Report 1.3: Microgrids

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Contents

1. Introduction

Microgrids are local installations typically connecting one or multiple generation sources with some set of loads. They range in size, from tiny off-grid solar home systems (SHSs) to power infrastructure spanning a university campus or military base. Many are grid-connected, enabling owners to consume inexpensive electricity from the larger Generation, Transmission, Distribution and Retail (GTDR) power system while providing redundancy in the case of outage. Many such systems also allow local generation sources to sell power into the GTDR system. Microgrids offer their owners control over their own electrical destiny in exchange for the cost of installing and maintaining parallel electrical infrastructure. They are deeply connected to the proliferation of distributed energy resources (DERs), as they offer DER owners the ability to optimize energy use in order to monetize distributed assets. As DERs continue to become cheaper, along with improvements in the interoperability of microgrid components, the extra cost associated with microgrids should fall. If this coincides with more expensive or less reliable centralized power, the value proposition of a microgrid is likely to appeal to an ever-increasing circle of users. In such a future, the power system may transform from today's centralized GTDR model into a decentralized network of local microgrids.

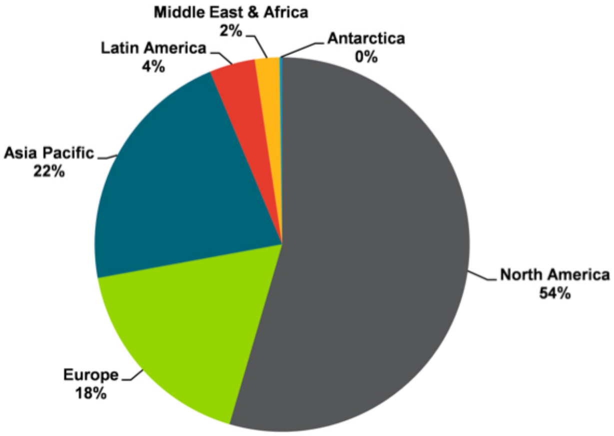

Figure 1: Microgrid capacity by region, at the end of 2016. From [10]

Navigant research, which regularly publishes a microgrid deployment tracker, has found that there are 2,258 projects worldwide in Q4 2018 representing 19.6 GW of planned or installed capacity [14]. While this represents a fairly small fraction of total electrical infrastructure (the US alone has 1.17 TW nameplate capacity installed), it is expected to continue growing rapidly at about a 15% annual rate [9]. Navigant has also found that the majority of installed microgrids are in North America (see figure MicrogridRegions) but that growth is broadbased. These numbers include both grid-connected and remote systems, but do not include very small installations such as individual solar home systems.

2. Driving forces for adoption

2.1. Outage avoidance

It was estimated in 2006 that power outages cost the US economy $79B annually (2002 dollars) in lost productivity [41]. As shown in figure 2, these costs are borne predominantly by businesses. A recent update to these estimates found that the cost of sustained interruptions may be higher than initially thought by 25%, implying the total cost of interruptions to be $115B in 2015 dollars [42]. The annual expense for a business can be high, estimated to be $9,373 (2002 dollars, annually) on average for each industrial customer. This creates an economic incentive commensurate with the cost of a microgrid for individual businesses to invest in equipment that would help avoid these losses. Some facilities such as hospitals and military bases have additional power reliability requirements going beyond lost productivity. All of these needs are major driving forces behind the installation of microgrids.

On a systems level, microgrids are frequently touted as a way to 'harden' infrastructure against natural disaster. This is because microgrids provide the basis for a more distributed electrical architecture with fewer critical failure points than the centralized GTDR model. When nearby infrastructure is damaged, many microgrids are capable of operating in 'island' mode as a self-sufficient system. This contrasts with power transported from long distances through transmission lines, in which a failure at any point along the line can cause substantial outages in whatever city or region the line supplies.

In addition, **a network of microgrids able to perform load balancing locally is less susceptible to cascading failure than the bulk power system** is [27, 28, 36, 46, 49, 50]. These cascading failure events, in which an outage in one area causes power to be re-routed and the resulting surge overwhelms additional infrastructure, are responsible for some of the most widespread power outages. This type of failure has been at the center of the largest blackouts in history, such as the 2012 blackouts which left 670 million people without power in northern India [39] This failure type is the direct result of a centralized GTDR system. With more microgrids managing distributed assets, less power would be transported over long distances which would make cascading failure less likely.

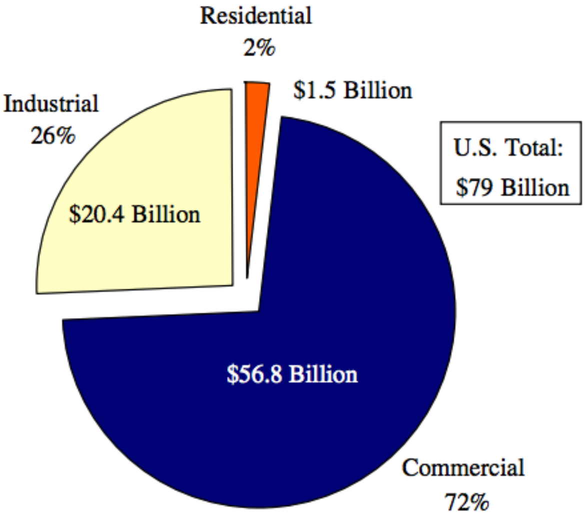

Figure 2: A breakdown of the cost of outages in the US, in 2002 dollars. From [41]

The resiliency benefits of microgrids were highlighted during Hurricane Sandy in 2012, when eight million customers suffered power outages. Much of downtown manhattan went dark, but isolated pockets - such as the NYU campus - maintained power due to microgrids capable of responding to outages by operating as islands as shown in figure 3, [16]. Another notable area of New York that maintained power is Co-Op city, a large housing development with a combined heat and power (CHP) cogeneration facility [13]. Working microgrids also contrasted with failed GTDR infrastructure during Hurricane Irma in the Carribbean [3] and the California wildfires [12].

Puerto Rico's power infrastructure was severely damaged by Hurricane Maria in September 2017. The existing GTDR system was highly centralized, with one transmission line encircling the island. There has been substantial government and private support for building a more decentralized power infrastructure going forward, making extensive use of connected microgrids [19, 20]. As one notable example, a large power distribution company AES has issued a proposal to rebuild Puerto Rico's power infrastructure as a collection of interconnected 'minigrids' [24].

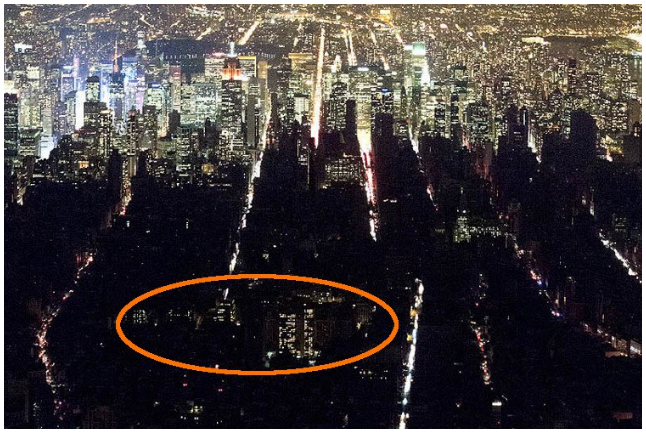

Figure 3: During the outages caused by Hurricane Sandy, much of the NYU campus maintained a reliable power supply due to an islandable microgrid incorporating a natural gas fired CHP generator (circled area). Sandy was a major demonstration of the benefits of microgrids that has spurred investment in the greater New York area. From [16].

2.2. Generation Cost

Aside from resilience, microgrids including distributed generation allow their owners access to inexpensive power which can often be sold into the bulk power system when generation outstrips local demand. Historically, the Public Utility Holding Companies Act of 1978 (PURPA) played a significant role in the development of grid-connected microgrid systems by allowing non-utility owners of generation capacity access to power markets [5, 21]. Whereas investor-owned utilities are subject to strict SEC regulation, PURPA defined a set of rules by which power installations meeting efficiency and size requirements could register as Qualifying Facilities exempt from oversight as a utility. PURPA furthermore required utilities to buy power from these facilities at the utility's own avoided cost (roughly the cost at which they would alternatively have been required to purchase power in wholesale markets). This opened up a new value stream for companies and institutions considering installing a microgrid with an efficient generation source. This policy especially lead to the growth of energy efficient CHP plants, producing both electricity and heat for local buildings (figure 4). These became common generation sources for local microgrids.

More recently, a group of companies have focused on developing software solutions that allow DER owners to maximize their profits by selling power into the grid. These allow clients to participate optimally in various markets including not only wholesale energy markets but those for ancillary services such as frequency and voltage support. These companies include Advanced Microgrid Solutions [2] and Stem [23], which aggregate DERs similar to demand response providers discussed in report 2.1.

Looking forward, the falling cost of solar is expected to be another driving force for the installation of microgrids. Increasingly, low power purchase agreement prices demonstrate solar to be cheaper than any other generation options in many regions [1]. In the AES proposal to build connected 'mini-grids' in Puerto Rico, it is suggested that using solar generation is a cost-effective option and cheaper than the cost of fuel over a ten year period [24]. Solar can be installed cost-effectively over a range of installation sizes smaller than traditional utility-scale power, and microgrids are the means by which owners gain access to the benefits of on-site generation.

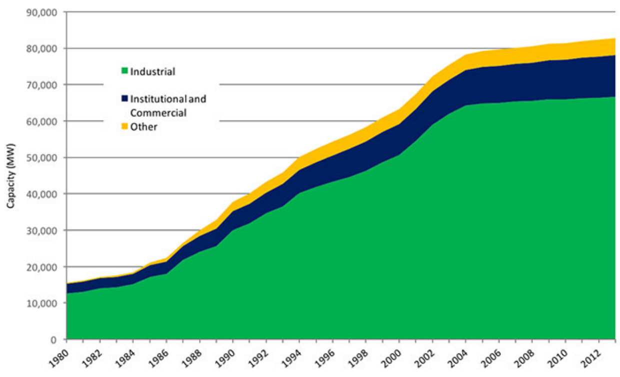

Figure 4: Total combined heat and power (CHP) capacity in the US. Following the 1978 passage of PURPA, which allowed many non-utility companies to sell power into the bulk power system, the installed capacity of CHP plants increased dramatically. From [5].

2.3. Government programs

Increasingly, a driver in microgrid installation is a set of government incentives to promote DERs and microgrids specifically. These policies have taken the form of government supported research, policies to remove barriers, requiring the private sector to install DERs, and direct support through incentives.

Both the US and the EU have invested in microgrid research as this technology has become increasingly part of a broader plan for improved power grid resilience. In particular over the past decade it has become clear that the controls systems required for a cybersecure and resilient network of microgrids (overlapping significantly with the requirements for smart grids) will be necessary in future systems with two-way power flows and need to be developed. The Smart Power Infrastructure Demonstration for Energy Reliability and Security (SPIDERS) project funded demonstration projects at three DoD sites in the US.

Regulatory action has both removed barriers for microgrid installation and required private entities to install microgrids or DERs in some cases. An early case of this was Texas HB 1831 and 4409 which required some new buildings to consider microgrids and DERs as an option during planning. Recently, CA SB1339 has streamlined interconnection standards and requires public utilities to accommodate grid-connected microgrids in a timely manner. Another major change in CA is the CA 2020 green building standard requiring new homes to install solar power, which will dramatically increase the number of DERs in the state. Puerto Rico has also recently adopted microgrid standards defining interconnection rules.

In addition, many states are directly supporting microgrids. These include the NY Prize program, which awards communities grants in order to plan and install microgrid systems. FL has committed $10M to microgrid support. CT has set aside $15M for microgrid development, attaching financing to property rather than individual owners using Commercial Property Assessed Clean Energy Financing (PACE). Other programs include the MA microgrid program and New Jersey TransitGrid.

3. System design and variations

It's an industry truism that 'if you've seen one microgrid... you've seen one microgrid'. The requirements for different microgrid systems span a vast range based on the specific requirements of a project. In particular the size of the system, the generation and storage resources it connects, the multiplicity of subsystem controller standards and the amount of pre-existing infrastructure vary greatly. As a result, system engineering and component integration are a significant fraction of microgrid installation costs. Efforts to standardize both hardware and controls systems will be discussed below and in report 2.3, respectively.

Generally to be considered a microgrid a system must incorporate distributed generation and load, and present itself to the main grid as a single entity. It should be capable of operating independently when power from the main grid is lost, protect its loads and assets from faults, assure power quality within its boundaries, and perform some degree of internal optimization (for example, cost optimization) in order to control its distributed assets [54].

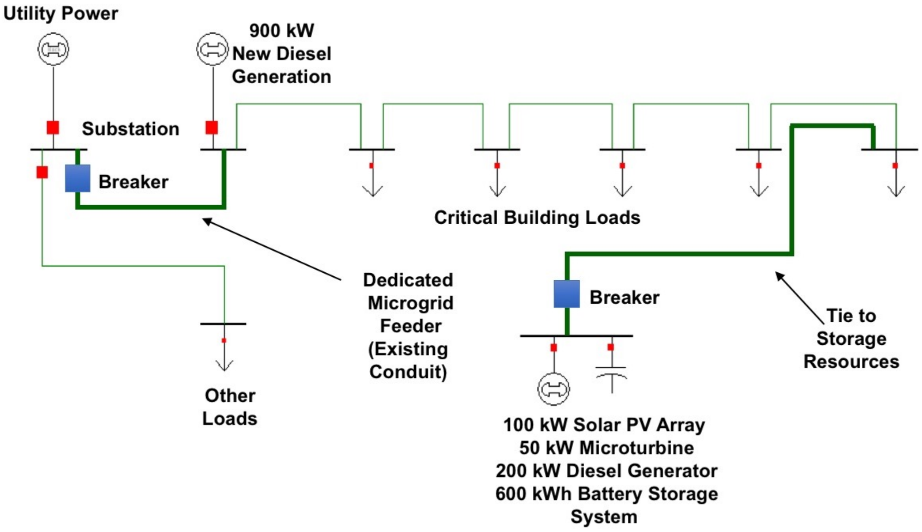

Figure 5: An example grid-tied microgrid system connecting five buildings to a set of generation and storage assets. From [40].

3.1. Grid connected systems

3.1.1. Grid connected systems in the developed world

Grid-connected microgrids of the past few decades have largely existed to provide heat and power to factories. As shown in figure 6, three quarters of microgrids in the US (which makes up a large fraction of all microgrids, as shown above in figure 1) are powered by natural gas. More than half of these are combined heat and power installations, which are predominantly (figure 4) industry owned. Among these industries chemical manufacturing, oil refining, and paper production are well-represented [11]. These privately financed industrial microgrids fulfill an economic value proposition for their owners combining value derived from:

- A reliable electricity supply used to avoid shutdowns during power failure

- Efficiency gains due to the use of waste heat in CHP installations

- Lower power prices through the avoidance of transmission and distribution charges

- Revenues from selling excess electricity into the larger power system

Notably, these industries have not installed microgrids or DERs due to a desire to be 'green.'

In contrast with natural gas powered microgrids, more solar powered microgrid capacity is planned than is currently in operation (figure 6). This represents a recent shift towards solar powered microgrids [22]. The shift is driven partially by the falling price of solar and storage, and partially by other factors such as incentives for clean energy generation.

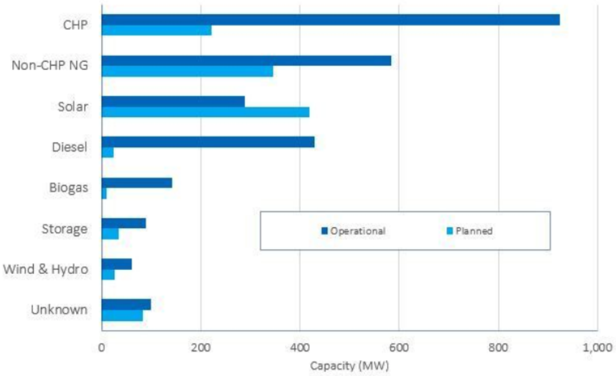

Figure 6: Planned and installed US microgrids by generation source. Most of the installed capacity are combined heat and power (CHP) facilities powered by natural gas (NG). Increasingly, solar is the generator of choice for new installations. From [7].

A major consideration in AC microgrids as compared to the bulk power system is system inertia. The bulk power system has a high inductance, leading to a high reactance to resistance X/R ratio of about 4. This inductance is the result of the long lengths of conductive cables making up power lines, as well as the coils of wire in generators. As a result, the inertia in the bulk power system is high and transients due to individual devices and events are easily absorbed. This high X/R ratio also results in a need to synchronize the frequencies of the bulk power system and generators for efficient injection of power. Methods to achieve this synchronization such as droop control have been extensively developed for the bulk power system. This has also resulted in the need to design protocols to 'blackstart' the transmission system when recovering from total power loss

This high X/R ratio is not typically true of microgrids, where much smaller system sizes lead to lower inductance. In addition, microgrids making use of DC generation and storage sources such as solar cells and batteries rely on inverters for power injection. Inverters use an internal switch in order to convert a DC voltage source to a 60 Hz (or 50 Hz) signal, followed by a bandpass filter in order to improve waveform quality. These circuits do not provide the microgrid with inertia similar to the coils of wire in an AC generator, contributing to the relatively low X/R of the microgrid as a whole. In addition, microgrids are designed to transition easily between grid-connected and island modes. These transitions can introduce significant transients which may manifest as power surges that can destroy microgrid components or connected electrical equipment, or negatively affect power quality. The sum of these problems has resulted in a significant amount of research on 'smart inverters' designed to automatically correct power quality issues in microgrids [33, 56], as well as advanced microgrid controls better able to prevent damaging transients and promote efficient power management [30, 34, 38, 51, 53, 57].

This has also resulted in a need to develop test systems able to simulate grid behavior on microsecond timescales. Such systems, like those developed by Typhoon HIL, are able to receive signals from microgrid controllers and component controllers (for example inverters and fossil fuel gensets), accurately simulate the behavior of a microgrid receiving these signals including the resulting transients, and output simulated sensor signals back to the controllers. This provides a way to test the ability of system components to respond to microgrid conditions without risking actual microgrid testbeds with expensive components, speeding the development of improved controllers.

Another issue connected with islanding is the interaction of islanded microgrids with the main grid during restoration of normal operations. This is particularly relevant for small installations such as grid-connected solar home systems, which line workers may be unaware of when working on downed power lines. The concern is that islanded systems may result in unexpected live wires, exposing work crews to risk of electrocution. As a result, anti-islanding provisions have been legally adopted and written in to inverter standards (IEEE 1547 and UL 1741). This has caused controversy, as homeowners with solar power should be able to use their solar panels even when the main grid is down. An IEA report found that the perception of increased risk to line workers is largely unfounded [32].

3.1.2. Grid connected systems in the developing world

The cost of outages is significant in the US and Europe, but it can be greater in developing countries where outages are more frequent and more severe. In Bangladesh, a developing country in which 78% of people have electricity access, outages cost the economy 3% of GDP per year [4]. In some cases the reliability of delivery is so terrible that it is a significant barrier to connecting to the grid in the first place. A correlational study found that for every 1% improvement in reliability in Kenya the number of grid connections increases by 0.67%, indicating that individuals would be more willing to connect if reliability were better [45]. For middle-rich families this coefficient rises to a 1.28% increase in interconnections. The penalty of low reliability, then, is keenly felt by consumers and shrinks the pool over which fixed costs must be spread.

A recent report by the Rocky Mountain Institute (RMI) examined interconnected microgrids as a cost-effective way of expanding access to reliable power in Nigeria [37]. It found that due to low collection rates of about 30% and low uptime on distribution networks of about two hours per day, distribution company revenues are significantly lower than costs; indeed the company loses about \$18/year per connected customer. By installing local microgrids connected to the distribution system and charging to service them, RMI found that reliability to the end user would be significantly improved and distribution company losses could be mostly eliminated.

3.2. Off grid systems

A major set of use cases for microgrids is remote areas without access to centralized GTDR infrastructure. It may not be economically viable to run power lines to remote areas, or people living or operating locally may want the benefits of electricity infrastructure and have to pay for it themselves. Military forward operating bases frequently have no centralized grid access. Mobile platforms such as ships require microgrids. The components used to build these systems vary from equipment borrowed from the distribution system, to the more specialized kit needed to interface with shipboard controls.

Additionally, small off-grid solar home systems (SHSs) are frequently an economical way to provide lighting and other basic electrical services in remote areas. This is a rapidly growing industry active in Latin America, Sub-Saharan Africa, and Southeast Asia. Almost one billion people worldwide lack access to an electric grid. Their energy needs are largely met through burning biomass, kerosene and diesel. They use these fuels predominantly to light their homes, charge cell phones, and cook food. While many of these people cannot afford to purchase a solar home system outright, they are able to spend on the order of $10 per month purchasing electricity that would otherwise be spent on kerosene and diesel (the energy requirements for cooking are too high as of yet for SHSs to be cost-effective). Upon applying these existing fuel budgets to the energy needed for LED lighting, phone charging, and efficient televisions, it becomes apparent that many people in the developing world are able to afford a price per kWh of energy that greatly exceeds rates charged in the developed world (table 1). This opens a business opportunity for companies to sell solar home systems to customers in the developing world and recoup costs through a ‘pay as you go’ model.

Technology	**Consumption/ Day (kWh)**	**Cost/Month (USD)**
LED Light	0.15	$2.32
Television	0.3	$4.58
Cell Phone	0.5	$7.63
Cooking	14	$217

Table 1: Examples of energy use in the developing world. Given are estimates of daily power consumption. Monthly cost estimates assume $0.50 USD/kWh charged for power, compared to $0.12/kWh in the US. This high rate corresponds to about a two-year payback period assuming $1USD/Watt solar installation and $200/kWh batteries charged every day, neglecting all other costs. In practice, SHS companies are able to charge more than $1USD/kWh in many cases.

This would appear to be a paradox: the world’s poorest people can afford electric rates much higher than those in developed countries. One way to understand it is that **in the developed world we do not value a marginal unit of electricity very highly.** That marginal unit - which we may use to keep the lights on in a room that no one is in or to run an extra refrigerator in the garage - defines what we are willing to pay for electric service. In classical economics, the market price is the price at which supply and demand curves intersect: the price paid for the least valuable marginal unit of consumption and the most expensive marginal unit of production. **However, the value of the first unit of electricity consumed - the marginal unit that makes the difference between having LED lighting or a cell phone at all versus being completely without electricity - is very high.** In a classical economic analysis the area under the demand curve greater than the actual amount paid is called consumer surplus, and it is high in the electrical system because electricity is a central element of our lives whilst being a small part of our monthly budget. **In rural areas of the developing world, where supply is limited, market prices are set by those first marginal units of power consumed and are thus much higher.**

Many companies are producing solar home systems for sale in the developing world using a pay as you go model. They include d.light, M-KOPA Solar, BBOX, M-PAYG, and Off-Grid Electric. These companies face many barriers including the need to raise capital upfront, the risk that SHS systems will be stolen, the risk that they will break and not be able to be economically serviced, and regulatory risk as many of the countries in which they operate could change relevant laws. Many of these companies are using technologies such as rural cell networks and mobile payments to great effect, allowing them to remotely monitor systems and collect fees cheaply. At least one, M-PAYG, is using a blockchain-based payment solution.

4. Interoperability

Report 2.3 will discuss interoperability and communications protocols in the energy system as a whole. This section will cover two topics relevant to microgrids specifically.

4.1. Microgrid controllers and standards

Microgrid control systems are an active field of academic research. Given some set of optimization criteria that may include power quality, reliability, generation cost, individual personal preferences, carbon emissions, and control signals from third-party aggregators given a say over individual assets, these systems aim to optimize device behavior. At a high level, it is unclear how microgrids of the future may want to balance these different demands. For example, some microgrids may want to provide interfaces for third parties to have a large degree of control over distributed assets. Optimization within this framework may conflict with optimization from a local cost-minimizing perspective [47].

Even when the desired optimization behavior is agreed on, there are a wide array of methods being developed in order to achieve them. Strategies developed for implementing microgrid control systems include centralized controls based on linear and non-linear optimizers, swarm and multi-agent algorithms, and various machine learning techniques [44]. Crucially, the types of high-level behavior desired aren't agreed upon beyond some basic functions such as assurance of power quality metrics and the ability to switch between islanded and grid-connected modes. As such, the IEEE standards defining microgrid controllers [25] and testing procedures [26] are extremely general aside from these basic functions. In particular, while the testing standard defines a procedure for testing it does not specify which scenarios are to be tested in this procedure.

At a lower level of abstraction as well, many of the communications protocols between microgrid components are proprietary and this results in difficulty when trying to assemble a system. These will be discussed in Report 2.3.

4.2. Modular microgrid systems

A major barrier to microgrid installation, as mentioned above, is that each system must be independently designed based on the specifics of a project. Because equipment coming from different vendors may not be interoperable, significant effort must be expended both choosing components and configuring them to work with each other. Because payback periods are highly dependent on component sizing [29,31], microgrid systems can be difficult to upgrade. Companies are attempting to overcome these problems by developing modular components that scale more gracefully.

Figure 7: One unit of a Power-Blox system. A combined energy storage system with a controller enables swarms of modular, interconnected devices to underpin a grid at any scale. It should be noted that these devices sell for about an order of magnitude more than Li-Ion batteries, at roughly $2000/kWh for the Li-Ion version.

Two subsystems that enable modularity and interoperability are the microgrid controller and storage units such as batteries. In order to have a truly modular system, controllers must be able to coordinate between large numbers of components. Storage enables components to interoperate over different currents and timescales, by breaking the requirement that power in must equal power out at every point in time. Some companies have based an interoperable system on a combination of storage and controller units. Power-Blox [18], for example, enables swarms of modular units to be connected in order to power a microgrid at (theoretically) any scale. One unit is shown in figure 7. Similarly, Plug-The-Sun's Raygo [17] system combines a controller, battery and payment platform in order to combine modular storage and controls with a pay-as-you-go business model. While these systems are smaller scale and would be expensive to deploy for a substantial microgrid, Go Electric [15] has developed a similar concept for larger-scale military and campus installations.

5. Microgrids vs. GTDR

The GTDR system and auction-based power market is founded on two basic assumptions. The first of these is that centralized generation of power is the cheapest way to give customers a reliable electricity supply. The second assumption is that the marginal cost of generation is a high proportion of the generator's fixed costs. These assumptions look increasingly flimsy. As the power system evolves, small to medium-scale distributed assets with low or zero marginal generation costs may increasingly become the cheapest way to provide reliable power. In this case, the bulk power system may be superceded by a network of microgrids.

It was discussed previously that the annual cost of outages in the US is on the order of $100B, and that the desire for reliability is a major factor in the installation of microgrids. In addition to this, both the frequency and the duration of outages are getting steadily worse. Reliability is measured through the System Average Interruption Frequency Index (SAIFI) and System Average Interruption Duration Index (SAIDI). A study over 2000-2009 found that SAIFI is increasing by abou 2% and SAIDI by about 5% annually, averaged over the entire united states [35]. This indicates that both the frequency and the duration of outages is worsening with time, which would be expected to make microgrids more attractive in the future. Another study found a similar increase over the nine years to 2013, and showed that the increase was due mainly to a greater number of extreme weather events [43]. During the nine years to 2012, there were 679 widespread power outages in the US caused by severe weather. It was estimated that these outages cost the economy $18B-$33B per year, and perhaps twice these figures on years with very extreme events [48]. This annual cost is a significant and growing part of the estimated $115B cost of outages overall presented earlier.

This trend, that the centralized GTDR system is becoming more unreliable due to extreme weather, is expected to continue due to the increased likelihood of extreme weather events caused by climate change. While during the period from 1980-2016 the average annual number of weather events incurring one billion dollars of damage or more was 5.8, the average over the five years to 2017 was 11.6. Additionally, 2017 saw by far the most total damage done at $300B. [52]. (These numbers are US-only, and adjusted for inflation.) It may be possible to mitigate this risk through the 'hardening' of GTDR infrastructure. However, microgrids represent an alternative mitigation strategy that is arguably more robust by its fundamental design.

The second assumption underlying the centralized GTDR system is that the marginal cost of generation is a significant portion of the total operating cost of a power plant. This is important because of the economic model underpinning the bulk power system. In this model, power is sold at auction (as described in more detail in report 1.1). Generators bid offer prices into the bulk power system, and a supply curve is constructed based on the aggregate of all offers as shown in figure 8. The clearing price is determined to be the cost of production bid by the marginal producer, and all other generators are compensated based on this price (in addition to modifications based on transmission constraints and losses). The marginal producer then makes no profit, while generators able to produce power at lower prices do make a profit.

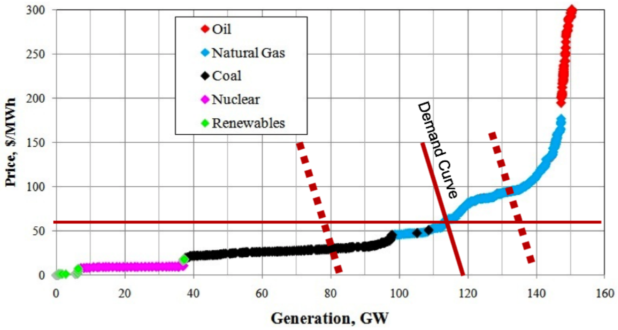

Figure 8: An example supply curve. Power from various generation facilities is bid into the bulk power system. The market clearing price is determined by the intersection of supply and demand, and entities with marginal costs below the market clearing price generally make a profit. From [8].

Crucially, this system produces a strong incentive to bid one's marginal cost of production into the market. If a generator bids higher than the marginal cost, they run the risk of not being chosen to produce and instead sitting idle. If a generator bids lower than the marginal cost, they run the risk of being called on to produce at a lower rate than their real marginal cost and thus losing money on each kWh generated. This system works well when the marginal producer's marginal generation cost is a high fraction of their total operating cost, because they will be compensated a high fraction of that total cost. Producers able to produce at lower costs, then, will produce a profit which will allow them to recover fixed costs. As shown in figure 9, this assumption holds when the marginal producer is a coal or natural gas plant.

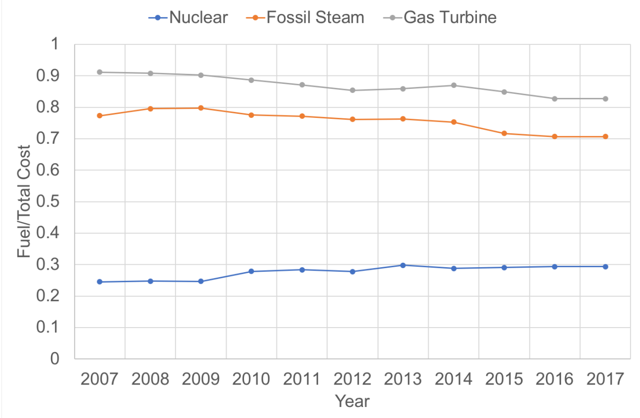

Figure 9: The ratio of fuel costs to toal (operations plus maintenance) cost for three technologies found in the traditional GTDR system. Coal and natural gas plants have high marginal costs relative to fixed costs. In traditional energy markets, these technologies have typically been the marginal producers which has allowed them and cheaper technologies (such as nuclear) to recoup fixed costs. Data from the EIA [6].

However, this system does not work well with high penetrations of solar or wind. These systems have a marginal production cost near zero because they use no fuel, and in the case of a subsidized installation they may have a negative marginal cost because they are paid separately to generate power. Negative marginal costs may also be the result of ramp rates: if a generator expects to be needed later in the day it may make economic sense to pay for the right to keep turbines spinning because ramping down would require them to forego future revenue. Thus, when the marginal generator is a solar or wind plant other grid resources have less opportunity to recoup their fixed costs. As shown in figure 10, in California the high penetration of solar has resulted in low or negative wholesale costs during the middle of the day. This has the effect of destabilizing the centralized GTDR system by making it economically unattractive to build new large-scale generation facilities.

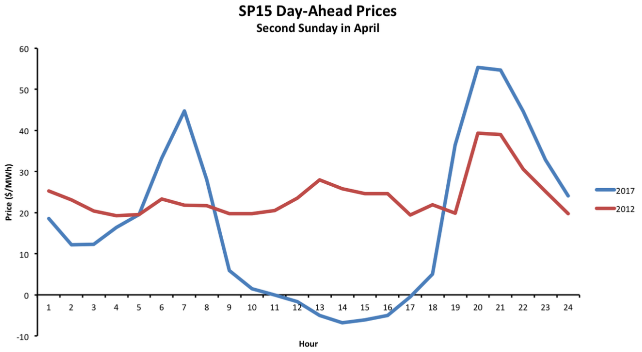

Figure 10: A comparison of wholesale electricity prices in CA on comparable days in 2012 and 2017. Due to increased solar generation, wholesale prices in 2017 are near or below zero for much of the day. This tremendous shift in prices threatens the existing structure of wholesale markets. Data from OASIS [55].

The combination of these factors - decreased GTDR system reliability, increased likelihood of extreme weather events, and a wholesale market that is increasingly unable to support new fossil fuel plants - may progressively improve the value proposition of microgrids and DERs for companies, institutions, individuals and municipalities. Furthermore, as customers leave the GTDR system the fixed costs of transmission and distribution infrastructure must be spread out over the relative few who remain. This could increase the cost of power further, creating additional incentive for customers to leave. This so-called ‘utility death spiral’ may eventually transform our power system from the centralized network that it is today into a decentralized network formed from a constellation of interconnected microgrids.

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