INTEGRATING HIGH LEVELS OF RENEWABLES INTO MICROGRIDS:
Opportunities, Challenges and Strategies

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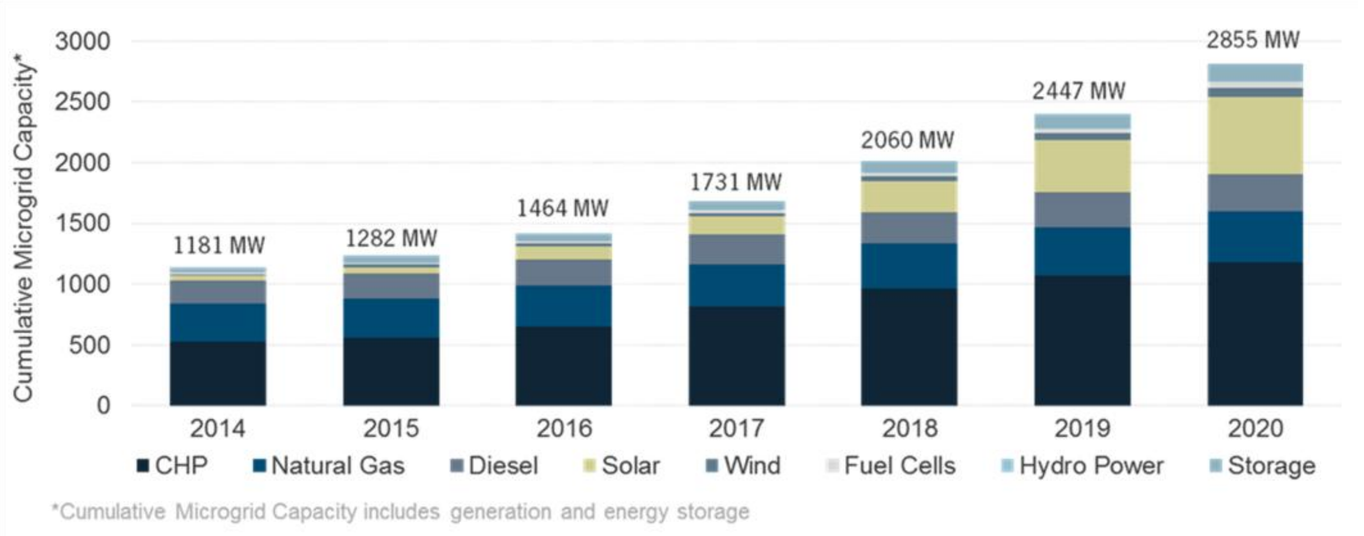
1. INTRODUCTION

The future of microgrids is bright, and increasingly powered by renewable resources. Over the next five years, GTM Research forecasts overall North American microgrid capacity to more than double. Meanwhile, the annual North American market value is expected to nearly quadruple, increasing from $225.7 million by the end of 2015 to $829 million by the end of 2020. Globally, microgrid adoption is also rapidly expanding, with fast-growing Asian markets expected to make up an increasingly larger share of overall deployments.

Figure 1.1 Cumulative Operational U.S. Microgrid Capacity by Resource Under Base-Case Forecast, 2014-2020E



Source: GTM Research

Catalyzed by dramatic decreases in the cost of deployment, the share of renewable energy generation and storage will continue to make up an increasingly larger portion of this growth. These factors enhance the economics of high-renewable microgrids while also improving system reliability and flexibility. This can enable both grid-connected and off-grid microgrids to support wide-reaching benefits, such as minimizing fuel and net energy costs, deferring system upgrade investments, and reducing peak demand or emissions.

Regional and application-specific factors drive customers to develop microgrids. In North America, reliability is the driving force, while in Europe microgrids are being tapped to help manage an already high level of renewable energy sources. For remote industrial operations and developing countries such as India, fuel prices and access to electricity via weak grids continue to drive specialized solutions.

Today, a range of technologies is making the implementation of microgrids more attractive to address a wide variety of applications. From the falling costs of solar power generation and energy storage to advances in control systems, the business case for microgrids is improving by the day.

Economics and customer preferences are driving microgrid owners to integrate higher concentrations of non-dispatchable renewables (50% to 100% of capacity) into their system. This presents technical and operational challenges, including intermittencies, system-balancing problems, power quality issues and more. However, with adequate planning and appropriate technologies (e.g., automated controls and storage), microgrid operators can now effectively address these challenges.

This paper provides an in-depth look at the multifaceted global microgrid market and the technologies and trends that are driving it.

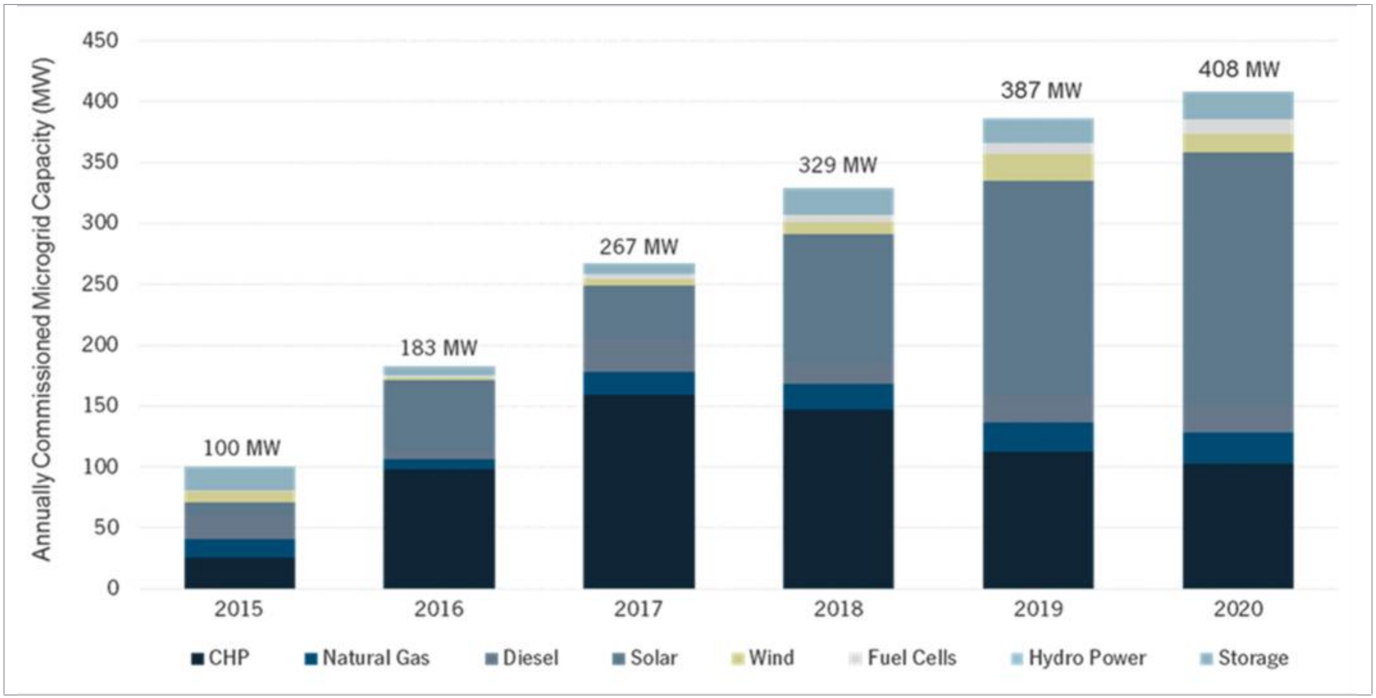
2. MICROGRID, UTILITY AND TECHNOLOGY TRENDS THAT ARE SHIFTING PROJECT ECONOMICS

2.1. Renewables, Reliability and Resilience Spur Microgrid Growth

When it comes to reliability as a growth driver for microgrids, North America is leading the way. The region has reached a tipping point between technology development and wider-scale commercial deployment. Earlier deployments tended toward smaller-scale projects sited in remote communities and at institutional facilities (e.g., universities, research facilities, military bases, etc.), often for technology development and demonstration purposes. But today, several factors are spurring significant commercial-scale expansion in this market.

Over the next five years, U.S. microgrid capacity is expected to more than double, reaching over 2.8 gigawatts by 2020. The strongest capacity growth is expected to come from solar generation, eventually eclipsing today's more common conventional sources of diesel and natural gas (often as combined heat and power). Meanwhile, the costs of solar panels and energy storage systems have dropped dramatically.

Figure 2.1 Annually Commissioned U.S. Microgrid Capacity Forecast by Resource Under Base-Case Forecast



Source: GTM Research

2.1.1. Defining the Need for Reliability

A reliable supply of power is a key driver of the modern economy. However, the need for reliability is not evenly distributed, nor is it threatened by the same factors globally. For certain types of businesses, regardless of where they are located, a reliable electric supply is paramount, such as the data center industry, in which uptime directly impacts profit margins. Microgrids can ensure extremely high reliability while also reducing fuel costs and emissions.

Across the globe, sensitivities to momentary and long-term outages are driving many utilities, customers, and third parties in the mature and the developing world to consider microgrid technologies. In North America, this stems from an increasing incidence of severe weather that has led to widespread multi-day outages over the last several years, as well as concerns over the reliability of aging infrastructure. In Europe, increasing penetration of renewables continues to lead to concerns regarding the impact of the loss of grid inertia, the ability of the system itself to absorb fluctuations in supply and demand. Customers in developing countries continue to suffer from weak grids, lack of supply and poor reliability. Microgrids provide another tool for utilities, customers and third parties to increase reliability, integrate additional renewables, and mitigate costs.

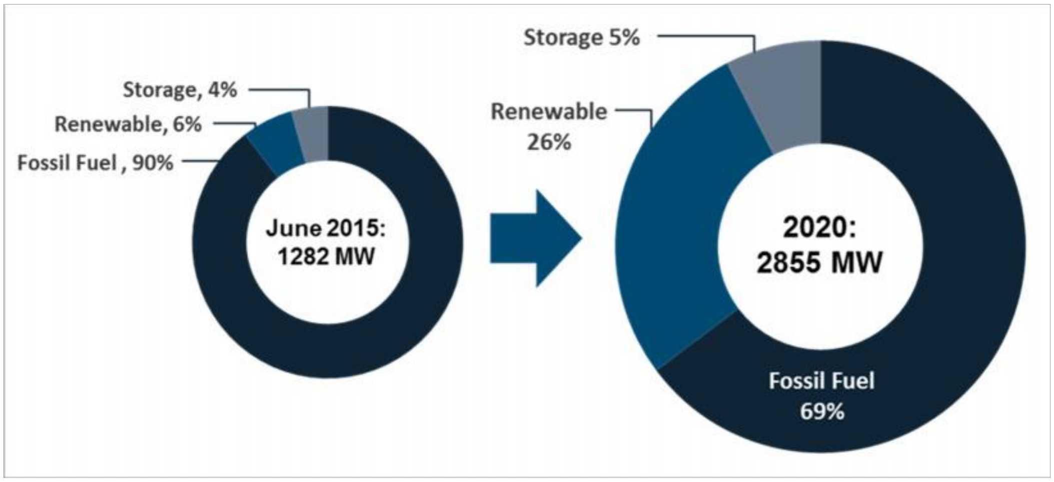
As utilities modernize their grids, regulators explore new approaches to unlock innovative microgrid business models and large customers (such as municipalities, data centers and industrial facilities) become more economically and logistically driven to ensure their own energy security, flexible microgrid solutions will become an increasingly attractive option.

2.1.2. How Renewables Improve Microgrid Economics

Integrating higher penetrations of renewable generation becomes an increasingly viable microgrid option in regions with high electricity rates or volatile fuel prices. For instance, remote communities in Alaska and Canada pay a high premium on importing diesel and must also accommodate the logistical risks associated with transportation. This takes on even more serious implications in areas where the supply of fuel is under threat from geopolitical forces. Although renewable energy production is variable and often intermittent, it provides long-term certainty on operating costs by offsetting fuel consumption and reducing engine run times.

As shown in the chart below, the North American microgrid market to date has relied primarily on conventional resources, specifically diesel- and natural-gas-fired generation. However, advances in underlying technologies are initiating a rapid change to the status quo. In particular, solar PV generation is emerging as a promising building block of next-generation microgrids. That’s good news for American microgrid operators, but also for remote and developing areas looking for a way to build self-sufficiency.

Figure 2.2 Present and 2020 Cumulative Operational U.S. Microgrid Capacity



Source: GTM Research

An effective microgrid platform is crucial for accommodating a high level of renewables — considering not only the energy (kilowatt-hours) but also instantaneous power (kilowatts). For example, renewable capacity might account for 50% of overall annual energy consumption of a given microgrid, while at certain times of the day, renewables may provide anywhere between 100% of the power generation (e.g., solar production equal to or exceeding load at midday) to none at all (e.g., diesel power only at night).

Energy storage (both batteries and flywheels) can further enhance the value proposition of high-renewable microgrids. For instance, by adding energy storage to a solar-diesel microgrid, an operator can shift excess daytime solar generation to meet demand after sunset. In this way, high-renewable microgrids can increasingly displace conventional (and typically more costly or polluting) generation sources, as well as utility grid electricity purchases. This kind of investment can directly reduce customer operational costs (e.g., fuel costs, utility energy consumption, demand charges, etc.), while also managing risks to energy supply and project finance.

While all of these factors tend to enhance the economics of a microgrid, each deployment is unique, with its own challenges and functional objectives. Typical economic drivers that determine the optimal penetration of renewables include:

- Installation costs for renewables and energy storage
- Fuel and power costs (and security of supply)
- Costs associated with outages
- Deferral opportunities for transmission and distribution
- Project lifetime and cost of capital

2.1.3. Microgrids as an Alternative to Capital Investments

In some instances, the implementation of a new microgrid may offer a cost-effective alternative to building additional generation or expanding transmission and distribution capacity.

For a remote or off-grid situation, it may be less expensive to build a greenfield microgrid to serve a community than to build the requisite transmission needed to connect it to the existing larger grid, depending on the resources available to that community. The microgrid may also offer greater reliability than a link to a distant main grid.

Grid-connected microgrids can also reduce projected costs of service for the local utility. If a feeder or substation upgrade is required to meet increasing demand or address power quality concerns, a local microgrid with on-site generation could meet the need without the significant capital investment associated with conventional solutions.

Clearly, each case must be evaluated individually, but as microgrid control technologies continue to advance and utilities gain experience integrating them within their distribution systems, microgrids will become a more attractive tool to address capacity, reliability and power quality concerns.

3. TECHNICAL CONSIDERATIONS FOR MANAGING HIGH-RENEWABLE MICROGRIDS

3.1. Renewable Penetration and Microgrid Objectives That Drive Technology Choices

Microgrids are more than an alternative way to maintain energy supply or cut operational costs for a facility, campus or municipality. They are a platform that can enable key power system functions which, in turn, can help microgrid owners achieve a variety of higher-order objectives, including:

- Grid reliability
- Resilience in the face of severe weather or natural disasters
- Meeting environmental targets (such as emissions reductions)
- Shrinking operating expenditures
- Securing cost-effective, long-term energy supply

In order to determine the best mix of generation, energy storage and control technologies for a particular project, it is important to evaluate microgrid projects based on a comprehensive methodology such as ABB's "8 S" concept. The 8 S's are a set of power system functions that microgrids may provide:

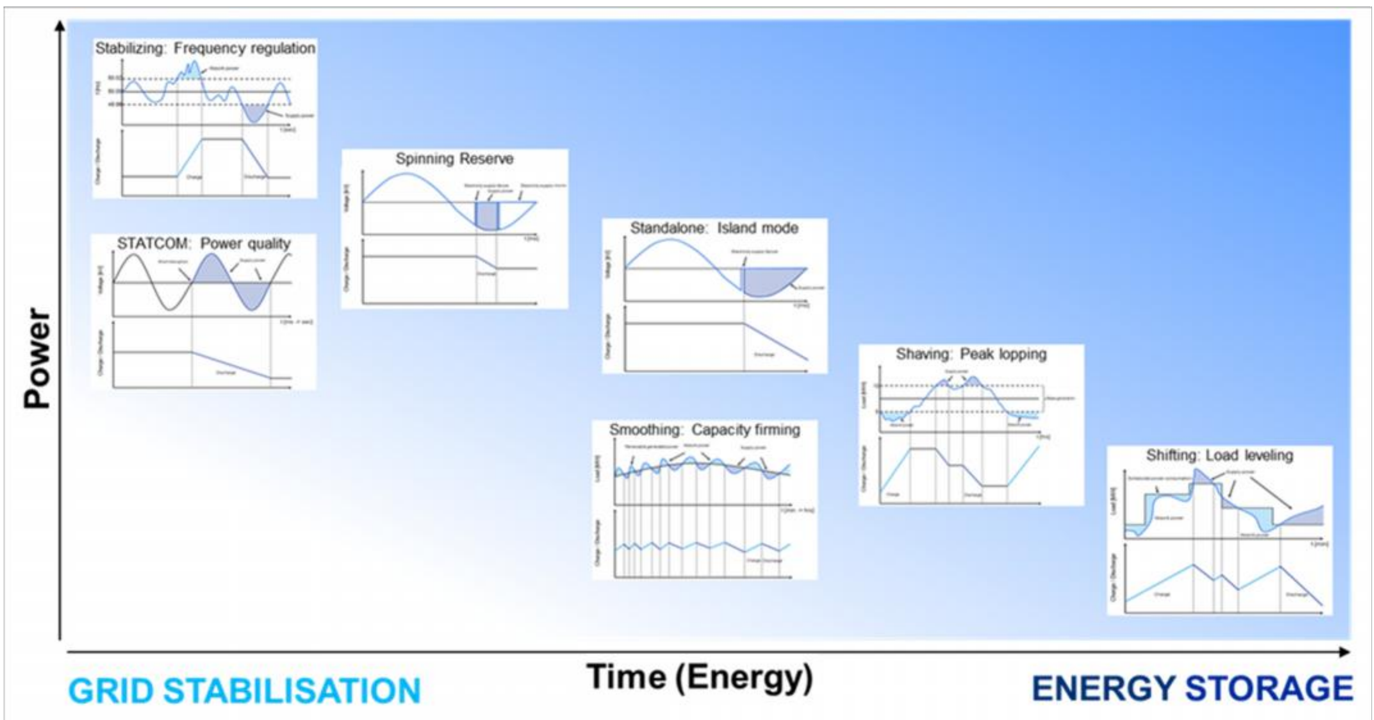
1. Stabilizing
2. Spinning reserves
3. STATCOM (static synchronous compensator)
4. Standalone operation
5. Smoothing
6. Shaving
7. Shifting
8. Seamless transfer

Supporting the microgrid owner's desired objectives may require one or more of these functions. In any microgrid deployment, the underlying components and system configuration determine which of these services are required to deliver owner objectives and maintain microgrid functionality. Therefore, when planning a microgrid deployment, upgrade or expansion (especially involving high levels of renewables integration), it's helpful to prioritize the owner's objectives and consider which microgrid services might best support those ends. This decision-making process can guide technology choices, as well as highlight the long-term value of upfront investments in hardware and software infrastructure.

If a cleaner energy mix is the primary objective for a grid-connected microgrid, it may suffice to simply install a low level of renewable generation and leverage the grid to balance fluctuations in local production. Additional investments in complementary assets (such as storage) may be justified if high-priority objectives include maximization of the proportion of renewable energy consumed on-site, reducing demand charges through peak shaving, or participating in utility load-shifting programs.

In general, where the desired penetration of renewables is higher, and where loads are more complex (less flexible or highly dynamic), a microgrid will need to incorporate additional functions from the list of 8 S's. This is achieved through careful selection of generation assets, energy storage, and controls.

Figure 3.1 Seven of ABB's Eight S's Microgrid Planning and Operation Framework



Source: ABB

3.2. Stabilizing: Frequency Regulation

Maintaining a steady frequency is crucial for keeping any power network (utility grid or microgrid) balanced and operational, as well as for protecting sensitive loads. If generation and load become unbalanced in a power system, a rapid series of automatic protection processes must be executed to restore the system to stable operational conditions. But if such procedures prove insufficient, auxiliary strategies can enable rapid load shedding in order to prevent a total system collapse.

Effective frequency regulation is often more challenging in a microgrid than across a large interconnected grid. Utility system operators typically have access to a much larger and more diverse portfolio of grid assets that can be used to stabilize frequency. When a microgrid is grid-connected, the macro-grid serves as a firm frequency reference and will buffer power imbalances within the microgrid. However, when in islanded operation mode, individual microgrid components have a relatively greater impact on system stability. A microgrid is likely to operate with only a few generators running at any time, and renewable fluctuations or the complete loss of one asset can represent over half of the on-line operating capacity.

A microgrid's ability to instantaneously react to frequency fluctuations in real time is essential for maintaining system stability. Either a flywheel or battery energy storage system can provide this capability. Battery storage is popular, but frequent, high-capacity charge and discharge cycles can erode batteries, significantly shortening their useful life and hindering overall performance.

On Kodiak Island, Alaska, the Kodiak Electric Association has installed two flywheel units to stabilize a remote microgrid, which also includes a relatively large wind farm, as well as a highly dynamic industrial load. These flywheels specifically:

- Provide frequency regulation and demand smoothing for a new crane
- Relieve stress on existing battery systems, extending their useful life
- Help manage intermittency from a 9-megawatt wind farm
- Reduce reliance on diesel generators

3.3. Spinning Reserve

Providing adequate spinning reserve capacity is vital to maintaining high-penetration microgrids. Fast-ramping generation and storage assets can rapidly compensate for the sudden loss of renewable generation that can result from intermittent cloud cover or wind lulls.

Flywheels or batteries can serve as auxiliary generators with ride-through capability. This can span from seconds to minutes for flywheels, or from minutes to hours for batteries. For instance, if production from a 1.5-megawatt wind turbine were suddenly to be lost, storage could seamlessly deliver that lost capacity while diesel or natural-gas-fired generators are brought on-line.

A microgrid control system is necessary in order to manage the system's spinning reserve, ensuring that there is enough on-line capacity to mitigate the loss of generation or an increase in load.

3.4. STATCOM: Voltage Control

The power system considerations discussed in the two previous subsections deal with active power, but reactive power is also crucial to power system stability. When voltage levels drop in a power system, impacts are very visible to end users in the form of dimming lights, equipment malfunctions, etc. Utilities primarily depend on synchronous generators, as well as a range of assets (such as capacitor banks and static VAR compensators), to maintain voltages within certain limitations (generally 5% of unity).

When in grid-connected mode, microgrids can often depend on the utility for voltage support. However, in islanded mode, the microgrid operator must be able to independently support power quality and accommodate any changes to system voltage levels.

If a microgrid has on-line thermal generation (such as a reciprocating engine), the synchronous machine can be used to supply reactive power and dynamically regulate system voltages. However, if a significant amount of power is being generated from renewables, other devices must be used to generate these VARs. Several devices can be used in microgrids to supply these functions, including STATCOMs, which supply fast-acting continuous voltage regulation. If a microgrid already has an installed energy storage system, the front-end inverter of this flywheel or battery storage devices can typically fulfill this role when properly sized.

3.5. Standalone: Grid Referencing in Islanded Mode

When a microgrid is operating in grid-connected mode, the utility provides a convenient, reliable voltage and frequency reference to maintain microgrid synchronous operation. But when a microgrid is islanded from the grid, it must rely on its internal assets to provide this reference. Currently, most islanded microgrids rely on synchronous fossil-fuel-fired generators to provide that reference.

A unique challenge exists for islanded microgrids operating completely on renewable generation. Such a system is often entirely inverter-based and lacks any spinning generators. Therefore, it must rely on intelligent inverters coupled with storage, which can operate in voltage and frequency control mode to provide its own reference points. Managing this process is one of the core control functionalities of a fully renewable microgrid.

3.6. Smoothing: Capacity Firming

In addition to addressing how power intermittencies of 1 second or less affect system stability, a microgrid must also be able to manage overall renewable production patterns in relation to a system's portfolio of flexible and non-dispatchable load.

A microgrid must accommodate slight changes in the renewable contribution to the total grid capacity. When renewable input deviates from its forecasted pattern, energy storage or dispatchable generators are often used to bridge this gap. Depending on the size and duration of these fluctuations, thermal generators may not be capable of absorbing them without issue, since this type of generation typically has ramp rate limitations. In such cases, storage may be required to provide the necessary "shock absorption," as it can offer extremely fast ramp rates. Effectively, this is a different form of stabilization, focused on compensating for renewable fluctuations by providing ramp rate control in the 1-second to 10-minute timeframe.

Flywheel storage can be, and often is, used to address shorter deviations. On Flores Island (in the Portuguese Azores), a flywheel system and controls are configured specifically to smooth out wind power fluctuations. However, flywheels become increasingly inefficient as fluctuations persist. For longer durations (typically more than 1 minute), the technical argument for battery storage becomes stronger.

3.7. Shaving: Peak Load Management

Moving into the hour timeframe, grid-connected microgrids have the ability to leverage internal resources through effective peak-load management. This can maximize economic benefits from tariff-related opportunities, such as demand charges or peak pricing.

To help reduce demand charges and/or reduce the amount of microgrid capacity that needs to be installed, microgrid operators can leverage internal resources during periods of internal peak demand. Dispatchable generators can serve as internal peaking plants, firing up during hot summer afternoons. Meanwhile, renewable energy can be stored in batteries and reallocated to times of peak demand. Similarly, microgrids can take advantage of controllable loads to reduce peak demand by implementing an internal demand response strategy.

Additionally, microgrid operators can offer load-shaving capacity to utilities as a service. For instance, through an agreed-upon compensation structure, a utility may request load-shedding or the dispatch of generation from a microgrid for congestion relief to a stressed line.

3.8. Shifting: Leveling Loads by Managing Their Timing

Peak shaving focuses on reducing peak power demand. In contrast, load and generation capacity-shifting addresses how to align longer-term overall energy consumption with generation and utility rate profiles. Through adequate incentives, a utility might motivate a microgrid operator to shift load from midday operations to off-peak periods. And for remote microgrids, capacity-shifting can help match renewable generation output to load consumption.

Operators may also opt to utilize longer-duration (low-power, high-energy) batteries to help shift both generation and load to more practical or economical timeframes. While such strategies further optimize microgrid operation on a daily basis, they can also be implemented during crises. For instance, a data center equipped with thermal storage can provide emergency cooling during outages.

3.9. Seamless: Transferring From Grid-Connected to Islanded Operation Without Interruption

Grid-connected microgrids can operate in either grid-connected or islanded mode. The transfer between these sources without service interruption is a key function. Such seamless transfers are usually initiated by microgrid operators if certain load and distribution system conditions are forecasted. For instance, an operator may choose to island the system from the grid through the SCADA interface when a severe weather warning is issued. Once the severe weather has passed the microgrid can be seamlessly synchronized back to the distribution system. Forecasted events provide opportunities to ensure reliability, while some unscheduled events such as faults on the distribution grid or within the microgrid may lead to short-term interruption of the supply to the microgrid depending on the type of protection systems and their setup.

4. CONTROLS ARE ESSENTIAL FOR BALANCING AND OPTIMIZING MICROGRIDS

4.1. Energy Balancing

Microgrid controls must promote a high degree of flexibility to changing circumstances and unique considerations. A controls solution that is both effective and economically viable requires a specifically tailored combination of controllers, field sensors and software platforms.

In microgrids, effective and responsive controls are critical because the stakes are so high, considering the scale of operation. For instance, if a microgrid is operating at 80% renewable energy, cloud cover on solar panels could drop that capacity by as much as half in under 60 seconds. For a utility grid, such a percentage drop in generating capacity would be catastrophic — the equivalent of several nuclear plants tripping offline simultaneously, which would undoubtedly result in widespread blackouts. On a microgrid, however, this is a routine occurrence.

Microgrid controls must be able to deploy a combination of applications to rapidly accommodate sudden, extreme fluctuations and other challenges. Having a clear understanding which of the eight services represent the highest priority in a given microgrid can help guide control architecture and logic choices. Latency is a paramount consideration for controls, as are system configuration options that might minimize reaction time.

4.2. Optimization: Meeting Specific Microgrid Targets

If the sole requirement of a microgrid was to maintain energy balance, then when renewable resources fluctuate, they could simply be turned off, and diesel or gas generators could be switched on. But in high-renewable microgrids, operators usually seek to achieve more than mere reliability.

Typical functional objectives for microgrids may include:

- Maximizing the amount of renewable energy consumed
- Minimizing greenhouse gas emissions
- Minimizing fuel consumption to reduce dependency on fuel imports
- Maximizing overall economic benefit
- Operating at the highest possible level of reliability

Each of these goals offers benefits and tradeoffs. For instance, minimizing emissions may require operators to run diesel generation at optimal loading for the emissions per kilowatt-hour. Or, if seeking to maximize renewables consumption, an operator may need to rely more heavily on constant cycling of energy storage to smooth out the power fluctuations intrinsic in high-renewable systems.

Under certain criteria, individual functional objectives often do overlap. This is an opportunity for microgrid operators to consider, and perhaps meet, multiple objectives simultaneously. Applying weighting factors to prioritize each goal can help operators choose whether to implement a multi-optimization function.

Usually, high-renewable microgrids prioritize both minimizing fuel consumption and maximizing renewable generation. These twin overarching goals, along with other considerations (such as resource mix), directly influence the development of a microgrid's software algorithms and its control architecture. For instance, a remote microgrid that includes wind turbines would need to rapidly respond to deviations (executing battery charging and discharging, as well as dispatchable generator ramping).

In grid-connected microgrids, minimizing operational costs tends to be a top priority. External programs are an opportunity not only to reduce operational costs, but also to yield new revenue streams that ultimately support the microgrid business case. However, coordinating with external programs can make it more challenging to weigh tradeoffs, since operators must also factor in rate structure, demand charges, demand-response opportunities, and other factors. The optimization engine and associated controls infrastructure must be able to dispatch internal resources in response to real-time price signals and utility or wholesale market dynamics.

When microgrids engage in utility reliability and economic programs, utilities typically desire at least some visibility into the operation of the microgrid, and potentially the ability to execute some control in order to have a timely response (e.g., microgrid disconnect). Thus, to some extent, utilities can envision viewing third-party-owned microgrids as assets on their system.

This transparency can be mutually beneficial. For instance, if the controllers for a microgrid can see when the price for electricity on the real-time market suddenly goes negative, it might dispatch a battery to store as much power from the utility as possible while that price condition persists.

4.3. Reliability of Controls

The reliability of the microgrid controls themselves – controllers, sensors and communication networks – are often overlooked. This leads many customers to deploy dedicated, low-latency (often less than 10 milliseconds) communication network linking controls and microgrid assets. Just as power systems are typically designed with extra generation to account for a unit failure, a control system should be designed to tolerate a failure of an individual element without resulting in a loss of the system. It is necessary to understand what happens to the system if a particular control or communication element fails. The point is to identify and address single points of failure and to create resilience through redundancy and flexibility.

4.4. Islanding and Microgrid Controls

Islanding is a hallmark capability of grid-connected microgrids. However, determining when and how to island, as well as reconnecting safely, requires careful application of control technology.

In order to reconnect, the microgrid must have some information about grid conditions for synchronization, specifically, frequency and voltage set points. With appropriate controls, synchronization can be achieved quickly, generally in less than 10 seconds. Also, controls can make islanding and reconnection operations more seamless (at least during planned transitions), eliminating brief outages that might affect electronics and customer loads (see Section 3.9).

4.5. Controllable Loads and Communication With Other Controls

Generally, interfacing microgrid controls with a utility SCADA system is fairly straightforward, since SCADA is standardized. However, it may not always be appropriate for a SCADA system to interface with all of the control points on a microgrid, since some microgrids encompass a large number of controllable assets (including generation, loads, building automation systems, protection relays and other intelligent electronic devices). From the utility's perspective, simplifying the SCADA interface and the control of the microgrid might mean that the microgrid control system aggregates both load and generation into total figures. This would allow a single point of control for the power interchange between the microgrid and the utility system.

However, this interfacing often isn't easy. There's no single standard for interconnecting with building automation systems and other controllers; these opportunities depend on the devices involved. Therefore, when selecting controls for a microgrid, it may be useful to consider potential compatibilities with existing controllers in order to maximize options for what can be optimized and how.

5. CONCLUSION

Microgrids offer tremendous potential to enhance reliability, resilience, and long-term energy security while also decreasing both fossil-fuel dependence and overall energy costs. Global microgrid capacity is forecasted to grow rapidly over the near term, driven by a range of factors that vary between regions and applications. Whether enhancing reliability and resilience, facilitating the integration of renewable energy sources, or establishing electricity service where there was none before, microgrids are poised to play a major role going forward.

Project design and equipment selection for high-renewable microgrids in particular can significantly affect system objectives and associated technical challenges. For example, proven technologies and control strategies can compensate for the inherent intermittencies created by renewable generation, providing operators with the flexibility to meet a variety of business, environmental and operational objectives.

The microgrid market is undergoing a transformation from a niche technology application to a commercially viable modernization tool serving utilities, institutions and remote communities. As barriers are overcome, high-renewable projects with goals related to reliability, energy cost reductions and grid modernization are expected to be the next growth phase in microgrid development. With the necessary internal system support (frequency stabilization, voltage support, etc.), microgrid operators are able to achieve multiple objectives. These extend beyond behind-the-meter benefits like reliability to include new revenue opportunities from utility and wholesale services.

As microgrid technologies continue to advance and costs decline, business models and regulatory structures are beginning to shift in recognition of the potential benefits these systems offer, both to the end customer and to the utility. Technical challenges remain, but with the right approach and the right tools, microgrid implementations are likely to increase in number and variety in the future.