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Microgrids: A review of technologies, key drivers, and outstanding issues

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ABSTRACT

Microgrids are now emerging from lab benches and pilot demonstration sites into commercial markets, driven by technological improvements, falling costs, a proven track record, and growing recognition of their benefits. They are being used to improve reliability and resilience of electrical grids, to manage the addition of distributed clean energy resources like wind and solar photovoltaic (PV) generation to reduce fossil fuel emissions, and to provide electricity in areas not served by centralized electrical infrastructure. This review article (1) explains what a microgrid is, and (2) provides a multi-disciplinary portrait of today's microgrid drivers, real-world applications, challenges, and future prospects.

1. Background

It has been noted recently that the world's electricity systems are starting to "decentralize, decarbonize, and democratize", in many cases from the bottom up [1]. These trends, also known as the "three Ds", are driven by the need to rein in electricity costs, replace aging infrastructure, improve resilience and reliability, reduce CO_2 emissions to mitigate climate change, and provide reliable electricity to areas lacking electrical infrastructure. While the balance of driving factors and the details of the particular solution may differ from place to place, microgrids have emerged as a flexible architecture for deploying distributed energy resources (DERs) that can meet the wide ranging needs of different communities from metropolitan New York to rural India.

In industrialized countries, microgrids must be discussed in the context of a mature "macrogrid" that features gigawatt-scale generating units, thousands or even hundreds of thousands of miles of high voltage transmission lines, minimal energy storage, and carbon-based fossil fuels as a primary energy source. Today's grid is not a static entity, though; we are traveling a historic arc that began with small-scale distributed generation (recognized as the original DC microgrids) pioneered by Thomas Edison in the late 19th century, that underwent consolidation and centralization driven by growing demand, and that is now experiencing the beginnings of a return to decentralization. From the 1920s through the 1970s, the increased reliability afforded by connecting multiple generating units to diverse loads, decreased construction costs per kilowatt (kW), and ability to draw power from distant large generating resources like hydropower drove the development of the grid we see today [2,3]. However, those advantages seem to have reached their limits and are increasingly undermined by environmental and economic concerns. Driven by utility restructuring, improved DER technologies, and the economic risks that accompany the construction of massive generating facilities and transmission infrastructure, companies that generate electricity have been gradually shifting to smaller, decentralized units over time [3]. This transition is driven by a range of DER benefits that have been studied in detail; [4,5], such as deferral of generation, transmission, and distribution capacity investments; voltage control or VAR (reactive power) supply, ancillary services, environmental emissions benefits, reduction in system losses, energy production savings, enhanced reliability, power quality improvement, combined heat and power, demand reduction, and standby generation. These benefits accrue not only to small, dispatchable fossil-fueled plants – many also accompany deployment of intermittent renewable generating sources, as shown by a foundational study of a 500 kW distributed generation PV plant in California [6,7]. The challenge of radically decreasing greenhouse gas emissions to avoid catastrophic climate disruption has also led to governmental policies that incentivize deployment of carbon-free generating sources, many of which lend themselves to distributed applications. While this paper focuses on

Abbreviations: AC, alternating current; AEP, American Electric Power; CERTS, Consortium for Electric Reliability Technology Solutions; DBOOM, design-build-own-operate-maintain; DC, direct current; DER, distributed energy resource; DSO, distribution system operator; ESS, energy storage system; EV, electric vehicle; IEEE, Institute of Electrical and Electronics Engineers; GW, gigawatt; IoT, Internet of Things; IPP, Independent Power Producer; JCTD, Joint Capability Technology Demonstration; kW, kilowatt; MGCC, microgrid central controller; MW, megawatt; NYISO, New York Independent System Operator; PCC, point of common coupling; PPA, power purchase agreement; PQR, power quality and reliability; PV, photovoltaic; REV, Reforming the Energy Vision; SDS, static disconnect switch; SPIDERS, Smart Power Infrastructure Demonstration for Energy Reliability and Security; VAR, volt-ampere reactive

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Table 1
Overview of microgrid generation and storage options.

Category	Options	Advantages	Disadvantages
Generation	Diesel and spark ignition reciprocating internal combustion engines [24]	• Dispatchable • Quick startup • Load-following • Can be used for combined heat and power (CHP)	• Nitrogen oxide and particulate emissions • Greenhouse Gas Emissions • Noise generation
	Microturbines [25]	• Dispatchable • Multiple fuel options • Low emissions • Mechanical simplicity • CHP-capable	• Greenhouse Gas Emissions
	Fuel cells (including solid oxide, molten-carbonate, phosphoric acid, alkaline, and low-temperature Proton Exchange Membrane or PEM) [117–119]	• Dispatchable • Zero on-site pollution • CHP-capable • Higher efficiency available versus microturbines	• Relatively expensive • Limited lifetime
	Renewable Generation (solar photovoltaic cells, small wind turbines, and mini-hydro)	• Zero fuel cost • Zero emissions	• Not dispatchable without storage • Variable and not controllable
Storage	Batteries (including lead acid, sodium-sulfur, lithium ion, and nickel-cadmium) [28]	• Long history of research and development	• Limited number of charge-discharge cycles • Waste disposal
	"Flow batteries", also know as "regenerative fuel cells" (including zinc-bromine, polysulphide bromide, vanadium redox) [28]	• Decouple power and energy storage [30] • Able to support continuous operation at maximum load and complete discharge without risk of damage	• Relatively early stage of deployment
	Hydrogen from hydrolysis [29]	• Clean	• Relatively low end-to-end efficiency • Challenge to store hydrogen
	Kinetic energy storage (flywheels) [29]	• Fast response • High charge-discharge cycles • High efficiency	• Limited discharge time • High standing losses

microgrids in areas with existing centralized electrical grids, it is important to remember that they also present many advantages to rural and remote communities in developing countries; these are covered in more detail below.

Starting in the late 1990s, as described below in Section 1.2, scientists and engineers in the United States and Europe began to explore decentralized solutions that could manage the integration of thousands or tens of thousands of distributed energy resources in a way that also maximizes reliability and resilience in the face of natural disasters, physical and cyber attacks, and cascading power failures. The solution they settled on was a grid architecture that could manage electricity generation and demand locally in sub-sections of the grid that could be automatically isolated from the larger grid to provide critical services even when the grid at large fails. This approach was given the name "Microgrid".

1.1. Microgrid definitions

A number of microgrid definitions [8] and functional classification schemes [9] can be found in the literature. A broadly cited definition, developed for the U.S. Department of Energy by the Microgrid Exchange Group, an ad hoc group of research and deployment experts, reads as follows:

> "[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* [10]."

This description includes three requirements: 1) that it is possible to identify the part of the distribution system comprising a microgrid as distinct from the rest of the system; 2) that the resources connected to a microgrid are controlled in concert with each other rather than with distant resources; and 3) that the microgrid can function regardless of whether it is connected to the larger grid or not. The definition says nothing about the size of the distributed energy resources or the types of technologies that can or should be used.

1.2. Foundational microgrid research

Systematic research and development programs [10,11] began with the Consortium for Electric Reliability Technology Solutions (CERTS) effort in the United States [12] and the MICROGRIDS project in Europe [13]. Formed in 1999 [14], CERTS has been recognized as the origin of the modern grid-connected microgrid concept [15]. It envisioned a microgrid that could incorporate multiple DERs yet present itself to the existing grid as a typical customer or small generator, in order to remove perceived challenges to integrating DERs [12,16,17]. Emphasis was placed on seamless and automatic islanding and reconnection to the grid and on passive control strategies such as reactive power versus voltage, active power versus frequency, and flow versus frequency [18]. The goals of these strategies were: 1) to remove reliance on high-speed communications and master controllers, yielding a "peer-to-peer" architecture; and 2) to create a flexible "plug-and-play" system that would not require extensive redesign with the addition or removal of DERs, in order to lower system first costs and provide the freedom to locate cogeneration facilities near thermal loads. The CERTS microgrid concept has been deployed in a test-bed setting [19,20] and in real-world microgrid projects [21,22]. While the initial motivation of CERTS was to improve reliability rather than to reduce greenhouse gas emissions, per se, CERTS microgrids can incorporate renewable microgeneration sources. The European Union MICROGRIDS project explored similar technical challenges such as safe islanding and reconnection practices, energy management, control strategies under islanded and connected scenarios, protection equipment, and communications protocols [13]. Active research continues on all of the topics pioneered in these early studies [23].

2. Microgrid characteristics

2.1. Generation and storage options

Several multidisciplinary studies cover the wide variety of distributed energy resources that can be deployed in microgrids [24–27]. Some examples of the options available for generation and storage today, including their advantages and disadvantages, are provided in Table 1, below. In general, microgrids are somewhat “technology agnostic” and design choices will depend on project-specific requirements and economic considerations. While not strictly required, incorporating some energy storage will help prevent microgrid faults [28]. Since most microgrid generating sources lack the inertia used by large synchronous generators, a buffer is needed to mitigate the impact of imbalances of electricity generation and demand. Microgrids also lack the load diversity of larger geographical regions, so they must deal with much greater relative variability. The array of technologies for energy storage currently under development that could potentially play a role in microgrids is extensive [29,30]. Much of the attention is focused on storage of electricity; however, storage of thermal and mechanical energy should be kept in mind where appropriate. The ability of storage technologies to provide ancillary services like voltage control support, spinning reserves, load following, and peak shaving among others, has also been analyzed [29].

2.1.1. Power electronics

Microgrids often include technologies like solar PV (which outputs DC power) or microturbines (high frequency AC power) that require power electronic interfaces like DC/AC or DC/AC/DC converters to interface with the electrical system. Inverters can play an important role in frequency and voltage control in islanded microgrids as well as facilitating participation in black start strategies [15]. The static disconnect switch (SDS) is a key microgrid component for islanding and synchronization; it can be programmed to trip very quickly on overvoltage, undervoltage, overfrequency, underfrequency, or directional overcurrent [21].

The interface with the main grid can be a synchronous AC connection or an asynchronous connection using a direct current coupled electronic power converter [28]. The former approach has the advantage of simplicity, while the later isolates the microgrid from the utility regarding power quality (frequency, voltage, harmonics) and is a natural match with DC-only microgrid strategies.

Since most distributed energy resources (including fuel cells, solar PV, and batteries) provide or accept DC electricity and many end loads, including power electronics, lighting, and variable speed drives for heating, ventilation, and air conditioning, use direct current internally, all-DC microgrids have been proposed to avoid losses from converting between DC and AC (and often again back to DC) power [2,31–35]. These losses can waste from 5% to 15% of power generation depending on the number of back-and-forth conversions. Additionally, faults in DC systems can be isolated with blocking diodes and issues of synchronization, harmonic distortion, and problematic circulating reactive currents are alleviated [34]. Lastly, a grid-tied DC-based, non-synchronous architecture simplifies interconnection with the AC grid and permits straightforward plug-and-play capabilities in the microgrid, allowing addition of components without substantial re-engineering [36].

It is worth noting that while the success of promising initiatives like “DC homes”, i.e. low voltage DC grids for residential applications, has been limited by a lack of DC appliances and the need for large grid-connected AC-DC converters, DC or hybrid AC/DC microgrids have flourished in maritime applications, datacenters, and so-called minigrids (another name used historically for remote microgrids) utilizing PV solar generation and batteries to charge electronic devices like laptops or cellphones.

2.2. Controls and functionality

Microgrids feature special control requirements and strategies to perform local balancing and to maximize their economic benefits [8,37–41]. There is general agreement that microgrid controls must deliver the following functional requirements: present the microgrid to the utility grid as single self-controlled entity so that it can provide frequency control like a synchronous generator [37]; avoid power flow exceeding line ratings; regulate voltage and frequency within acceptable bounds during islanding; dispatch resources to maintain energy balance; island smoothly; and safely reconnect and resynchronize with the main grid [42]. Microgrids can essentially be controlled in the same way as the main grid, i.e. by using a three level hierarchical control [37]. Control of frequency and voltage – so-called primary and secondary control – can be achieved either under the guidance of a microgrid central controller (MGCC) that sends explicit commands to the distributed energy resources [43] or in a decentralized manner, like CERTS, in which each resource responds to local conditions. In addition, microgrids generally include a tertiary control layer to enable the economic and optimization operations for the microgrid, mainly focused on managing battery storage, distributed generation scheduling and dispatch, and managing import and export of electricity between the microgrid and the utility grid [39,40,44,45]. Hierarchical control architectures that manage power within a microgrid and mediate exchanges with the main grid have been deployed using a “multi-agent system” approach in two European microgrids, one in the Greek island of Kythnos and another in the German ‘Am Steinweg’ project [46]. Increasingly, microgrid research and development is focusing on adding “intelligence” to optimize operational controls and market participation [18,37,38,46–54].

3. Microgrid motivation

The factors driving microgrid development and deployment in locations with existing electrical grid infrastructure fall into three broad categories: Energy Security, Economic Benefits, and Clean Energy Integration, as described in Table 2, below.

The main driver of microgrid development in the United States has been their potential to improve the resiliency (the ability to bounce back from a problem quickly) and reliability (the fraction of time an acceptable level of service is available) of “critical facilities” such as transportation, communications, drinking water and waste treatment, health care, food, and emergency response infrastructure. One major area of activity is the Northeastern U.S., where aging infrastructure and frequent severe weather events have led to billions of dollars of losses in recent years. As a result, States have been exploring the feasibility of extending microgrids beyond critical facilities to serve whole communities [55,56] and have begun funding demonstration projects [57,58]. The most notable example of state support for community microgrids is New York State's “New York Prize”, a $40 M competition to assist communities on the path from feasibility studies through implementation.[1] States in the U.S. are also looking to microgrids to replace retiring generation capacity and to relieve congestion points in the transmission and distribution system.

In Europe, climate change and the need to integrate large amounts of clean renewable energy generation into the grid have been more significant drivers spurring microgrid activity. Climate scientists have concluded that to avoid a global average temperature rise exceeding 2 °C over pre-industrial levels, currently accepted as the threshold between “safe” and “dangerous” climate change, human society needs to reduce the proportion of electricity produced by burning fossil fuels from 70% (in 2010) to under 20% by 2050 [59]. Many of the energy resources scaling up to fill this gap are decentralized, intermittent, and non-dispatchable, making them a challenge to integrate into a legacy grid designed for a one-way flow of electricity from centralized generating plants to customer loads. Deploying intermittent renewables in with co-located flexible loads and storage technologies in microgrids allows for local balancing of supply and demand makes widespread distributed renewable deployment more manageable. Rather than having to track and coordinate thousands or millions of individual distributed energy resources, each microgrid appears to the distribution

[1] https://www.nyserda.ny.gov/All-Programs/Programs/NY-Prize.

Table 2
Drivers of microgrid development and deployment.

Category	Driver	Overview	Recent Examples
Energy Security	Severe Weather	There is a growing concern that weather-related disruptions will become more frequent and more severe over time across the United States due to climate change, lending a sense of urgency to addressing grid resilience. Microgrids can provide power to important facilities and communities using their distributed generation assets when the main grid goes down.	• Grid outage costs from severe weather in the United States alone from 2003 to 2012 averaged $18B-$33B per year due to lost output and wages, spoiled inventory, delayed production, and damage to the electric grid [120]
	Cascading Outages	Because electrical grids are run near critical capacity, a seemingly innocuous problem in a small part of the system can lead to a domino effect that takes down an entire electrical grid [121]. Microgrids alleviate this risk by segmenting the grid into smaller functional units that can be isolated and operated autonomously if needed.	• The United States Northeast Blackout of August 2003 impacted 50 million people and 61,800 MW of load [122]
	Cyber- and Physical Attacks	The grid today increasingly relies on advanced information and communications technologies, making it vulnerable to cyberattack [123]. The centralized grid also contains large, complex components that are expensive and slow to replace if damaged. Microgrids, through their decentralized architecture, are less vulnerable to attacks on individual pieces of key generation or transmission infrastructure. Natural [124,125] or man-made [126–129] electromagnetic pulse (EMP) events could also have potentially catastrophic results.	• Cyberattacks on Ukraine [130] in 2015 and Israel in 2016 (successfully thwarted) [131]. • Large transformers were physically attacked at a major California substation in 2013 [132,133].
Economic Benefits	Infrastructure Cost Savings	Investment in the U.S. electricity grid has not kept pace with generation. As a result, capacity is constrained in many areas and components are quite old, with 70% of transmission lines and transformers now over 25 years old. The average power plant age is over 30 years [120,134]. Microgrids could avoid or defer investments for replacement and/or expansion.	• Defered construction of a $1B substation in the Brooklyn and Queens area of New York [135] • It costs $40,000 to $100,000 per mile (depending on design, terrain, and labor costs) to build new primary distribution systems [2]
	Fuel Savings	Microgrids offer several types of efficiency improvements including reduced line losses; combined heat, cooling, and power; and transition to direct current distribution systems to avoid wasteful DC-AC conversions. Use of absorption cooling technology in a combined heat and power application could help address summer critical peak electrical demand [11].	• Transmission and distribution losses waste between 5% and 10% of gross electricity generation [2,3] • If the supply of reused waste heat is well matched to the thermal loads, efficiencies of combined heat and power systems can reach 80–90% [2], much higher the average efficiency of the existing U.S. grid (only ~30–40% [2136]).
	Ancillary Services	Traditional ancillary services include congestion relief; frequency regulation and load following; black start; reactive power and voltage control; and supply of spinning (due to their ability to mimic the inertia of traditional generation), non-spinning, replacement reserves [137,138]. Power quality (reactive power and voltage harmonics compensation). When discussing microgrids, intentionally islanded operation should be added to this list [15].	• Recent rulings 755 and 784 from the U.S. Federal Energy Regulatory Commission (FERC) mandate that fast responding reserves like those used in microgrids be compensated based on their speed and accuracy, opening new revenue possibilities [139,140].
Clean Energy Integration	Need to firm variable and uncontrollable resources	Important clean energy sources to address climate change like solar PV and wind are variable and non-controllable, which can cause challenges like overgeneration [141], steep ramping [141,142], and voltage control [143,144] problems for the existing grid if deployed in large quantities. Microgrids are designed to handle variable generation, using storage technologies to locally balance generation and loads.	• In locations with high renewable penetration like California, Texas, and Germany, electricity prices have occasionally gone negative, reflecting an imbalance between supply and demand [145,146]

utility as a small source or consumer of electricity with the ability to modify the net load profile in ways that benefit the main grid [12].

Despite differences in the priority given to resilience and emissions in the U.S. and Europe, microgrid fuel savings and ancillary grid services are important components of the business case in both areas. Extensive research is now underway to design microgrids using advanced analytical approaches in order to maximize these benefits across a broad range of criteria, including land use, water use, employment, CO_2 emissions, investment costs and cost of electricity, among others [60–62].

4. Deployment

While much has been written about the concept and promise of microgrids, much can also be learned from examples of real, operating microgrids. For an exhaustive list of existing, experimental, and simulated microgrid systems, the reader is recommended to consult a recent review by Mariam et al. (2016) in this journal [27]. According to Navigant Research, which has tracked microgrid deployment since 2011, the United States has been the historical leader in deployed capacity; today, though, the U.S. and Asia have roughly the same capacity of operating, under development, and proposed microgrids, each with 42% of the market. Europe trails with 11%, Latin America with 4%, and the Middle East and Africa currently have just a 1% share. Total capacity was approximately 1.4 GW in 2015 and is expected to grow to roughly 5.7 GW (considered a conservative estimate) or 8.7 GW (under an "aggressive" scenario) by 2024 [63]. Navigant breaks the microgrid market into the following segments (with % of total deployed power capacity as of Q1 2016): Remote (54%), Commercial/Industrial (5%), Community (13%), Utility Distribution (13%), Institutional/Campus (9%), and Military (6%) [36]. It should be noted that Navigant Research does not track purely diesel-generator based remote microgrid systems; to be considered, they must include at least one renewable generating source. While it is not possible here to present an exhaustive description of different microgrid applications, we highlight a few below.

4.1. Campus/Institutional

Deploying onsite generation, especially in a combined cooling, heat, and power (CCHP, also known as “trigeneration”) application with multiple loads collocated on a campus owned by a single entity has been a successful model so far and typically includes the largest microgrids to date, with capacities ranging from 4 to over 40 MW [63]. Santa Rita Jail, located in Alameda County, California, is a real institutional microgrid proof-of-concept employing the CERTS concept [21]. The microgrid includes a 1-MW fuel cell, 1.2 MW of solar PV, two 1.2-MW diesel generators, a 2-MW/4-MWh Lithium Iron Phosphate electrical storage system (chosen because this chemistry features high AC-AC round trip efficiency and offers improved thermal and chemical stability compared to other battery technologies, despite some sacrifice in energy density), a fast static disconnect switch, and a power factor correcting capacitor bank. The CERTS protocol allowed all of these distributed energy resources to work together during grid-connected and island modes without requiring a customized central controller. The ability of an institutional microgrid to deliver peak load reduction, and the tradeoffs between optimizing net load shape for the facility versus for grid needs, has been demonstrated using Santa Rita Jail as an example, using DER-CAM software to determine optimal equipment scheduling and dispatch [64].

4.2. Military microgrids

Cost-effective energy security, “the ability of an installation to access reliable supplies of electricity and fuel and the means to use them to protect and deliver sufficient energy to meet critical operations during an extended outage of the local electrical grid [65],” is the main driver for grid-connected military microgrids (off-grid solutions for operational deployment are also being developed). A good example of military microgrid research and demonstration efforts is the Smart Power Infrastructure Demonstration for Energy Reliability and Security (SPIDERS) Joint Capability Technology Demonstration (JCTD) [66], a three-phase program, with the scope and complexity growing with each phase. Phase 1 took place at Joint Base Pearl Harbor-Hickam, Hawaii in 2012 and 2013 featuring a single distribution feeder, two electrically isolated loads, two diesel generators, and a PV array. Phase 2 took place in 2013 and 2014 at Fort Carson, Colorado and included three distribution feeders, seven building loads, three diesel generators, a 1-MW PV array, and 5 bidirectional electric vehicle chargers. The final phase 3, at Camp Smith, Hawaii, finished in late 2015; it used new and existing generation sources to support the loads of the entire base. A more detailed description of SPIDERS, including the project's cyber-security components, and comparisons to other military microgrids are available in the literature [65,67].

4.3. Residential

The question of optimal aggregation scale is an open one in the microgrid literature and an active area of investigation. For example, is it better to integrate detached home residential customers into large community microgrids or to deploy microgrid technology at the level of individual homes? The advantages of a fully decentralized building-integrated microgrid approach [68] include control over energy resources by customers and the fact that individual homes are already connected to the electrical distribution network, so that any changes performed behind the utility meter to add microgrid capabilities will likely not introduce significant legal or regulatory complications beyond what is already encountered for interconnection of rooftop solar installations today. At the same time, this fully decentralized approach, especially if it includes islanding capability, forfeits cost-saving economies of scale and the generation and load diversity that comes with networking multiple generators and loads. For example, the cost of interconnection protection can add as much as 50% to the cost of a microsource (i.e. serving an individual home or small building) project so it may be better to site multiple microsources behind a single utility interface [69]. Some authors envision a nested system where energy management systems at the building level communicate with each other and neighborhood-level master controllers to coordinate distributed energy resources, including shared community energy resources and loads like street lighting [47]. The building-integrated microgrid deployment model would likely benefit from innovative financing (akin to solar leasing models) due to the expense of generating resources, controllers, power electronics, and integration with existing building systems. Literature exploring so-called “customer microgrids” examines the technical feasibility and economic viability of this mode of broad decentralized residential deployment [70,71]. Many of these studies are motivated by the question of whether it is feasible and or/desirable to cost-effectively gain full autonomy from the electrical grid using PV and battery storage [70,72].

One appealing residential microgrid application combines market-available grid-connected rooftop PV systems, electrical vehicle (EV) slow/medium chargers, and home or neighborhood energy storage system (ESS). During the day, the local ESS will be charged by the PV and during the night it will be discharged to the EV. The effect is twofold: (1) feed-in tariff schemes are not necessary since little power needs to be exchanged with the main grid; and (2) voltage quality at the PCC is improved [48]. The inclusion of the ESS alleviates overvoltages during the day due to excess PV power generation and undervoltages during the night caused by the huge current drained to charge the vehicle.

4.4. Remote and rural microgrids

More than 1 billion people in developing and underdeveloped countries currently lack access to reliable electricity – or to any electricity at all. Often, the limited electricity that is available is generated using expensive diesel fuel. In particular, for rural areas in these countries, electricity is a key resource for meeting basic human needs, and microgrids may be the best way to deliver that electricity [73,74]. Remote microgrids combining clean generation and storage, in some cases facilitated by innovative mobile payment platforms, can provide a lifeline to those people, allowing children to study at night, medical systems to provide reliable service, and entrepreneurs to improve their livelihoods. These remote microgrids are leveraging the same advances in power electronics, information and communications technologies, and distributed energy resources that are driving changes in the grid in industrialized countries, allowing developing nations to potentially leapfrog to a world of smart microgrids, in the same way that mobile communications allowed them to connect to each other and the outside world without building up extensive landline networks.

So-called “hybrid” microgrids [75] that incorporate renewable energy sources, often as an add-on to diesel generator-based systems, show great potential to diversify generation and lower microgrid operating costs in island communities that rely on expensive imported oil for generating electricity and in remote areas far from existing electricity infrastructure [76–81]. Remote microgrids need not use a one-size fits all approach to system design; with careful resource evaluation and understanding of demand profiles, projects can be optimized to fit local conditions [82,83]. However, careful attention needs to be paid to the impact of resource variability on level of service as well as the level of maintenance required to keep the system running or to restore service in the case of generator failure. Examples of research featuring remote microgrids include Huatacondo Island in Chile [84], Xingxingxia in Xinjiang, China [85], and Lencois island in Brazil [86].

5. Challenges

5.1. Legal and regulatory uncertainty

There are two key legal issues that impact microgrids: first, whether they are deemed to be electrical distribution utilities and are therefore subject to oversight by state regulatory agencies; and second, even if they are exempt from state regulation as utilities, do they fit into existing legal frameworks governing the sale and purchase of electricity and rights to generate and distribute electricity? A clear legal identity for microgrids is needed to achieve the regulatory certainty required to make microgrid projects "bankable" – otherwise the potential costs are too high and benefits too uncertain to justify investing time and money [55]. Several states in the United States have evaluated microgrids in the context of the current legal and regulatory framework pertaining to electricity generation, transmission, and distribution. The resulting reports are a good starting point for understanding the issues states are wrestling with regarding the future of their electrical distribution systems [55,56,87,88].

5.2. Interconnection policy

One fundamental source of legal uncertainty centers on the laws regulating connection of distributed energy resources to the grid. Following deregulation in the United States in the late 1990s, there were no nation-wide standardized requirements for small independent power producers to connect their equipment to the grid. Manufacturers and project developers had to deal with a patchwork of requirements that varied from utility to utility [89], adding substantial cost and time to the microgrid development process. The development of IEEE 1547 (released in 2003) was an important step toward a consistent set of rules for integrating distributed energy resources ($<$ 10 MVA) to the grid in a safe manner [90]. Until recently, though, the main focus of interconnection policy for distributed energy resources, including IEEE 1547, was on ensuring that those resources would disconnect in the case of grid failure (a so-called "unintentional islanding" situation) to protect the safety of line workers. It wasn't until the IEEE approved standard 1547.4 in 2011, that standardized protocols became available for safe *intentional* islanding and reconnection of microgrid systems. IEEE 1547.4 includes guidance for planning, design, operation, and integration of distributed resource island systems with the larger utility grid. It covers functionality of microgrids including operation in grid-connected mode, the transition to intentionally islanded mode, operation in islanded mode, and reconnection to the grid, specifying correct voltage, frequency, and phase angle. Finally, IEEE 1547.4 also covers safety considerations, protection, monitoring, communications, control, and power quality. California's Rule 21 also addresses interconnection requirements, to help remove barriers put in place by legacy utility providers, by establishing standardized technology- and size-neutral requirements, a clear review process, testing and certification procedures, set fees, and a streamlined application process. Interconnection is of paramount importance: if microgrids are not able to connect to the utility grid, they must operate permanently in an islanded mode, forfeiting the opportunity to derive revenue from grid services they could otherwise provide and crippling their business case.

5.3. Utility regulation

A microgrid is likely to be considered an electric corporation if it intends to serve multiple, otherwise unrelated, retail customers, cross a public way with power lines, and/or obtain a franchise from a local authority. The reasons for this conclusion are discussed below in more detail. If a state utility regulatory agency decides that services provided by microgrids qualify them as utilities, that body can regulate the rates charged for electricity and decide whether to approve facility construction, among other powers, all of which have major implications for microgrid developers and owners. In the event that the microgrid ***is*** deemed to be a distribution utility, it may assume an obligation to serve, meaning that it would be required to provide service upon the written or oral request of a potential retail customer.

All microgrids that intend to use public ways to distribute electricity to customers (for example sending thermal energy or electricity across a public street) require permission from the local municipal authority [55]. This permission can be in the form of a "franchise" or other "lesser consent". A microgrid's ability to obtain this permission depends in large degree on whether a pre-existing electric utility has been given an exclusive franchise, effectively blocking out competitors. In New York, for example, if the existing franchise is non-exclusive, state law still mandates that a competitive process be used to determine the franchise grantee, allowing incumbents and other service providers to compete against the microgrid developer for the franchise.

Due to their small scale and limited scope of services, it is unlikely in most cases that a microgrid would require a franchise and therefore, that most microgrids would ***not*** be under the jurisdictional authority of the utility regulatory agency; however, these cases are being decided on a project-by-project basis in the courts. In addition, microgrids selling to retail customers may have to comply with various consumer protection laws. Finally, regardless of their status as a distribution utility, microgrids that produce power through combustion (such as microturbines or diesel generators) are subject to federal and state laws governing emissions and will require a permit under certain conditions. The choice of business or ownership model will also impact the degree to which utility franchise or lesser consent come into play; these considerations are discussed in more detail below.

Today's regulations governing electric utilities in the United reflect a process referred to as "restructuring", and colloquially as "deregulation", that occurred in the mid- to late-1990s in many states in the U.S., following the example of deregulation in other major industries like airlines, railroads, telecommunications, and others [91]. In general, restructuring introduced a separation between the generation, transmission, and distribution functions of what were previously vertically integrated monopolies. In the case of New York, generators can sell electricity into a competitive wholesale markets or directly to local distribution utilities or retailers for resale to customers. A system operator (in the case of New York, the NYISO) is responsible for maintaining a balance between supply and demand at all times. The ecosystem of players in the restructured New York electricity market includes smaller generating companies called Independent Power Producers (IPPs). Microgrids, as such, do not fit neatly into the classes of market participant defined by restructuring, perhaps because they transcend the categories of generation, transmission, and distribution. As a result, further work is needed to incorporate them into the regulatory legal structure.

5.4. Utility opposition

Although grid-tied microgrid customers will likely stay connected to the grid for the foreseeable future, only islanding in the case of utility grid failure, self-consumption of microgrid generated energy could erode the revenue base that has traditionally paid for utility infrastructure investments. There is also still reluctance to add large amounts of distributed energy resources to the grid because of perceived management, safety, and protection challenges. As a result, many utilities are seeking to impose additional fees on DER owners and threatening to halt net metering programs. Market restructuring, like that proposed in New York's "Reforming the Energy Vision (REV)" effort, will be required to move from a situation where microgrids are viewed as a threat to one in which distributed energy resource services are valued by the utility grid and fairly compensated [92]. As part of this restructuring, utility regulators will fully unbundle generation, transmission, and distribution services and allow independent power producers to compete in wholesale (and potentially retail) markets.

Real time or time of use (ToU) electricity prices will become the norm so that microgrids receive the economic signals they need to manage their DERs to provide grid services like frequency regulation, black start, and congestion relief, and to maximize their own revenues. However, utility restructuring has not been a universal phenomenon and progress slowed dramatically following the challenges experienced in California in the early 2000s [91].

Even for deregulated utilities, the structure of electricity markets and the manner in which investor-owned utilities are paid for providing service (using so-called "cost of service" accounting) still represent impediments to distributed energy resource adoption in general, including microgrids. Decoupling electric company revenues from electricity sales, which is already done in 14 states in the USA, is a major step toward removing utility resistance to microgrids based on concerns about a so-called "utility death spiral" where widespread self-generation leads to demand reduction for the grid's electricity, which in turn leads to higher electricity costs for traditional customers, fueling additional uptake of self-generation to the point that utilities cannot cover their costs.

A potential path forward is to move from the traditional cost-of-service paradigm to a performance-based approach [93] that recognizes that the utility grid is being asked to provide functions that are much different from those they have historically been responsible for, such as resilience, security, and clean generation. In this new paradigm, utilities would be incentivized to invest in upgrading infrastructure and improving efficiency as opposed to selling the maximum number of kilowatt hours. Several States in the USA have taken it upon themselves to commission or formulate their own plans for how to modernize their grids and electricity markets to provide more reliable, efficient, and clean, electricity to their customers [94–96]. Countries like Great Britain are also formulating plans for evolution of the grid to a more clean, secure, and distributed energy future and examining the social, legal, and regulatory factors that help or hinder that transition [97].

Utilities are also coming around to the view that they may be well positioned, if allowed by regulators, to provide microgrid services to their existing customers since they have extensive knowledge, distribution infrastructure already in place, and franchise rights from local authorities. Electrical utilities have begun testing microgrid concepts in laboratory-type settings. One example is Duke Energy, which maintains two test microgrid facilities: one in Gaston County, North Carolina [98], and one in Charlotte, North Carolina [99]. The first installation focuses on interoperability and building partnerships with manufacturers; the second, originally built to test virtual power plant capabilities, is a solar PV and storage microgrid serving a fire station. The partnership between the CERTS team and American Electric Power (AEP) to develop a CERTS test bed represents a productive partnering model between industry and the government [19]. Other utility companies [100], like Arizona Public Service, Consolidated Edison, Commonwealth Edison, Green Mountain Power, NRG Energy, San Diego Gas and Electric and Southern California Edison [101] are also exploring microgrids as a way to provide additional services to customers, defer capital investments, improve overall reliability, and to manage potential disruption to their business model.

6. Future prospects and open questions

6.1. Competing smart grid paradigms

While it has been argued that microgrids are a better approach to contain and manage local problems [102] and could even serve as a possible pathway to a "self-healing" smart grid of the future [103], it is possible that society will find grid architecture paradigms like "smart supergrids" [104,105] or "virtual power plants" [44,106,107] – which do not feature local balancing of generation and loads or isolating segments of the grid – to be more compelling architectures. Smart supergrids rely on improved fault detection, isolation, and restoration capabilities to alleviate congestion, route power around faults, and shorten recovery time from outages. Virtual power plants rely on software and analytics to manage widely dispersed distributed energy resources, although grid-connected microgrids can also function as virtual power plants, as mentioned above. New information and communications developments, broadly known as the "Internet of Things (IoT)" are also facilitating the emergence of a decentralized, so-called "transactive" energy market platform where individual distributed energy resources and loads can bid to buy and sell electricity from each other [108]. Whether microgrids become the dominant strategy to deploy large amounts of intermittent renewables and improve resilience depends on whether the benefits are perceived to be great enough in relation to the costs, when compared to the alternative smart grid paradigms. It is possible that – even in situations where there is low value placed on islanding for resilience and reliability – it will be deemed advantageous to collocate virtual power plant assets in microgrid-like architectures.

6.2. Market structure and degree of market decentralization

The EU "More Microgrids" project [109] presented four different scenarios of microgrid resource ownership including: ownership by the distribution system operator (DSO), where the DSO owns the distribution system and is responsible for retail sales of electricity to the end customer; ownership by the end consumer or even consortium of *prosumers* (entities that both import and export electricity); ownership by an independent power producer; or, ownership by an energy supplier in a free market arrangement. According to Navigant Research [36], the majority of grid-tied microgrids today are owned and financed by facility owners, especially in the campus/institutional category. It is important to recognize that microgrids, especially community microgrids, can utilize the existing distribution system infrastructure, radically reducing their costs.

Three models have been proposed for integrating energy prosumers into the grid – peer-to-peer, prosumer-to-grid, and prosumer community groups – and identified barriers to their adoption [110,111]. In the peer-to-peer model, perhaps the farthest from today's centralized grid model, the underlying platform would support the ability of electricity producers and consumers to directly buy and sell electricity and other services from each other, with a fee going to the manager of the distribution grid for providing distribution services [112]. Pilot projects of this type are starting to appear in places like Brooklyn, New York, the Netherlands, and the United Kingdom. Researchers, practitioners, and even large European energy companies, for applications like electric vehicle charging, are starting to apply secure peer-to-peer platforms like blockchain-based distributed ledgers to peer-to-peer energy markets [113,114].

One focus area is the market for voltage control in distribution networks with microgrids. Some researchers propose that each microgrid in a future multi-microgrid network act as a virtual power plant – i.e. as a single aggregated distributed energy resource – with each microgrid's central controller (assuming a centralized control architecture) bidding energy and ancillary services to the external power system, based on the aggregation of bids from the distributed energy resources in the microgrid (responsive loads, microgenerators, and storage devices) [115]. They conceive of the distribution system operator running a day-ahead market for reactive power, which is required for the flow of power from large generators to customers across a radial transmission and distribution network, and propose a mechanism for optimal market settlement. This vision is similar to that presented in New York's Distributed Energy Resource Roadmap [116] which proposes to open the state's wholesale electricity market to DER aggregators.

Innovative business models such as power purchase or energy services agreements and design-build-own-operate-maintain (DBOOM) will likely play a big role in the ability of microgrids to scale [36]. Once microgrid design and procurement becomes more streamlined, power purchase agreements (PPAs) are poised to play a larger role in the microgrid market [36]. The PPA is currently a very successful business model in the U.S. residential and commercial solar PV markets because it can be used to capture tax and other related incentives while avoiding large upfront capital costs for the facility hosting the system. The infrastructure in a PPA is owned by a third party and leased to customers to provide electricity and related services to end customers. In the case of microgrids, improved security, reliability, and sustainability can be marketed along with economic benefits like energy cost savings. In the case of combined cooling, heat, and power projects, thermal energy can be bundled in the PPA along with electricity. It is reasonable to expect that operations and maintenance will be included in the PPA, since PPA revenues depend on systems performing to their potential.

7. Conclusion

The costs of solar photovoltaic generation and battery storage are rapidly dropping, to the point that they are closing in on cost parity with traditional electricity sources. As a result, broad adoption of these technologies may soon accelerate to the point that *energy prosumption*, where end users import *and* export electricity, is the norm rather than the exception. Before millions of distributed energy resources are connected to the electrical grid, it behooves society to plan ahead and to understand what architecture will best integrate these and other distributed energy technologies. Microgrids are poised to manage this transition by balancing supply and demand locally while ensuring reliability and resilience against what appear to be escalating natural and man-made disturbances.

Whether microgrids remain a niche application or become ubiquitous depends on two main factors: (1) to what degree regulatory and legal challenges can be successfully surmounted, and (2) whether the value they deliver to property owners and communities in terms of power quality and reliability (PQR) and other economic benefits outweigh any cost premiums incurred to capture those benefits. These questions are now being answered in court rooms and commercial markets around the globe as electricity grids evolve to address social and economic concerns and incorporate 21st century technology to update Thomas Edison's original vision of the grid.

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