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Lessons from international experience for China's microgrid demonstration program

John Romankiewicz [a,*], Chris Marnay [a], Nan Zhou [a], Min Qu [a,b]

[a] Energy Analysis and Environmental Impacts Department, Environmental Energy Technologies Division, Lawrence Berkeley National Laboratory, 1 Cyclotron Road, MS 90R2002, Berkeley, CA 94720, United States

[b] Xi'an Polytechnic University, No. 19 Jinhuanan Road, Xi'an 710048, Shaanxi Province, China

HIGHLIGHTS

- We discuss major microgrid demonstration programs in the U.S., E.U., and Asia.
- We identify barriers faced by microgrids to date and propose policy solutions.
- Two detailed case studies of government sponsored microgrid demonstrations are provided.
- We outline eight recommendations for microgrid demonstration programs, with a focus on China's upcoming program.

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ABSTRACT

Microgrids can provide an avenue for increasing the amount of distributed generation (DG) and delivery of electricity, where control is more dispersed and quality of service is locally tailored to end-use requirements, with applications from military bases to campuses to commercial office buildings. Many studies have been done to date on microgrid technology and operations, but fewer studies exist on demonstration programs and commercial microgrid development. As China prepares to launch the largest microgrid demonstration program in the world, we review progress made by demonstration programs across Europe, Asia, and the Americas as well as microgrid benefits and barriers. Through case studies, we highlight the difference in experience for microgrids developed under the auspices of a government-sponsored demonstration program versus those that were commercially developed. Lastly, we provide recommendations oriented towards creating a successful microgrid demonstration program.

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1. Introduction and motivation

Ustun et al. (2011) found that technical challenges still must be overcome for microgrids to cost-effectively and reliably integrate distributed generation into the grid. Basu et al. (2011) highlight that the microgrid sector is promising but still immature in its development, and that more research and pilot projects are needed to push microgrids to deployment stage. NYSERDA (2010) and Schwaegerl (2009), however, emphasized the economic and regulatory barriers that microgrids are facing as opposed to the technical challenges. This study continues along in this vein through the lens of demonstration programs across Europe, Asia, and the Americas, with a discussion of microgrid benefits and barriers, illustrated by relevant case studies.

China has shown growing interest in microgrids as one avenue to a low-carbon electricity transition. Difficulties with China's large-scale centralized renewables installations and low-carbon electricity transition have been highlighted in the literature, including problems with wind energy grid integration (Wang et al., 2012), lack of utility planning and regulatory tools (Kahrl et al., 2011), and needed improvements to China's Renewable Energy Law (Schuman and Lin, 2012). Meanwhile, China's National Energy Administration (NEA) has promoted distributed generation as an additional source of low-carbon electricity. The targets laid out in the 12th Five Year Plan are to build 100 *New Energy City* pilots, 1000 natural gas-fired distributed generation projects, and 30 new energy microgrid demonstration projects (NEA, 2011a, 2011b). In preparation for China's launch of the microgrid demonstration program, Lawrence Berkeley National Laboratory (LBNL) conducted an international survey of microgrid technology and policy to date for the Chinese Academy of Sciences – Institute for Electrical Engineers (Marnay et al., 2012). The main findings of this study are summarized in this paper.

Section 2 provides an overview of microgrid definitions, technologies, and drivers. Section 3 reviews major international publicly

* Corresponding author. Tel.: +1 510 486 7298; fax +1 510 486 6996.
E-mail address: jpromankiewicz@lbl.gov (J. Romankiewicz).

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funded microgrid demonstration programs over the past 15 years. Section 4 describes the main benefits that microgrids provide and the barriers that both demonstration sites and commercially developed microgrids have often faced, while Section 5 provides additional evidence of these benefits and barriers through case studies. Finally, Section 6 outlines concrete policy recommendations for emerging economies undertaking microgrid demonstration programs, and Section 7 provides extra context for China's planned program. The outcome of China's program will have important ramifications not only for its own low-carbon energy transition but also for the continued global development of microgrid technology and policy.

2. Overview of microgrids

2.1. Definition of microgrid

The term microgrid loosely refers to any localized cluster of facilities whose electrical sources (generation), sinks (loads), and potentially storage (both electrical and thermal) and load control function semi-autonomously from the traditional centralized grid, or macrogrid. Researchers have created a wide variety of microgrid definitions depending on the context of technology and function, but few formal definitions exist. Following are two efforts:

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 (CIGRÉ C6.22 Working Group).

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 (U.S. DOE Microgrid Exchange Group (MEG), 2010).

The above CIGRÉ C6.22 and U.S. Department of Energy (DOE) MEG definitions have two common basic requirements: (1) a microgrid must contain both sources and sinks under local control, and (2) a microgrid must be able to function both grid connected and as an electrical island. *Control* represents the key microgrid feature that differentiates it from traditional distributed generation. A microgrid must have islanding capability, which implies a control regime available for macrogrid blackouts. Additionally, while parallel to the macrogrid, the microgrid acts as a locally controlled system, in stark contrast to the wholly passive loads of the legacy power supply paradigm. Note that the CIGRÉ C6.22 and DOE MEG definitions say nothing about required microgrid technologies, scale, motive, fuels, or the quality of power delivered to loads, while both definitions emphasize control.

The microgrid's ability to present itself to the macrogrid as a controlled entity has two important implications: (1) it can provide complex macrogrid services, e.g. buffering small-scale variable renewable generation or providing ancillary services to the macrogrid, and (2) it can coordinate with other entities in the network, such as other microgrids or other sites with generation, storage and/or controlled loads. In addition to the benefits of potentially providing clean and affordable energy under local control and supplying valuable grid services, some microgrids can locally control power quality and reliability (PQR) and tailor it to meet individual load requirements, in contrast to the universal homogeneous PQR service provided by the macrogrid. For example, this might mean a small local DC system involving solar PV and storage is the best solution even though PQR may be poor, whereas in another case it may mean highly reliable and clean power is required, such as for a site whose loads demand it, e.g. an urban telecom facility (Marnay and Lai, 2012). In other words, the PQR of delivered power should be compatible with the PQR requirements of the loads and constrained by what is economically available and environmentally desirable. Note that, matching PQR in this way can expand economic benefit compared to the homogeneous PQR of the legacy grid. Also, lower power generation emissions are not guaranteed by microgrids, since local generation can be dirty, e.g. uncontrolled diesel generation. Further, distributed generation can result in higher human exposures if emissions at ground level in urban centers substitute for remote emissions from high stacks.

Microgrids can be wholly within one traditional customer site, and in fact most existing demonstrations are of this type, especially in the U.S. Alternatively, a microgrid might involve several sites connected by a fragment of the existing distribution network. The difference between these two types is critical from the regulatory and policy perspectives. The former is downstream of a single meter or point of common coupling (PCCs), which implies a significantly simpler regulatory environment quite distinct from the latter case in which some part of an existing regulated electricity provider's (REP) distribution network assets are involved.

2.2. Common microgrid technologies

Fig. 1 displays the components seen in current microgrid demonstrations. There are both loads and generation sources. Among loads, there may be *critical loads* which require high or

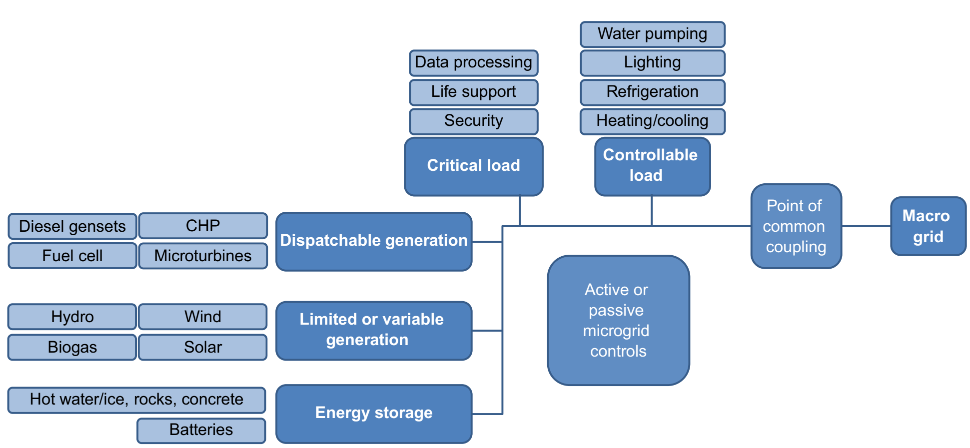

Fig. 1. Overview of the main components in a common microgrid.
Source: adapted from Siemens (2011).

near-perfect reliability, such a hospital life support system. There may also be *controllable loads* which either require lower reliability or whose time-of-service may be rescheduled without reducing service quality, such as pumping, heating, cooling, or refrigeration. Note that microgrid objectives are not easily represented as a single goal, e.g. reliability targets or sense of independence are not amenable to quantification in monetary terms. Within generation, there are *dispatchable* sources which are, such as fuel cells, microturbines, or possibly CHP systems. Many renewable sources have limited or no dispatchability, such as wind and solar, while others may be fully dispatchable or not, such as hydropower or biogas, depending on water flow and gas availability, which vary considerably. These latter *energy limited* resources' dispatchability depends not only on the availability of the generator but also the fuel, i.e. available water or bio-gas. Energy storage of electricity, heat, and fuel is often incorporated into microgrids as a way to accommodate supply variability or to take advantage of pricing structures for macrogrid power. Smaller power systems generally have greater load variation than the macrogrid, making control and storage technology particularly crucial to microgrids. Lastly, microgrid controls can range widely in sophistication across applications.

2.3. Deployment drivers

Motivations for promoting distributed generation and microgrids are apparent across at least four distinct stakeholder groups, with many common threads amongst them, as seen in Fig. 2. Energy customers are increasingly interested in improving their energy efficiency and reducing their environmental footprint, while the electricity supply industry worries about increasing or simply maintaining PQR while serving growing demand and meeting clean energy mandates. Pursuing climate change mitigation, energy security, and other environmental goals, governments, both at the local and national levels, are driving clean energy adoption. Additionally, profit seeking technology providers from many diverse sectors, such as information technology and telecommunications, are playing a disruptive role in microgrid development by seeking out potential opportunities to innovate.

Given these drivers, many governments have enacted and implemented a series of policies to increase the share of clean energy and distributed generation (Liebreich, 2011); however, the interconnection of distributed generation to the conventional network brings technical challenges such as circuit protection, maintaining PQR, and stability issues (Siemens, 2011). Microgrids could be an enabler of increased distributed generation by creating an electrical ecosystem more amenable to small-scale resources (Marnay et al., 2008).

Microgrids promise remediation of some macrogrid concerns, such as renewables mandates, resiliency, and variable resource buffering. While large renewable energy projects, such as offshore wind or large desert solar installations, require extensive environmental review, and often face public opposition, microgrids may face fewer siting issues. Finally, reliability poses a concern for many stakeholder groups. Customers certainly value reliability, and many are willing to pay for it, but methods for systematically evaluating PQR are still rudimentary. Note that the cost of universal homogeneous PQR provision in the macrogrid represents a cross-subsidy from customers who value it little towards those who value it highly. That is, the cost of maintaining high universal PQR tends to be socialized across all grid customers.

A disruptive force stimulating microgrids is the entry of unregulated technology providers. Companies keen to provide both hardware and services to current REP customers are developing and deploying technologies that can increase customer autonomy. A key enabler of microgrids is improved power electronics, which allow efficient power conversion, system control, and PQ management, making control of small-scale systems feasible, economic, reliable, and safe.

By now, almost all of the major economies of the world have clean energy support policies, usually in the form of an RPS, feed-in tariffs, cap and trade programs or other climate legislation, and other financial incentives for clean energy such as tax credits or grants (Liebreich, 2011). Yet, renewable energy targets alone may not be enough to incentivize microgrids, as the REP will seek the lowest cost option to meeting their targets, which will often be utility-scale renewables. Microgrid development would likely benefit more immediately from specific distributed generation targets beyond rooftop PV, as well as targets for building-scale CHP. Microgrids offer the ability to absorb renewable energy at scale, to tailor PQR to the requirements of local loads, and to integrate ancillary service (AS) provision, demand response (DR) and control, all of which are abilities that utility-scale renewables cannot directly offer alone. Section 4 will detail these potential services, the benefits they bring, and how they might be incentivized. Lastly, carbon prices via cap and trade or carbon tax legislation may provide a price signal in the medium-term for more microgrid development.

3. International review of microgrid programs to date

This section summarizes the main microgrid research programs implemented to date, the agencies involved, and the key demonstration sites they have spawned. Table 1 summarizes this information and Fig. 3 provides a program timeline. While there has been significant progress in microgrid technology and interconnection standards, widespread microgrid deployment has not yet occurred. Much government-sponsored microgrid programs have focused on technology development without significant attention to larger deployment possibilities. Meanwhile, private companies

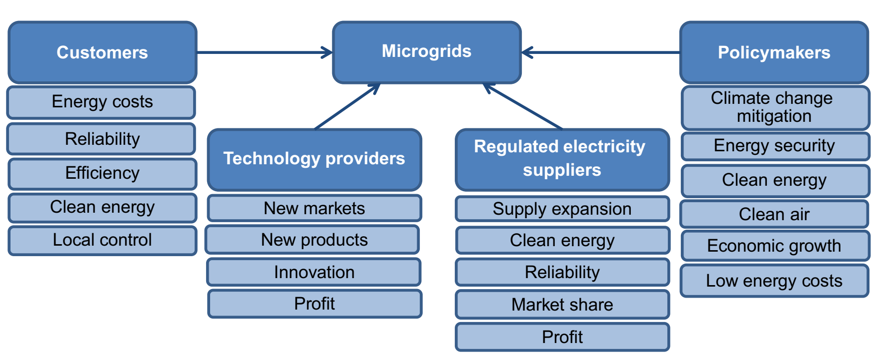

Fig. 2. Drivers for microgrids across four stakeholder groups.

Table 1
International selection of policy drivers and microgrid projects.

Region	Country	Renewable energy/ microgrid policies	Other policies, drivers, and interests	Agencies involved	Demonstration sites	Research facilities
Asia	Japan	RPS (2002), feed in tariff (2012) Interconnection guidelines (1995); electric law amendments allowing IPPs and partial liberalization (1995, 1999, 2003); New Energy Basic Plan (2010)	Highly dependent on fossil fuel imports, partially liberalized electricity market, unofficial nuclear phase out (Fukushima), 25% reduction in greenhouse gas emissions by 2020	NEDO; METI	Hachinohe, Sendai, Aichi, Kyotango, Yokohama (Tokyo Gas), Aperture Project (U.S.)	Tokyo (Shimizu) lab/demonstration
	South Korea	RPS – 2% by 2012, 4% by 2015, 10% by 2022	Focus on smart grid, Green Growth law, 30% below BAU greenhouse gas target for 2020	KERI	Jeju Island Smart Grid test bed	KERI microgrid
	Singapore	Singapore Initiative in New Energy Technology (SINERGY) (2007)	Nearly entirely dependent on fossil fuel imports, 16% below BAU greenhouse gas target for 2020	Energy Market Authority, A*STAR Inst. of Chemical and Engineering Sciences	Pulau Ubin,	Experimental Power Grid Center (EPGC) Laboratory
	China	15% non-fossil target for 2020 (2009) Renewable energy law (2006) 100 New Energy cities, 30 microgrid pilots (2011) Draft management methods for distributed energy (2011)	50 GW CHP target, natural gas targets, feed in tariffs for renewable energy, 40–45% carbon intensity reduction target for 2020 (below 2005 levels)	NEA; Chinese Academy of Sciences: Inst. of Electrical Engineering	Xiamen Univ.	Hangzhou Dianzi Univ., Hefei Univ. of Technology
Europe	EU	20-20-20 European Commission target (translated into legislation at the national level in various forms): 20% renewable energy, 20% reduction in CO_2 emissions below 1990 levels, and 20% reduction in energy consumption by 2020; R&D Framework Programmes: More Microgrids and Horizon 2020; EU Emissions Trading Scheme	20% reduction in greenhouse gas emissions by 2020, feed in tariff programs in Spain, Germany, Italy, etc., unbundling of distribution system operators	European Commission (funding), regional and local governments (support and implementation), Director General for Energy and Transport	Kythnos Island, Mannheim Wallstadt, Bornholm Island, Eigg Island	National Tech. Univ. of Athens Power Systems Laboratory, Fraunhofer Inst.
Americas	U.S.	30 states with RPS, 44 states with interconnection policy, 44 states with a net metering policy	Development of CERTS technology, DER-CAM and μGrid software, IEEE 1547 standard development, proposed 80% clean energy goal by 2035, 17% reduction in greenhouse gas emissions by 2020 off 2005 levels	DOE, CEC, DOD, NREL	SPIDERS (Hickham AFB, Fort Carson, Camp Smith); RDSI grants (Santa Rita Jail, Borrego Springs, Univ of Hawaii, Univ of Nevada Las Vegas, ATK Space Systems, City of Fort Collins, Illinois Institute of Tech, Allegheny Power, ConEd NY); UCSD);	CERTS (Univ of Wisconsin, AEP)
	Canada	Green Energy and Green Economy Act of Ontario, Ontario feed in tariff, British Columbia clean energy act (2010), Renewable Energy Standard Offer Program (2006)	Western Climate Initiative, 17% reduction in greenhouse gas emissions by 2020 off 2005 levels for participating provinces; notional clean energy standard – 90% from hydro, nuclear, wind, solar, or CCS by 2020 (from current 77%)	Natural Resources Canada, NSERC Smart Microgrid Network	Hartley Bay, BCIT microgrid, Boston Bar	
	Chile	RPS of 20% by 2020	Strong renewable resources (solar, geothermal, wind), 20% below BAU greenhouse gas target for 2020		Huatacondo	

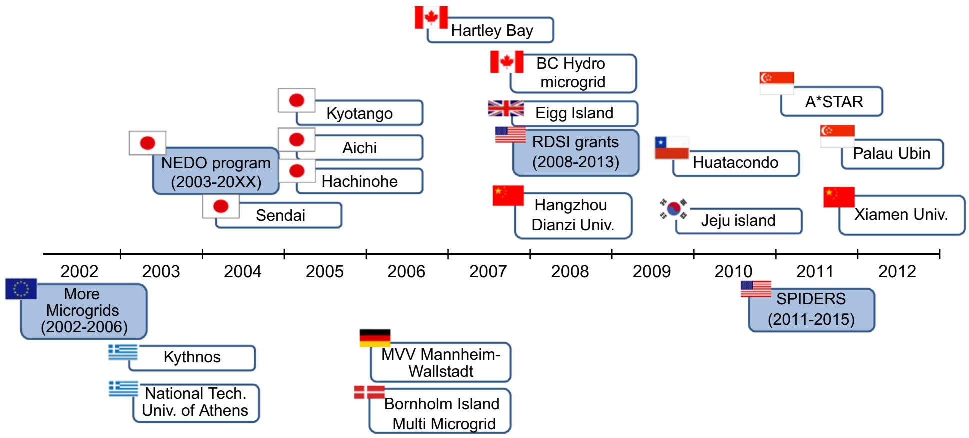

Fig. 3. Timeline of microgrid programs (blue) and select demonstration sites (white) to date. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

and public institutions (such as universities) are pushing the boundaries of policy environments to find where microgrids can succeed now. While this section focuses on research programs, Section 5.3 will look at some of these customer-based microgrids.

3.1. Europe

The EU was the early leader in microgrid development, with comprehensive R&D efforts dating back to 1998. The EU Framework Programs (FP) provide research funds for a wide range of projects across many fields in science and engineering, including comprehensive research and demonstrations in the area of microgrids during FP 5, 6, and 7. One initiative within FP 5 focused on large-scale integration of micro-generation onto low voltage grids while another initiative within FP 6, known as “More Microgrids,” focused on microgrid control and operations. These research projects have launched many microgrid demonstration sites over the years, most notably the Kythnos Island Microgrid and Mannheim Wallstadt microgrid (Ustun et al., 2011).

3.2. Asia

Japan was the early leader in Asian microgrid research, with the New Energy and Industrial Technology Development Organization (NEDO) funding of a number of successful demonstration projects starting in 2003 (Ustun et al., 2011). The major March 2011 earthquake, tsunami, and nuclear accident in Japan has caused a dramatic resurgence of interest in distributed and renewable energy. More recently, an increasing number of private sector entities is engaging in microgrid development. One former NEDO microgrid demonstration project in Sendai successfully operated as an island for about 2 days following the 2011 disaster, providing power and heat to a teaching hospital and other campus buildings (NEDO, 2008; Reilly et al., 2012). Given Japan's dependence on fossil fuel imports and its ambitious clean energy and climate targets (Ecofys, 2012), microgrids should prove to be an increasingly promising energy option.

In addition to Japan, other Asian countries have been developing microgrid demonstration programs in recent years, notably South Korea, and Singapore, and of course more recently, China.

Singapore and South Korea each have one microgrid demonstration project under development, with South Korea showing particular interest in developing more smart grid or microgrid demonstrations similar to its Jeju Island smart grid test bed. Additionally, Singapore's official launch in late 2011 of its Experimental Power Grid Center (EPGC) under the A*STAR Institute of Chemical and Engineering Sciences signals increasing interest and research capability (A*STAR Inst of Chemical and Engineering Sciences, 2008; Ustun et al., 2011). The EPGC is a particularly interesting facility because it can test equipment intended to meet many electrical codes found in Asia.

3.3. Americas

In recent years, the U.S. has become a leader in microgrid demonstration and technology development, under two flagship microgrid grant programs run by the Department of Defense (DOD) and DOE. DOD is running a USD 38.5 million grant program known as Smart Power Infrastructure Demonstration for Energy, Reliability, and Security (SPIDERS). It is pursuing three different military base microgrid demonstrations with reliability and energy security as its main goals (Department of Defense, 2011). DOE has granted over USD 50 million to nine projects (worth over USD 100 million including participant cost share), collectively known as the Renewable and Distributed Systems Integration (RDSI) grants. Each project must demonstrate a 15% peak load reduction in the local distribution feeder (or substation) using demand response and distributed energy resources (Bossart, 2009). While many projects had some common microgrid characteristics and technologies, the Santa Rita Jail and the Illinois Institute of Technology are the two notable successful projects that are now fully operational microgrids according to DOE's own definition. The U.S.'s huge economic stimulus program ARRA, also supports significant microgrid technology development with one notable true microgrid demonstration by the Portland Gas and Electric Company. Beyond the large DOD and DOE research programs, the State of Connecticut is pushing microgrid development. In the wake of multiple harsh winter storms and hurricanes over the past few years, the state government has launched a Microgrid Grant and Loan Pilot Program, which will award USD 15 million across 27 microgrid projects to cover design, interconnection, and other engineering costs but not equipment purchase (Schain, 2013).

Additionally, other efforts in standards, technology, and software development have enabled the microgrid sector to emerge worldwide (Basu et al., 2011; Marnay et al., 2008). Various U.S. stakeholders were instrumental in driving the authoring and publication of standards for interconnection of distributed energy resources to the grid as well as islanding standards for microgrids, notably IEEE 1547. Consortium for Electric Reliability Technology Solutions (CERTS) microgrid control technology has enabled key projects at the Santa Rita Jail, the Sacramento Municipal Utility District headquarters, and Maxwell Air Force Base. Finally, the Distributed Energy Resources Customer Adoption Model (DER-CAM) developed by LBNL as well as other models such as HOMER and

RETScreen have been instrumental in helping various microgrid projects to optimize equipment selection and operation.

Other geographies throughout the Americas also have developments in the microgrid sector. Canada and Chile both have microgrid demonstration sites serving remote communities, increasing reliability and lowering dependence on costly fossil fuel imports by air, barge, or truck. Canada also has an R&D program called the NSERC Smart Microgrid Network, with a total funding of USD 4.4 million over 5 years and a flagship project at the British Columbia Institute of Technology (Wong, 2011).

4. Barriers and benefits to microgrid development

The barriers to large scale microgrid deployment can be roughly broken down into two categories: economic and institutional. Economic barriers concern the balance between the economic benefits microgrids create and their costs. The essential question is whether these benefits and costs can be properly reflected in the market environment to incentivize economic microgrid development that is simultaneously beneficial to the customer, REPs, and society as a whole. Benefits or costs accruing to other macrogrid customers should also be reflected in microgrid incentives, preferably via market structures. Note that analyzing these benefits and costs will also require contextual considerations such as the geographic location of the microgrid in the macrogrid, local gas and electricity rates, local policies, and regional macrogrid power supply mix. Institutional barriers refer to those introduced by the need for unfamiliar practices by the industry, including interconnection procedures, plus utility, building, environmental, and safety codes.

The benefits that microgrids offer to the customer, REP, and society at large can be broken down into the following categories: economic, PQR, environmental, energy security, and safety. These vary considerably across jurisdictions. Table 2 provides an overview of major benefits and the stakeholders that can benefit.

The three direct economic benefits are perhaps the easiest to understand. If a microgrid is able to cost-effectively produce its own power, heating, and cooling services, it may reduce its overall energy costs. If there is a time-of-use pricing regime, then there may be additional energy savings or arbitrage opportunities, and there may be times when microgrid generation exceeds its critical loads allowing exports. Particularly during peak demand periods, this service could be valuable to the macrogrid on-peak, and indeed, load reduction in itself is a major benefit to the macrogrid. The key question is how the microgrid will be compensated for its energy exports and provision of macrogrid services.

Indirect economic benefits derive from postponing periodic upgrades needed in macrogrid transmission and distribution (T&D) systems, and by reducing their coincident load, microgrids reduce T&D congestion and losses. Microgrids can have a positive impact on macrogrid PQR, through load reduction and the provision of DR and AS.

Historically, many REPs have not welcomed development of microgrids and distributed energy resources generally, and in certain situations, have actively inhibited their development, placing them in the "land of penalties" seen in Fig. 4. They have delayed interconnection of projects or charged prohibitively high connection fees, exit fees (explained below), or backup/standby fees. Being natural monopolies, the incentives faced by REPs are primarily determined by the regulatory regime in which they operate. The lost revenues that microgrid generation represents may or may not hurt the REP financially, and any corresponding benefits or costs may or may not be passed along other customers, public institutions, or others. Because the industry structure varies considerably – notably with generation in public control, in open competitive markers, in vertically integrated entities, or in various hybrids – unraveling incentives is a non-trivial exercise. Also, note that the situation is not static, rather loads are growing, macrogrid supply technology evolves, and pressures for regulatory reform are strong. Thorough analysis of these possibilities lies beyond the scope of this work.

For microgrids to capture the benefits just discussed, policy and technological remedies need to assist microgrids in getting from the "land of penalties" to the "land of payments."

Fig. 4 conveys the general conclusion that technology and policy solutions can help microgrids enter into an environment where the economically valuable services it provides are properly valued with payments or incentives instead of penalties. Technology improvement should consistently lead to improved microgrid functions and services. As technology costs come down, interconnection practices become standardized, and microgrid controls (both passive and active) consistently improve, microgrids will become both increasingly feasible and also of higher quality and robustness. Policy can help incentivize the initial R&D and

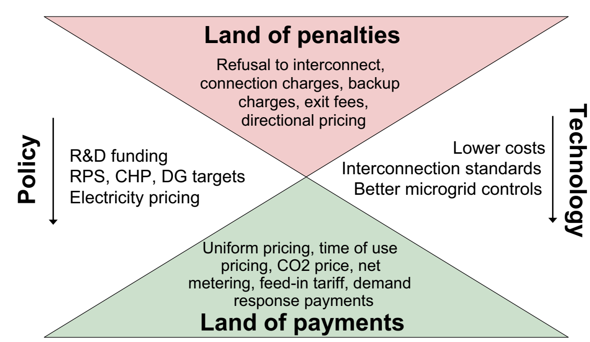

Fig. 4. Land of penalties to land of payments using policy and technology remedies.

Table 2
Microgrid value distribution.
Sources: adapted from NYSERDA (2010).

Benefit class	Specific benefit	Customer	REP	Society
Economic (direct)	Reduced electricity and fuel costs	X		
Economic (direct)	Sale of excess power to grid	X	X	
Economic (direct)	Participation in AS & DR markets	X	X	
Economic (indirect)	Reduced system congestion costs		X	X
Economic (indirect)	Reduced transmission and distribution losses		X	X
Economic (indirect)	Reduced operating reserves		X	
Power reliability	Reduced power outages on-site	X		
Power reliability	Potential for black-start capabilities		X	X
Power quality	Potential for reactive power/voltage control	X	X	
Environmental	Increased use of renewable energy		X	X
Environmental	Reduced SO_2, NO_x, CO_2 emissions		X	X
Security and safety	Avoided major system outages	X	X	X

Table 3
Valuing the economic benefits of microgrids.
Sources: Schwaegerl (2009).

Economic benefit of microgrid	Regulatory barrier: "Land of penalties"	Resolution: "Land of payments"
Reduce energy costs	Increased service charges, stand-by, or exit fees	Disallow unwarranted increases in charges due to loss of use-of-service revenue
	No real-time or time-of-use pricing	Create time-of-use or real-time pricing scheme
Sell excess power to REP	Interconnection charges	Apply a fair and cost-effective interconnection review process
	No compensation provided	Mandate REP purchase of excess power
	Directional pricing used	Consider uniform pricing
	Net-metering not allowed	Mandate net-metering, consider allowing provisions for a mixture of supply technologies
Participate in demand response markets	No compensation provided	Create incentive payments for demand response (interruptible tariffs or contracts)
	Min. capacity limit set too high	Lower capacity limit so microgrids of all sizes can participate
Increase use of renewable energy	No incentives for renewable energy	Consider RPS or feed-in tariff policies
Reduce CO_2 emissions	No CO_2 price	Consider carbon pricing policy

demonstration phases with funding and targets for microgrid demonstrations (or specific distributed generation and combined heat and power [CHP] targets to be more inclusive). Working on electricity pricing policy will ensure that microgrids can capture a just share of the economic benefits. As seen in Table 3, there are many potential changes on the policy "wish list" relevant to electricity pricing alone. When customers purchase less energy from the REP, it has been inclined to request increased service charges or exit fees due to its lost revenue and consequent stranded assets. These charges often eliminate the benefits the customer had initially gained and therefore should not be allowed by regulators unless clearly justified. Note that under dynamic circumstances, such as rapidly rising consumption (as is the case in many developing world regions), then the REP's risk of stranded assets is greatly reduced. There may be cases where the REP needs to invest in a particular service area's generation or distribution portfolio, but a large customer in that area ends up developing a multi-faceted microgrid capable of relieving congestion, exporting energy at times, and increasing renewables penetration. This would be an ideal win-win scenario.

Yet, in many electricity service jurisdictions around the world, incumbent REPs function as natural monopolies with vested interests in the current low efficiency design of generation, distribution, and transmission services. As customers increasingly participate in the electricity market via solar, microgrids, and other distributed energy resource solutions and bring new efficiencies to generation and T&D services, the very nature of the incumbent REPs' business will be threatened. Some REPs will fight off distributed energy resource development as long as possible, while other may pursue new business models capable of capturing value throughout the energy supply chain as customer capabilities increase. Those business models are beyond the scope of this paper, though many research institutes are beginning to explore this topic in depth (Goldman et al., 2013; Rocky Mountain Institute, 2013).

5. Case studies

The following two case studies illustrate how microgrid demonstrations have come to fruition, outlining technologies used, keys to success, and lessons learned. Both microgrids were developed for technology demonstration with government research oversight and support. A third section reports important lessons from commercial microgrids not part of specific microgrid demonstration programs.

5.1. Santa Rita Jail microgrid

Alameda County's Santa Rita Jail in Dublin, California, about 75 km east of San Francisco, is the fifth largest U.S. prison, housing up to 4500 inmates. Following a series of distributed energy resources and efficiency measures installed at the Jail, it is also often referred to as the *Green Jail*. The microgrid project aims to demonstrate the first commercial implementation of the CERTS microgrid technology, using a large-scale battery, new and legacy renewable energy sources, and a fuel cell. Alameda County's goals were as follows:

- Reduce peak electrical load and monthly demand charges
- Store renewable and fuel cell energy overproduction
- Shift electricity consumption to off-peak hours
- Improve grid reliability and reduce electrical voltage surges and spikes
- Enable the Jail to be a net-zero customer during the most expensive summer peak hours
- Expand the Jail's onsite generation capacity to include three renewable energy sources: solar PV, wind turbines, and solar thermal water heaters

In the spring of 2002, the Jail installed a 1.2 MW rated rooftop PV array, followed in 2006 by a 1 MW molten carbonate fuel cell (MCFC) with CHP capability. Most recently, with the aid of DOE and California Energy Commission (CEC) grant funds, as well as funding and participation from industry partners Chevron Energy Solutions, Satcon Power Systems, and Pacific Gas and Electric, the Jail achieved full microgrid capability with the installation of a large 2 MW–4 MWh lithium iron phosphate battery, a solid state islanding switch, and associated power electronic and control upgrades. In addition to generation equipment, the Jail has also implemented a series of building equipment retrofits (in lighting, HVAC, refrigeration, and other end uses) to improve efficiency and reduce peak electricity demand (General Services Agency, 2012; DeForest, et al., 2011; Marnay et al., 2011) Table 4.

A major contributor to the Santa Rita Jail microgrid's success was the central role of a local government entity, Alameda County. The facilities of local governments often offer good host sites for microgrid projects, and federal and state governments are keen to support a progressive local authority whose resources are few and budgets smaller. A second contributor was the diversity of partners involved. Local, state, and federal government entities were all involved plus partnership with the local REP (PG&E), technology providers (Satcon and S&C Electric), an engineering services company focused on renewable energy and CHP (Chevron Energy Solutions), and multiple research laboratories (University of Wisconsin (UW), LBNL, and the National Renewable Energy Laboratory (NREL)). Many of the partners had a large financial stake in the project, while others were seeking pilot projects for microgrid technology, e.g. UW with its involvement in the development of CERTS Microgrid technology. Satcon, S&C Electric, and Chevron

Table 4
Main characteristics of Santa Rita Jail microgrid.
Sources: DeForest et al. (2011) and Marnay et al. (2011).

Criterion	Description
Technologies used (supply)	1.2 MW rooftop solar PV, 240 kW ground mounted tracking solar PV, 1 MW MCFC, two 1.2 MW backup diesel generators, four 2 kW wind turbines, 2 MW – 4 MWh battery, static disconnect switch
Load sources (demand)	HVAC, lighting, computers and servers, security systems, cooking, refrigeration, hot water
Electrical storage	2 MW – 4 MWh lithium iron phosphate battery
Thermal storage	Solar water heating
Total supply	Solar PV and fuel cell only: 604 kW (average), 1474 kW (peak)
Total demand	3 MW (peak)
Heating/cooling equipment	Fuel cell has waste heat that can be utilized
Investment	USD 14 million (does not include solar PV and energy efficiency measures)
Grants received	DOE, CEC, DOD, and PG&E
Dates of operation	2002-present
General energy conversion efficiency	Electrical efficiency 35%, thermal efficiency 17% (of fuel cell)

Table 5
Main characteristics of Sendai microgrid.
Source: NEDO (2008).

Criterion	Description
Technologies used (supply)	Two 350 kW NG gensets, 250 kW MCFC, 50 kW rooftop solar PV
Load sources (demand)	City buildings (water plant, high school), hospital (communication apparatus, medical instruments, nursing care facilities, computers) university buildings (computers, servers, lighting, ventilation)
Electrical storage	Lead-acid battery: 600 Ah
Total demand	University: 1170 kW (peak), 260 kW (minimum), City: 420 kW (peak), 80 kW (minimum) [Data from 2005–2007]
Investment	USD 25 million (estimate)
Local electricity price	12 ¥/kWh (USD 0.13/kWh)
Local gas price	60 ¥/ nominal m^3(USD 0.63/ nominal m^3)
Grants received	NEDO
Dates of operation	2007–2008 (city + university), 2009-present (university only)
Heat recovery efficiency	Gas gensets: 34.5%; fuel cell: 18%

were capable technology and engineering companies. With the combination of the static switch, droop control in the battery inverter, and new controls in the diesel generators, the CERTS microgrid has functioned well in the field. The Jail's involvement of LBNL as a partner helped them to optimize the economics and lower the risk involved in the project. The long established interest of the County in innovative energy technology also provides a powerful historic data set stretching back for a decade enabling sophisticated planning and operation of the microgrid.

The major lesson learned is that the cost of the battery was high and its purchase was only feasible with federal and state government grants. Electrical storage costs still need to fall considerably to enable its widespread adoption. The Jail has high PQR requirements and can now operate fully islanded. The overall goal of this and other eight RDSI projects was to demonstrate a 15% reduction in local feeder peak. Considering all the efficiency and on-site generation and storage investments made over a decade, this target was met. In general, organizing demonstration programs in this way, around a single uniform goal, will not illicit the best projects. Rather projects should be evaluated on microgrid success at meeting its local requirements.

5.2. Sendai microgrid

The Sendai microgrid located in northeast Honshu Island, Japan that supplies multiple levels of PQR. It was NEDO's funded from 2004 to 2008. The main collaborators on the project were the NTT Facilities Research Institute, Tohoku Fukushi University, and the City of Sendai. The goal of the project was to supply multiple AC power qualities, as well as DC. After the demonstration phase, some changes were made, most notably the addition of CHP with a heat loop. The project continues to operate today as a university-owned installation, serving a small private university specialized in medical training.

The loads served during the NEDO phase were on either side of a city street, with municipal facilities, a water plant, and a high school, on one side, and the University on the other. This project included its own solar PV array, fuel cell, and gas-powered generators to provide electricity to these customer loads. The project was estimated to cost USD 25 million from 2004 to 2008, and was almost entirely funded by NEDO. Further improvements after the demonstration phase ended were made using Tohuku Fukushi University funds. Table 5 details the main characteristics of the microgrid.

From 2007 to March 2008, after various validation tests using dummy loads for the system, electrical power was supplied to facilities in the city and university zones. Eight months of testing showed that the system met its evaluation criteria and was able to provide stable electrical power to loads. Meanwhile, the cost, space, power loss, and CO_2 emissions were compared with a baseline of 15 years of cost and performance data. It was found that the system could reduce energy costs by 14–30%, reduce equipment space by 23–42%, cut CO_2 emission by 12%, and have equivalent or slightly decreased electrical loss compared to the pre-existing system.

The microgrid continues to function today, but now supplies power and heat only to the university zone. The Sendai area has a reinforced high-pressure natural gas distribution network (Ustun et al., 2011; NEDO, 2008; Reilly et al., 2012). Its reliability was dramatically tested by the March 2011 Japan earthquake and tsunami. By restarting its gas-fired engines, the microgrid functioned successfully as an island for most of the two-day blackout that followed the disaster, providing uninterrupted DC power, AC power and heat to the hospital, and limited AC power to other loads. It successfully reconnected to the grid and continued to function until natural gas supply was disrupted 2 weeks later due to further complications from the earthquake.

Similar to the Santa Rita Jail microgrid, the Sendai microgrid also benefited from a supportive local government host. The supply of power to both city and university zones involved crossing a public road, which would normally invoke utility codes making the microgrid subject to public utility regulation. The City was able to sidestep the regulation. The microgrid also benefited from the oversight and consistent involvement of NTT Facilities, which sees great potential for widespread microgrid deployment in its own facilities, and strived for project success.

The project also benefited from very generous funding from NEDO, without which, much of the demonstration would not have been possible. Given the generosity of funding, Sendai lost some focus regarding economics of the project, although it did meet all of its design goals as described above. Additionally, NEDO wanted each microgrid project to emphasize one aspect of microgrid functionality. Sendai's focus was solely on delivering multiple levels of PQR; however, microgrids are designed to have multiple technologies providing a number of functions and benefits. When the NEDO demonstration phase ended in 2008, NTT Facilities and the University reduced the microgrid's scope to the university zone only, and added CHP. Microgrid demonstrations should be planned to be either as economic as possible, or to represent anticipated economic conditions. Designing and executing demonstrations based solely on specific technical goals are likely to prove highly uneconomic, and this outcome can overshadow any technical achievement and impede future deployment.

5.3. *Privately and publicly developed microgrid projects*

In large part, demonstrations launched under specific government sponsored microgrid programs were heavily subsidized and immune to many barriers due to the number and type of cooperative partners involved, often including the REP. China's upcoming program will likely carry these characteristics as well. Yet, microgrids have recently seen healthy growth in deployment beyond government-sponsored programs, with one report finding that 405 microgrid projects in development across the world, with 219 projects in North America alone (Martin, 2013). These projects are often developed by large institutional customers like government agencies or universities who have long investment horizons, reliability and energy cost concerns, and a desire or mandate to increase efficiency and renewable energy use on-site. Indeed, not all progress is recent; some of these projects date back one or two decades. It is only the recent technology cost reductions in solar PV, power electronics, energy storage, and natural gas aided by advances in metering infrastructure and a general increase in customer energy literacy that have really pushed the market into a new surge of growth. Some of the institutionally developed microgrids, most recently the White Oaks headquarters of the U.S. Food and Drug Administration (FDA) near Washington DC, show exciting examples of both the economic benefits that microgrids can present, as well as how barriers have been largely overcome. The FDA's microgrid cost is USD 71 million for a system with a 21 MW peak capacity, but USD 11 million are expected in energy and maintenance cost savings while increased reliability has already been proven by successful islanding (Burr, 2013).

Cornell's most recent expansion of its large microgrid (which includes both CHP and district cooling) satisfied the 8–10% returns required by the university's endowment when placing new investments. When Cornell applied to have its new expanded cogeneration facility certified as a qualified facility (QF) under the Public Utilities Regulatory Policies Act, it experienced regulatory pushback from the local REP and the Federal Energy Regulatory Commission who held that REPs should not need be obligated to purchase power from a large QF's (> 20 MW) if it had “non-discriminatory access” to wholesale markets. An exception was granted because the QF could not have such non-discriminatory access to the wholesale markets due to the variable nature of its power production, linked to its steam production and influenced by weather patterns.

New York University's (NYU) recent redesign of its microgrid which operates in parallel with Manhattan's congested distribution grid will cost USD 126 million, but can be funded with tax exempt bonds. The microgrid can regularly participate in the New York Independent System Operator's (NYISO) demand response program, freeing up grid capacity to support reliability in lower Manhattan. Interestingly, the microgrid was not originally designed to export energy or provide AS to the macrogrid, but will be providing such energy and services under its grid-parallel expansion and redesign. For electricity exported, the price will be set based on the NYISO's location-based marginal price at the time of export plus a factor for T&D losses, a relatively progressive price policy which correctly prices in the benefits that microgrids provide (NYSERDA, 2010).

6. Policy recommendations for a microgrid program

As microgrid deployment grows slowly in some regions, others are still at the first phase of their demonstration programs. While demonstration programs have historically focused on technology development, if planned correctly, they can also help a jurisdiction identify policy requirements. The key recommendations offered here can be broken down into those for the demonstration program as a whole and those for individual demonstration projects.

Recommendations for microgrid demonstration program:

1. *Set overall goals for the demonstration program*: Based on the benefits sought and the stakeholders involved, the program administrator can set overall goals for the microgrid demonstration program in reliability (ability to island, power outages), energy efficiency (both supply and demand side), renewable energy use, energy savings (for both microgrid participants and REPs), or CO_2 emissions reduction. However, the goals should account for the localized nature of microgrid benefits. In other words, the goals should be set along the same axes as the valuable expected benefits at the site, e.g. improved reliability or carbon footprint reduction.
2. *Promote results-oriented demonstrations based on overall goals*: Microgrid development has reached the stage where a range of potential benefits is known and has been demonstrated, but they have been rarely quantified in a rigorous manner. Once overall program goals have been set, quantifiable goals and metrics should be set for the individual demonstration projects. Cost sharing between government and private sector partners is another way to promote results-oriented demonstrations.
3. *Allow for post-demonstration analysis and peer review*: A key component of any demonstration should be evaluation following completion of the project. Amassing enough data during a demonstration, and providing budget and opportunity for ex-post analysis can produce valuable results for the project itself, future projects, and overall policy.
4. *Develop standards and processes for interconnection of microgrids:* Any policymaker considering a microgrid program should put standards in place (potentially based on IEEE's 1547 series) as soon as possible, with input from REPs and engineering associations. Additionally, they should develop a process for streamlining interconnection reviews in the short-term but evaluating large scale impacts of distributed generation in the long-term and coming up with a cost-effective

response. The amount of distributed generation will rise in most regions of the world, so REPs and policymakers should plan proactively for their impact.

Recommendations for individual microgrid demonstration projects:

5. *Ensure project is close to economic viability*: Various tools have been developed internationally to assess a project's economic viability (pre-implementation) from the perspective of a microgrid customer who is usually seeking to cut energy costs and/or change PQR, while increasing control over electricity delivery on their site. Project proposals should require economic analysis using these tools showing the expected shortfall to viability. Most demonstrations will remain cost-prohibitive requiring grants or subsidies to stimulate cost reductions.
6. *Include customer microgrids*: Many of the successful microgrid demonstration projects have been located at customer sites downstream of 1 m, where there are fewer regulatory barriers. Maxwell Air Force Base, Sendai, and Santa Rita green jail projects are all great examples of successful microgrid projects downstream of one meter.
7. *Match technology with end-use requirements*: Demonstrations built around energy supply resources not suitable for the site's energy loads are misguided. Matching PQR of the energy supply to the requirements of end use loads is a defining feature of a successful microgrid, such as the Santa Rita Jail. On the one hand, sensitive loads (military bases, hospitals, data centers, etc.) require high PQR while on the other hand, some customers' sites may not even need PQR as high as the legacy macrogrid provides.
8. *Integrate energy functions, such as CHP and CCHP*: Demands for electricity, heating, cooling, and other fuel use, should all be taken into account when designing an optimal microgrid. Even though there is often a policy preference for renewables, some of the best economic and carbon abatement opportunities (for low to moderate abatement targets) lie with CHP as well as combined cooling, heating, and power, technologies (CCHP), deployed successfully by the Sendai and University of California San Diego (UCSD) projects, respectively.

7. Ramifications for China's microgrid program

As China develops its microgrid demonstration program, there is a possibility that China will approach microgrids solely as a supply side solution (a way to balance out intermittent renewables). However, for microgrids to realize the maximum amount of benefit in reliability, energy efficiency, and use of renewable energy, they must integrate supply solutions with demand-side efficiency and storage as well, where appropriate. If China follows the program and demonstration specific recommendations outlined in the previous section, the program will be an opportunity for China to explore the different capabilities that microgrids can offer and how those might contribute to its larger low-carbon electricity goals.

According to the authors' understanding of China's upcoming microgrid program, there will be three different types of microgrids developed in remote, ocean island, and urban environments to demonstrate different types of technology combinations according to resource availability. The demonstrations are expected to deploy significant amounts of renewables and natural gas, and as such, will likely receive large subsidies. The urban microgrids are expected to explore different business arrangements, such as customer-owned and operated, ESCO developed, and utility microgrids for small neighborhoods or districts. More broadly speaking, China's market conditions do not yet provide fertile ground for rapid distributed energy resource development and microgrid deployment. High natural gas prices, poor urban solar resources, and interconnection barriers all inhibit wider development in the world's largest electricity market. Yet, this microgrid demonstration program will provide important opportunities to increase technical capacity and understanding of microgrid functionality and developer arrangements.

8. Conclusions

Microgrids can provide an avenue for increasing the amount of distributed generation and delivery of electricity, where control is more dispersed and quality of service is locally tailored to end-use requirements. Much of this functionality is very different from the predominant utility model to date of centralized power production which is then transmitted and distributed across long distances with a uniform quality of service. This different functionality holds much promise for positive change, in terms of increasing reliability, energy efficiency, and renewable energy while decreasing carbon emissions. All of these functions should provide direct cost savings for customers and REPs as well as positive externalities for society. As outlined in this paper, allowing microgrids to function in parallel with the grid requires changes in electricity governance and incentives to capture cost savings and actively price in positive externalities. Having hosted successful research and demonstration programs, the E.U. and U.S. are now playing host to experimentation in larger scale microgrid deployment and distributed generation penetration. In China, the scale of its planned program is significant, and focusing on the program and demonstration specific recommendations laid forth in this report will aid China in exploiting and exploring the technical capabilities of microgrids, even though deployment will be much slower to develop.

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