microgrid investment, construction, and operation strategies. This section reviews some key microgrid software developed by U.S. research institutes, focusing on the tools' capabilities, functions, and strength. Software discussed in this section are tools often found in public domain and have been widely applied. Many other modeling tools have been developed outside of the United States and are not in the public domain for microgrid research [36,101–103].

5.1. DER-CAM and DEEP

DER-CAM (Distributed Energy Resource, Customer Adoption Model) is a microgrid optimization software tool developed by Berkeley Lab [104]. Its derivative version, DEEP, and MODER, further modeled district-scale heating and cooling, adding features such as demand response [105]. DER-CAM is developed using mixed integrated linear programming and coded on the GAMS platform. It can simulate the optimal technology configuration of a microgrid system, integrating distributed resources and loads for electricity, heating, and cooling. As an economic-driven model, its main objective functions are expressed as minimizing system cost or carbon emission. Multi-objective optimization is feasible by trading off cost and CO_2 emission [106]. The model is developed in a static-state fashion where inputs and outputs are often calculated in minutes or hourly time steps. Transient and short-term system behaviors are not included in DER-CAM, nor does it capture the thermal and power quality change in microgrids. DER-CAM requires users to input weather and technologies data. It does not simulate load profiles, which can be obtained through user inputs or a reference building database it developed using DOE prototype building models. Even though it is a linear model, segmented linearization is often used in DER-CAM to capture some non-linear effects in a microgrid system [107]. DER-CAM can simulate both grid-connected and island modes, and power and thermal energy can be imported to or exported from a microgrid. More recent developments in DEEP and MOD-DR allow a microgrid to be an independent retailer who can interact with the megagrid to acquire energy from the wholesale market and sell energy to end users. Different business models can be simulated using these developments to capture the energy system's dynamics through wholesale and retail transactions [105,108].

5.2. HOMER

HOMER (Hybrid Optimization Model for Multiple Energy Resources) is a microgrid simulation software developed by the National Renewable Energy Laboratory. The model is developed to evaluate a small-scale micropower (microgrid) system equipment options with constraints [109]. The overall modeling methodologies for HOMER are similar to those used in DER-CAM: to minimize microgrid system investment and operation life-cycle costs [102]. HOMER can perform both simulation and optimization for one-year performance analysis. In the simulation, variable time-steps can be chosen based on users' application [110]. Power transmission and distribution networks can also be modeled in HOMER to account for losses from source to load. At the distribution level, DC and AC feeders can be modeled heterogeneous power quality, and controls can be set up for different end-user devices [111,112]. For microgrid system controls, HOMER is implemented with rule-based strategies to optimize system operation with time-steps [111]. Sensitivity analysis is commonly used in HOMER for users to compare techno-economic performance microgrids design [113]. HOMER can simulate demand response in a microgrid and calculate the economics through balancing load reduction with distributed energy resource generation [114]. HOMER itself is an electricity modeling-oriented focus software; technologies for heating and cooling, and heating and cooling loads calculations, are not included. As one of most popular microgrid modeling software, HOMER has been developed into several versions with different functions and license types. Its user-friendly interface also makes microgrid modeling illustrative. Another important feature of HOMER is that it comes with comprehensive technology libraries, which enable users to simply "drag-and-drop" elements to model their microgrid system.

5.3. Microgrid design toolkit

The Microgrid Design Toolkit (MDT) is a software tool developed by the Sandia National Laboratory. MDT is a new effort supported by DOE's microgrid research [29]. The tool is designed to provide early-stage decision-making for microgrid system planning [115]. MDT gives users the capability to search a variety of microgrid technology configurations to provide alternative design decisions on microgrid system costs, performance, and reliability. The model has two major capabilities. The microgrid sizing capability is a mixed-integer linear programming optimization to determine microgrid technology sizing. The second capability calculates microgrid performance in the island mode through two components: (1) technology management optimization—a genetic algorithm searching model and (2) the performance reliability model—a simulation model for reliability [116]. Unlike other DOE tools, MDT's strength lies in its microgrid reliability calculation, providing trade-off analysis between cost and reliability. MDT has been widely used in DOE demonstration microgrid projects such as the SPIDERS program introduced in Section 2 [13].

5.4. Smart grid computational tool

The Smart Grid Computation Tool (SGCT) is software developed by the Electric Power Research Institute through DOE's ARRA funding [38]. SGCT was developed to support ARRA's smart grid demonstration projects and to provide cost-benefit analysis. The tool requires users to define the power distribution asset. The SGCT has embedded about 20 common assets (e.g., electric storage devices) which are commonly used in smart grid and microgrids [117]. Then, the tool provides 15 common functions of a smart grid technology. Then, mechanisms are needed to define what action a function can bring to the grid system. The benefit module will calculate the actual monetary values of a smart grid system can bring over a time horizon. Then, finally, the net present value cost is calculated and compared with the benefit calculation. Unlike other tools described above, the SGCT is a techno-economic analysis tool focusing on long-term system cost-benefit analysis, rather than technology energy balance-based simulation or optimization.

5.5. GridLAB-D

GridLAB-D is an agent-based smart grid simulation software developed by the Pacific Northwest National Laboratory. It can simulate and solve large-scale independent devices in a smart grid or microgrid network [118–120]. The software is designed to be flexible for modular development to allow users to develop and model customized grid technologies. GridLAB-D can not only simulate distributed power networks, but also simulate the transmission network power flow. It can model power system components such as transmission and distribution lines, transformers, voltage regulators, fuses, switches, shunt capacitor banks, and so on. The agent-based characteristics enable GridLAB-D to simulate a microgrid's component-level performance, which many of the other, previously mentioned models cannot provide [121]. GridLAB-D can be used to conduct many of the microgrid-related simulation including, but not limited to: demand response [122], voltage level regulation [123], microgrid resilience simulation [124,125], distributed battery storage and control [126], microgrid energy management, and peak load reduction [127]. GridLAB-D can be integrated with other simulation environment such as MATLAB and Volttron to perform grid integration control or hardware-in-the-loop control simulation [124,128].

Table 2, below, compares software reviewed above for microgrid and smart grid research. Tools are compared based on their following features: computational algorithm (e.g., simulation, optimization), linear or non-linear model, climate data, cost information, equipment data, island mode simulation, power and thermal quality modeling, demand response, steady-state or transient simulation, multi-objectives modeling, and stochastic/sensitivity simulation.

In general, U.S. microgrid tools development has demonstrated some trends. First, microgrid simulation has evolved from traditional power system-based simulation and optimization to comprehensive power and thermal energy integration modeling. The integration of power with simulation modeling provides users systematic modeling capabilities in a microgrid system to address complex energy demand and generation requirements. The second trend is that software tools have evolved from energy system engineering-based simulation to techno-economic analysis. The cost-benefit calculation enables the simulation to provide microgrid design and operation feasibility recommendations and fulfills the needs of different levels of the control system. Finally, microgrid system reliability modeling has become an important area. Trade-off and sensitivity analysis between system cost-benefits and reliability or resilience are critical for microgrid project development. This requires software tools to provide computational analysis capability beyond the scope of energy and cost.

6. Conclusion

In summary, microgrid development in the United States show that it needs active government policies at different levels, programs featuring funding and demonstration projects to showcase technological and economic feasibility, advanced research on distributed energy resource technologies and controls, and software tools to assist in design and performance analysis.

Many other countries are striving for microgrid development and demonstration. The following recommendations can be made based on lessons learned from the U.S. microgrid industry. First of all, microgrid policies and demonstration programs should be set up with clear targets. A variation of targets for different purposes can be established with feasible technology solutions. Second, the social and economic benefits of microgrids should be accurately defined when setting up research and demonstration projects. It is also important that these benefits make microgrid projects economically viable and facilitate long-term system operation. Finally, it is important to avoid a pure technological focus for demonstration projects, even though technologies are core elements of a microgrid system. Demonstration projects should also include feasible market mechanisms to help scale-up microgrid development in the long run. The experience summarized from this research on policies, demonstrations, control and software tools in the U.S. can be used for microgrid construction in the rest of the world.

There are still a lot of research needed in microgrids. The current trends on resiliency research require multiple microgrids to interact with each other to improve the overall system resiliency. Such interaction often requires trade-offs between economic benefits and resilient performance. With more and more direct current (DC) technologies such as renewables, storage and end use, DC microgrid becomes attractive to deliver distributed energy to end use devices more efficiently. The emerging interest in DC microgrids requires a new set of development on standards, safety and protection, and controls. With the end use devices become efficient and intelligent, using communication DC power network to transmit energy and signals gets a lot attentions. This kind of "Nanogrid" with communication network will make microgrid more and more intelligent. All of the research can make a smart, efficient and reliable future for microgrids.

Acknowledgments

The U.S. authors recognize Berkeley Lab's support from DOE – The United States under Contract No. DE-AC02-05CH11231 and by Energy Foundation. Assistance was also provided by Tianjin Electric Power Corporation, China, through research materials and guidance.

Appendix A

See Table A1.

Table A1
Summary of microgrid policies and programs at federal, state, and utility levels by technology.

		Solar Photovoltaics	Combined Heat and Power	Wind Turbines	Fuel Cells	Storage	Electric Vehicles
Federal	Investment Tax Credit	30%, exp. 1/1/2019 26%, exp. 1/1/2020 22%, exp. 1/1/2021 10%, Permanent	≤50 MW 10%, exp. 1/1/2017	≤100 kW 30%, exp. 1/1/2017	30%, exp. 1/1/2017		
	Loan Guarantee Program	1 billion for all distributed energy projects	1 billion for all distributed energy projects	1 billion for all distributed energy projects		1 billion for all distributed energy projects	
	Grant from ARRA	Eligible	Eligible	Eligible		Eligible	Eligible
	Combined Heat and Power Technical Assistance Partnerships		Key services include market opportunity analyses, education and outreach, and technical assistance				
State (California)	RPS	California's RPS: 50% of electricity from eligible renewable energy resources by 2030		California's RPS: 50% of electricity from eligible renewable energy resources by 2030	California's RPS: 50% of electricity from eligible renewable energy resources by 2030	California's RPS: 50% of electricity from eligible renewable energy resources by 2030	
	Sales Tax Incentives	Applicable to photovoltaic systems used for providing electricity to farm equipment and machinery					
	Property Assessed Clean Energy	1. Energy Independence Program; 2. Los Angeles County PACE; 3. CaliforniaFIRST; 4. Home Energy Renovation Opportunity (HERO); 5. SAMAS Commercial Program; 6. Figtree PACE	1. Figtree PACE	1. Energy Independence Program	1. Energy Independence Program; 2. Figtree PACE	1. Figtree PACE	1. Energy Independence Program; 2. Los Angeles County PACE
	Power Purchase Agreement	A third-party developer owns, operates, and maintains the photovoltaic system that is sited on the property of a host customer who purchases the system's electric output from the solar services provider					
Utilities/ISOs	Feed-in-Tariff (FIT)	1. Renewable FIT (< 3 MW) 2. Marin Clean Energy FIT (≤1 MW) 3. Palo Alto Clean Local Energy Accessible Now 4. LA Department of Water and Power FIT		1. Renewable FIT (< 3 MW) 2. Marin Clean Energy FIT (≤1 MW)	1. Renewable FIT (< 3 MW) 2. Marin Clean Energy FIT (≤1 MW)		
	Self Generation Incentive Program		Incentive rates: 0.6 USD/W	Incentive rates: 0.9 USD/W	Incentive rates: 0.6 USD/W	About $57 million for small residential storage (≤10 kW) incentive rates: $0.35 or $0.4/MW	
	Rebate Program	The California Solar Initiative Managed by CPUC		Emerging Renewables Program Managed by CEC	Emerging Renewables Program Managed by CEC		
	Net Energy Metering	≤1 MW		≤1 MW	≤1 MW		

References

[1] Wilson Adam, Asmus Peter. Microgrid Deployment Tracker 4Q17, Navigant; 2017.

[2] Romankiewicz John, Min Qu, Marnay Chris, Zhou Nan. International microgrid assessment: governance, incentives, and experience (IMAGINE). Lawrence Berkeley National Laboratory; 2013.

[3] Ustun Taha Selim, Ozansoy Cagil, Zayegh Aladin. Recent developments in microgrids and example cases around the world—a review. Renew Sustain Energy Rev 2011;15:4030–41.

[4] Marnay Chris, Aki Hirohisa, Hirose Keiichi, Kwasinski Alexis, Ogura Saori, Shinji Takao. Japan’s pivot to resilience. IEEE Power Energy 2015;13(3).

[5] Hirose Keiichi. Behavior of the Sendai microgrid during and after the 311 Great East Japan Disaster. Telecommunications energy conference 'Smart Power and Efficiency' (INTELEC). IEEE; 2013.

[6] Energy Foundation. Research on key technologies and development of distributed smart microgrid. Research Report; 2012 [in Chinese].

[7] Energy Foundation. Recommendations on Implementation scheme for demonstration of microgrid Technology in China during the 12th FYP, Research Report; 2012 [in Chinese].

[8] Jiayi Huang, Jiang Chuanwen Xu, Rong. A review of distributed energy resources and MicroGrid. Renew Sustain Energy Rev 2008;12:2472–83.

[9] Prasenjit Basak S, Chowdhury S Halder, nee Dey, S.P. Chowdhury. A literature review on integration of distributed energy resources in the perspective of control, protection and stability of microgrid. Renew Sustain Energy Rev 2012;16(8):5545–56.

[10] Pesin Michael. U.S. Department of Energy Electricity Grid Research and Development, presentation at the American Council of Engineering Companies, Environment and Energy Committee Winter Meeting. 9 February; 2017.

[11] CIGRÉ Working Group C.22). Microgrids 1, Engineering, Economics, & Experience. Paris, France. Ref. 635, October; 2015 http://www.e-cigre.org/publication/635-microgrids-1-engineering–economics–experience.

[12] Mariam Lubna, Basu Malabika, Conlon Michael F. A review of existing microgrid architectures. J Eng 2013; Article ID 937614, 8 pages.

[13] Navigant Research. MG Deployment Tracker 4Q16; 2016. https://www.navigantresearch.com/research/MG-deployment-tracker-4q16.

[14] Hatziargyriou Nikos, Asano Hiroshi, Iravani Reza, Marnay Chris. Microgrids. IEEE Power Energy Mag 2007;5(4).

[15] Hartono BS, Budiyanto, Setiabudy Rudy. Review of microgrid technology. Quality in research. IEEE; 2013.

[16] Mahmoud MS, AzherHussain S, Abido MA. Modeling and control of microgrid: an overview. J Franklin Inst 2014;351:2822–59.

[17] Bower Ward, Ton Dan, Guttromson Ross, Glover Steve, Stamp Jason, Bhatnagar Dhruv, et al. The Advanced Microgrid Integration and Interoperability. Sandia National Laboratory report: SAND2014-1535. March; 2014.

[18] Lasseter Robert, Akhil Abbas, Marnay Chris, Stephens John, Dagle Jeff, Guttromson Ross, et al. The CERTS MicroGrid Concept. Consortium for Electric Reliability Technology Solutions: White Paper on Integration of Distributed Energy Resources. Lawrence Berkeley National Laboratory; 2002.

[19] Hatziargyriou Nikos. Microgrids: architectures and control. John Wiley & Sons, IEEE Press. Dec 6; 2013.

[20] Li Wang, Lee Dong-Jing. Load-tracking performance of an autonomous SOFC-based hybrid power generation/energy storage system. IEEE Trans Energy Convers 2010;25(1).

[21] Peças Lopes, JA, Moreira CL, Madureira AG. Defining control strategies for microgrids islanded operation. IEEE Trans Power Syst 21(2);2006.

[22] Cañizares Claudio A, Palma-Behnke Rodrigo. Trends in microgrid control IEEE-PES task force on microgrid control. IEEE Trans Smart Grid 2014;5(4).

[23] Guerrero Josep M, Chandorkar Mukul, Lee Tzung-Lin, Loh Poh Chiang. Advanced control architectures for intelligent microgrids—Part I: decentralized and hierarchical control. IEEE Trans Indust Electron 2013;60(4).

[24] Guerrero Josep M, Loh Poh Chiang, Lee Tzung-Lin, Chandorkar Mukul. Advanced control architectures for intelligent microgrids—Part II: power quality, energy storage, and AC/DC microgrids. IEEE Trans Indust Electron 2013;60(4).

[25] Pourmousavi S Ali, Hashem Nehrir M. Real-time central demand response for primary frequency regulation in microgrids. IEEE Trans Smart Grid 2012;3(4).

[26] Saleh Mahmoud S, Althaibani Ammar, Esa Yusef, Mhandi Yassine, Mohamed Ahmed A. Impact of clustering microgrids on their stability and resilience during blackouts. In: International Conference on Smart Grid and Clean Energy Technologies. IEEE; 2015.

[27] Sinha Sunanda, Chandel SS. Review of software tools for hybrid renewable energy systems. Renew Sustain Energy Rev 2014;32(April): 192–205.

[28] Zhou W, Lou C, Li Z, Lu L, Yan H. Current status of research on optimum sizing of stand-alone hybrid solar–wind power generation systems. Appl Energy 2010;87:380–9.

[29] Gu Wei, Wu Zhi, Bo Rui, Liu Wei, Zhou Gan, Chen Wu, et al. Modeling, planning and optimal energy management of combined cooling, heating and power microgrid: a review. Elect Power Energy Syst 2014;54: 26–37.

[30] U.S. DOE. https://energy.gov/oe; 2017.

[31] Renewable and Distributed Systems Integration Program https://www.smartgrid.gov/recovery_act/overview/renewable_and_distributed_systems_integration_program.html.

[32] Marnay Chris, DeForest Nicholas, Lai Judy. A Green Prison: The Santa Rita Jail Campus Microgrid panel paper. In: IEEE PES general meeting. San Diego, CA. p. 24–25 July.

[33] U.S. DOE. Enhancing the smart grid: integrating clean distributed and renewable generation https://www.energy.gov/sites/prod/files/oeprod/DocumentsandMedia/RDSI_fact_sheet-090209.pdf.

[34] SPIDERS Joint Capability Technology Demonstration; 2015. https://energy.gov/eere/femp/downloads/smart-power-infrastructure-demonstration-energy-reliability-and-security-spiders.

[35] Energy Surety Microgrids™ Supporting Renewable Technologies and Energy Assurance http://energy.sandia.gov/energy/ssrei/gridmod/integrated-research-and-development/esdm/.

[36] Bonneville Power Authority. Power grid gets smarter with new Oregon MG.” June. https://www.bpa.gov/news/newsroom/Pages/Power-grid-gets-smarter-with-new-Oregon-MG.aspx.

[37] http://www.pnwsmartgrid.org/.

[38] Liu Xu, Marnay Chris, Feng Wei, Zhou Nan, Karali Nihan. A review of the ARRA smart grid projects and their implications for China. January. LBNL- 1007122; 2017.

[39] Ton Dan, Reilly Jim. Microgrid controller initiatives. IEEE Power Energy 2017;15(4).

[40] Geza Joos, Reilly Jim, Bower Ward, Neal Russ. The need for standardization. IEEE Power Energy Mag July/August 2017; 2017.

[41] Title XVII Supplement III regarding Distributed Energy Projects. August 24; 2015. https://energy.gov/sites/prod/files/2015/08/f26/DEP_Supplement_REEE_Solicitation_%20082415.pdf.

[42] U.S. DOE Loan Programs Office. http://energy.gov/lpo/loan-programs-office.

[43] U.S. DOE CHP Technical Assistance Partnerships. https://energy.gov/eere/amo/chp-technical-assistance-partnerships-chp-taps.

[44] DSIRE Database. Renewable Portfolio Standard Policies. February; 2017. http://ncsolarcen-prod.s3.amazonaws.com/wp-content/uploads/2017/03/Renewable-Portfolio-Standards.pdf.

[45] Jones KB, Bartell SJ, Nugent D, Hart J, Shrestha A. The urban microgrid: smart legal and regulatory policies to support electric grid resiliency and climate mitigation. Fordham Urb LJ 2013;41:1695.

[46] Ton DT, Wang WP. A more resilient grid: The US department of energy joins with stakeholders in an R&D plan. IEEE Power Energ Mag 2015;13(3):26–34.

[47] Happold Consulting. Sandy Success Stories; 2013. https://issuu.com/burohappold/docs/sandysuccessstories_june2013__1_.

[48] https://www.nyserda.ny.gov/All-Programs/Programs/NY-Prize/Feasibility-Studies.

[49] https://www.nyserda.ny.gov/ny-prize.

[50] California Energy Commission; 2017. http://www.energy.ca.gov/research/MG/.

[51] California Energy Commission. Demonstrate Business Case for Advanced Microgrids in Support of California’s Energy and GHG Policies. GFO-17-30. http://www.energy.ca.gov/contracts/GFO-17-302/.

[52] Solar Energy Industries Association. Third-Party Solar Financing. https://www.seia.org/initiatives/third-party-solar-financing.

[53] PACE Nation. PACE legislation. http://pacenation.us/pace-legislation/.

[54] California Energy Commission. California Microgrid Roadmap. http://www.energy.ca.gov/research/microgrid/.

[55] Marnay Chris. Microgrids: finally finding their place. In: Fereidoon P Sioshansi, editor. Future of utilities: utilities of the future. London: Academic Press; 2016.

[56] Van Benthem A, Gillingham K, Sweeney J. Learning-by-doing and the optimal solar policy in California. Energy J 2008:131–51.

[57] California Public Utilities Commission. Renewable feed-in tariff program. http://www.cpuc.ca.gov/feedintariff/.

[58] California Public Utilities Commission. Net Energy Metering. http://www.cpuc.ca.gov/General.aspx?id = 3800.

[59] California Energy Commission. Million Solar Homes and California's Solar Initiative. http://www.energy.ca.gov/renewables/emerging_renewables/more_info.html.

[60] Itron. Final Report: SGIP 2014-2015 Impact Evaluation. November 4; 2016.

[61] California Public Utilities Commission. Self-generation incentive program handbook. December 18; 2017.

[62] Taylor M. Beyond technology-push and demand-pull: lessons from California's solar policy. Energy Econ 2008;30(6):2829–54.

[63] Ton DT, Smith MA. The U.S. Department of Energy's microgrid initiative. Elect J 2012;25(8):84–94.

[64] U.S. DOE. Progress Report for OE ARRA Smart Grid Demonstration Program Aggregation of RDSI, SGDP, and SGIG Results; 2015.

[65] Bialek T. Borrego Springs MG demonstration project. California Energy Commission CEC-500-2014-067; 2014.

[66] Forsten K. The integrated grid—a benefit-cost framework. Palo Alto (CA): Electric Power Research Institute; 2015.

[67] Politico. The Coolest Shipyard in America; 2016 http://www.politico.com/magazine/story/2016/07/philadelphia-what-works-navy-yard-214072.

[68] Sumner Dennis, Vosburg Tom, Brunner Steve, Gates Judy, Howard Nathan, Merton Andrew, et al. Research, development and demonstration of peak load reduction on distribution feeders using distributed energy resources for the City of Fort Collins. No. FC26–08NT02876. City of Fort Collins, CO (United States); 2015.

[69] U.S. DOE. DOE Microgrid Workshop Report. August 30–31; 2011. http://energy.gov/sites/prod/files/Microgrid%20Workshop%20Report%20August%202011.pdf.

[70] Smith David J. The Philadelphia navy yard advanced microgrid: an integrated platform for energy efficiency, distributed generation and resilience. In: International district energy association conference. Boston, MA; 2015.

[71] IEEE. IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems. New York, NY: The Institute of Electrical and Electronics Engineers, Inc.; 2003.

[72] Lasseter RH, Eto JH, Schenkman B, Stevens J, Vollkommer H, Klapp D, et al. CERTS microgrid laboratory test bed. IEEE Trans Power Deliv 2011;26(1).

[73] Eto J, Lasseter R, Schenkman B, Stevens J, Klapp D, Volkommer H, et al. Overview of the CERTS microgrid laboratory test bed. In: CIGRE/IEEE PES joint symposium; 2009.

[74] Nichols DK, Stevens J, Lasseter RH, Eto JH, Vollkommer HT. Validation of the CERTS microgrid concept the CEC/CERTS microgrid testbed. In: Power engineering society general meeting. IEEE; 2006.

[75] Alegria Eduardo, Brown Tim, Minear Erin, Lasseter Robert H. CERTS microgrid demonstration with large-scale energy storage and renewable generation. IEEE Trans Smart Grid 2014;5(2).

[76] Meng Lexuan, et al. Microgrid supervisory controllers and energy management systems: a literature review. Renew Sustain Energy Rev 2016;60:1263–73.

[77] Ton Dan, Reilly James. Microgrid controller initiatives: an overview of R&D by the US Department of Energy. IEEE Power Energ Mag 2017;15(4):24–31.

[78] Olivares Daniel E, et al. Trends in microgrid control. IEEE Trans Smart Grid 2014;5.4:1905–19 (78).

[79] Jiayi Huang, Chuanwen Jiang, Rong Xu. A review on distributed energy resources and MicroGrid. Renew Sustain Energy Rev 2008;12(9):2472–83.

[80] Vandoorn TL, et al. Review of primary control strategies for islanded microgrids with power-electronic interfaces. Renew Sustain Energy Rev 2013;19:613–28.

[81] He Jinwei, et al. An islanding microgrid power sharing approach using enhanced virtual impedance control scheme. IEEE Trans Power Electron 2013;28(11):5272–82.

[82] Kim Jaehong, et al. Mode adaptive droop control with virtual output impedances for an inverter-based flexible AC microgrid. IEEE Trans Power Electron 2011;26(3):689–701.

[83] Kim Jong-Yul, et al. Cooperative control strategy of energy storage system and microsources for stabilizing the microgrid during islanded operation. IEEE Trans Power Electron 2010;25(12):3037–48.

[84] Gouveia C, et al. Coordinating storage and demand response for microgrid emergency operation. IEEE Trans Smart Grid 2013;4(4):1898–908.

[85] Microgrids: architectures and control. John Wiley & Sons; 2014.

[86] Marnay C, DeForest N, Stadler M, Donadee J, Dierckxsens C, Mendes G, et al. A green prison: Santa Rita jail creeps towards zero net energy (ZNE). In: Proc. ECEEE [12]; 2011.

[87] DeForest N, Stadler M, Marnay C, Donadee J. Microgrid dispatch for macrogrid peak-demand mitigation. In: Proc. ACEEE summer study on energy efficiency in buildings; 2014.

[88] Panwar Mayank, et al. Dispatch in microgrids: lessons from the fort collins renewable and distributed systems integration demonstration project. Elect J 2012;25(8):71–83.

[89] Hughes Justin, Dominguez-Garcia Alejandro, Poolla Kameshwar. Coordinating heterogeneous distributed energy resources for provision of frequency regulation services; 2017.

[90] Vrettos Evangelos, et al. Experimental demonstration of frequency regulation by commercial buildings–Part II: results and performance evaluation. IEEE Trans Smart Grid 2016.

[91] Etemadi Amir H, Davison Edward J, Iravani Reza. A decentralized robust control strategy for multi-DER microgrids—Part I: Fundamental concepts. IEEE Trans Power Deliv 2012;27(4):1843–53.

[92] Pipattanasomporn Manisa, Feroze Hassan, Rahman Saifur. Multi-agent systems in a distributed smart grid: Design and implementation. In: Power Systems Conference and Exposition. PSCE'09. IEEE/PES. IEEE; 2009.

[93] Smith Randall B, et al. Agent-based control of distributed infrastructure resources. No. SAND2005-7937. Sandia National Laboratories; 2006.

[94] Madureira AG, et al. Advanced control and management functionalities for multi-microgrids. Int Trans Elect Energy Syst 2011;21(2):1159–77.

[95] Resende FO, Gil Nuno José, Lopes JA. Service restoration on distribution systems using Multi-MicroGrids. Int Trans Elect Energy Syst 2011;21(2):1327–42.

[96] Shahidehpour Mohammad, et al. Networked microgrids: exploring the possibilities of the IIT-bronzeville grid. IEEE Power Energy Mag 2017;15(4):63–71.

[97] Lu X, Bahramirad S, Wang J, Chen C. Bronzeville community microgrids: a reliable, resilient and sustainable solution for integrated energy management with distribution systems. Electr J 2015;28(10):29–42.

[98] Uluski Robert, et al. Microgrid controller design, implementation, and deployment: a journey from conception to implementation at the Philadelphia Navy Yard. IEEE Power Energy Mag 2017;15(4):50–62.

[99] GridLA B-D [Online]. Available: http://gridlab.org.

[100] Schweitzer Engineering Laboratories, Microgrid Control System Guideform Specification. https://microgridknowledge.com/microgrid-controller-nrel/.

[101] Gamarra Carlos, Guerrero Josep M. Computational optimization techniques applied to microgrids planning: a review. Renew Sustain Energy Rev 2015;48(August):413–24.

[102] Mendes Gonçalo, Ioakimidis Christos, Ferrão Paulo. On the planning and analysis of integrated community energy systems: a review and survey of available tools. Renew Sustain Energy Rev 2011;15(9): 4836–54.

[103] Bouzid Allal M, Guerrero Josep M, Cheriti Ahmed, Bouhamida Mohamed, Sicard Pierre, Benghanem Mustapha. A survey on control of electric power distributed generation systems for microgrid applications. Renew Sustain Energy Rev 2015;44(April): 751–66.

[104] Marnay Chris, Venkataramanan Giri, Stadler Michael, Siddiqui Afzal S, Firestone Ryan,Chandran Bala. Optimal technology selection and operation of commercial-building microgrids. IEEE Trans Power Syst 2008;23(3).

[105] Jin M, Feng W, Liu P, Marnay C, Spanos C. MOD-DR: microgrid optimal dispatch with demand response. Appl Energy 2017;187:758–76.

[106] Braslavsky Julio H, Wall Josh R, Reedman Luke J. Optimal distributed energy resources and the cost of reduced greenhouse gas emissions in a large retail shopping centre. Appl Energy 2015;155(October): 120–30.

[107] Milan Christian, Stadler Michael, Cardoso Gonçalo, Mashayekh Salman. Modeling of non-linear CHP efficiency curves in distributed energy systems. Appl Energy 2015;148(June): 334–47.

[108] Jin Ming, Feng Wei, Marnay Chris, Spanos Costas. Microgrid to enable optimal distributed energy retail and end-user demand response. Appl Energy 2017;210:1321–35.

[109] Givler T, Lilienthal P. Using HOMER Software, NREL's micropower optimization model, to explore the role of gen-sets in small solar power systems. NREL Technical Report; 2005.

[110] HOMER; 2018. https://www.homerenergy.com/.

[111] Whitefoot John W, Mechtenberg Abigail R, Peters Diane L, Papalambros Panos Y. In: Proceedings of the ASME 2011 international design engineering technical conferences & computers and information in engineering conference IDETC/CIE. August 29–31. Washington, DC; 2011.

[112] Kumar Pavan, Bhimasingu Ravikumar. Optimal sizing of microgrid for an urban community building in South India using HOMER. In: IEEE international conference on power electronics, drives and energy systems (PEDES); 2014.

[113] Hafez Omar, Bhattacharya Kankar. Optimal planning and design of a renewable energy based supply system for microgrids. Renew Energy 2012;45(September):7–15.

[114] Montuori Lina, Alcázar-Ortega Manuel, Álvarez-Bel Carlos, Domijan Alex. Integration of renewable energy in microgrids coordinated with demand response resources: economic evaluation of a biomass gasification plant by HOMER Simulator. Appl Energy 2014;132(November):15–22.

[115] Arguello Bryan, Eddy John, Gearhart Jared, Jones Katherine. Microgrid Design Toolkit (MDT) technical documentation and component summaries. Sandia Report: SAND2015-8849. September; 2015.

[116] Eddy John, Miner Nadine E, Stamp Jason. Sandia's microgrid design toolkit. Elect J – Special Issue: Contemp Strategies Microgrid Operat Control 2017;30(4): 62–7.

[117] U.S. DOE. User Guide for The U.S. Department of Energy Smart Grid Computational Tool (SGCT). August; 2011. https://www.smartgrid.gov/.

[118] Chassin David P, Fuller Jason C, Djilali Ned. GridLAB-D: an agent-based simulation framework for smart grids. J Appl Math. 2014;2014. Article ID 492320.

[119] Chassin DP, Schneider K, Gerkensmeyer C. GridLAB-D: an open-source power systems modeling and simulation environment. In: IEEE/PES, transmission and distribution conference and exposition; 2008.

[120] Schneider KP, Chassin D, Chen Y, Fuller JC. Distribution power flow for smart grid technologies. In: Power systems conference and exposition. PSCE '09. IEEE/PES; 2009.

[121] Gomez-Sanz Jorge J, Garcia-Rodriguez Sandra, Cuartero-Soler Nuria, Hernandez-Callejo Luis. Reviewing microgrids from a multi-agent systems perspective. Energies 2014;7(5):3355–82.

[122] Wei Zhang, Kalsi Karanjit, Fuller Jason, Elizondo Marcelo, Chassin David. Aggregate model for heterogeneous thermostatically controlled loads with demand response. In: Power and energy society general meeting. IEEE; 2012.

[123] Schneider KP, Fuller JC, Chassin D. Evaluating conservation voltage reduction: an application of GridLAB-D: an open source software package. In: Power and energy society general meeting. IEEE; 2011.

[124] Xu Yin, Liu Chen-Ching, Schneider Kevin P, Tuffner Francis K, Ton Dan T. Microgrids for service restoration to critical load in a resilient distribution system. IEEE Trans Smart Grid 2018;9(1).

[125] Xu Yin, Liu Chen-Ching, Schneider Kevin P, Ton Dan T. Toward a resilient distribution system. In: Power & energy society general meeting. IEEE; 2015.

[126] Wang Dan, Ge Shaoyun, Jia Hongjie, Wang Chengshan, Zhou Yue, Lu Ning, et al. A demand response and battery storage coordination algorithm for providing microgrid tie-line smoothing services. IEEE Trans Sustain Energy 2014;5(2).

[127] Zhu Jianmin, Jafari Mohsen, Lu Yan. Optimal energy management in community micro-grids. Innovative Smart Grid Technologies - Asia (ISGT Asia). IEEE.

[128] Rangel Ricardo. Integrating VOLTTRON and GridLAB-D to create a power hardware-in-the-loop test bed. Pacific Northwest National Laboratory; 2014.