Pacific Northwest NATIONAL LABORATORY

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Microgrid Handbook for Army Resilience

A Technical Review

October 2025

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Pacific Northwest National Laboratory
Richland, Washington 99354

Foreword

The Army recognizes the need for its installations to operate as independently and efficiently as possible with secure energy and water resource that cannot be limited or shut off by external forces or events, whether natural or man-made. In an effort to make this possible, the Army has identified microgrids as an effective way to achieve the goal of secure power for operations, both for domestic and international installations. This document is designed to educate Army Installation leaders about what microgrids are, options for their components, financing, and operations, as well as other regulatory and technological considerations.

There is no such thing as an off-the-shelf microgrid, however, and extensive study is required to determine individual site needs and available resources before a microgrid itself can be planned. Installations will need to prepare an Installation Energy and Water Plan (IEWP) in accordance with Army Directive 2020-03, *Installation Energy and Water Resilience Policy* (Army 2020). The IEWP process is a systematic approach to planning for the energy and water needs of Army installations and facilities. The IEWP process helps the Army to identify and implement energy and water efficiency measures, renewable energy technologies, and other resilient solutions to sustain critical missions by withstanding an extended utility outage.

The IEWP process is based on the following principles:

- **Resilience:** The IEWP process helps the Army to build resilient energy and water systems that can withstand and recover from disruptions.
- **Efficiency:** Efficiency includes activities to decrease the amount of energy and water required to support Army missions. Army energy and water infrastructure must be adapted to reduce usage to maintain effectiveness and support future capabilities with high-intensity usage.
- **Affordability:** In order to optimize Army energy and water expenditures, investments must be considered both up front and over their life cycle. Energy and water requirements must be met affordably to prioritize resources for significant mission-enabling capabilities.

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List of Acronyms

BESS	battery energy storage systems
CAES	compressed air energy storage
CBM	condition-based maintenance
CERL	Construction Engineering Research Laboratory
CHP	combined heat and power
CIMCRC	Critical Infrastructure Microgrids and Community Resilience Centers
DER	distributed energy resource
DLA	defense logistics agency
DoD	U.S. Department of Defense
DOE	U.S. Department of Energy
ECMs	energy conservation measures
EMS	energy management system
ERCIP	energy resilience and conservation investment program
ESCO	energy service company
ESPC	energy savings performance contract
EVs	electric vehicles
FAR	federal acquisition regulations
FEMP	Federal Energy Management Program
FES	flywheel energy storage
GW	gigawatt
HMI	human-machine interface
IBM	improvement-based maintenance
IBR	inverter-based resource
IDIQ	indefinite-quantity
IEEE	Institute of Electrical and Electronics Engineers
IEWP	Installation Energy and Water Plan
IoT	Internet of Things
kW	kilowatt

kWh	kilowatt-hour
LHC	land holding command
MCS	monitoring and control system
MICC	mission and installation contracting command
MILCON	military construction
MW	megawatt
MWh	megawatt-hour
NARUC	National Association of Regulatory Utility Commissioners
NASEO	National Association of State Energy Officials
NWA	non-wires alternative
O&M	operations and maintenance
OCAR	Office of the Chief, Army Reserves
PCC	point of common coupling
PLC	programmable logic controller
PMU	phasor measurement unit
PPA	power purchase agreement
PUC	Public Utility Commission
PV	photovoltaic
RBM	risk-based maintenance
RCM	reliability-centered maintenance
REP	renewable energy procurement
RTU	remote terminal unit
SCADA	supervisory control and data acquisition
SMG	small- and medium-sized grid
SPE	special purpose entity
TBM	time-based maintenance
TOU	time-of-use
TPM	total productive maintenance
UESC	utility energy service contract

USACE	United States Army Corp of Engineers
VAR	volt-amperes reactive

Executive Summary

This Microgrid Handbook was assembled to serve as an introduction to microgrids for all Army Reserve energy system stakeholders. This handbook contains an introduction to the concept of a microgrid, an overview of its components, design, planning, and deployment, a look to the future of microgrids, additional topics of relevance, as well as a set of case studies. For ease of navigating this document, an interactive footer has been added to jump between sections. From any page in the document, click on any of the icons described below to navigate to that section.

Table of Contents: Quickly jump back to the table of contents any time by clicking the voltage source icon on the left side of the footer image.

Section 1. Introduction to Microgrids and IEWP Process: After introducing the IEWP process, this section begins by answering the question, "What is a microgrid?" Microgrids are self-contained energy systems that can operate independently of the main power grid. They are becoming increasingly popular as a way to improve energy resilience and reliability, especially for critical infrastructure such as military installations. This document provides guidance on the design of resilient microgrids for military installations. Key features of a microgrid are introduced in this section, including electrical one-line diagrams, supervisory control and data acquisition (SCADA) systems, relays and coordination studies, and phasor measurement units (PMUs). Next, the benefits, applications, and challenges of microgrids are discussed.

Section 2: Microgrid Components – Microgrids are typically made up of the following components:

- Energy generation systems produce electricity for the microgrid. Generators can be fueled by a variety of sources, including diesel, natural gas, propane, hydrogen, and renewable energy sources such as solar and wind.
- Energy storage systems store electricity generated by the microgrid for later use. Energy storage systems can help stabilize the microgrid and provide backup power during outages. Battery energy storage systems (BESS) are the most common type of energy storage system.
- Microgrid loads are the power-consuming devices and systems—ranging from base operational facilities and communication centers to tactical equipment—that support mission-critical functions. Effectively managing these loads is essential to ensure reliable energy distribution and operational readiness in dynamic military environments. Managing loads by determining criticality and reducing energy consumption can have a large impact on sizing of energy generation and storage systems.
- Control systems monitor and operate the microgrid. Control systems assure that the microgrid is operating safely and efficiently, and that it is meeting the needs of the installation.

This section describes local generation, end-use loads, and energy storage. Microgrid monitoring and control systems (also known as SCADA – Supervisory Control and Data Acquisition systems) are then introduced, followed by a section discussing utility interconnection, and concluding with other microgrid components. Current issues in BESS safety are also discussed.

Section 3: Microgrid Planning and Design – When designing a microgrid for a military installation, there are many factors to consider, including:

- Mission requirements: The microgrid must be able to meet the mission requirements of the installation. This includes considering the types of equipment and facilities that need to be powered, as well as the criticality of those loads.
- Resilience: The microgrid must be able to withstand and recover from disruptions, such as cyberattacks, natural disasters, and power outages.
- Cost: The microgrid must be economic to build and operate. Cost-benefit analyses should quantify potential savings from enhanced resiliency and reduced downtime and consider the operations and maintenance tail while also evaluating the return on investment through improved energy efficiency and operational readiness. Additionally, funding models and potential partnerships—such as public–private partnerships or defense budget allocations—can play a crucial role in ensuring that the microgrid is both affordable and sustainable over its operational lifespan.
- Security: The microgrid must be secure from cyberattacks and other threats.

This section begins with site selection, then provides insights into the design, implementation, and operation of microgrids. The document includes sections that are relevant to microgrid development, including:

- Microgrid Planning: This section discusses the importance of developing a comprehensive microgrid plan. The plan should identify the microgrid's goals and objectives, as well as the technical, economic, and environmental factors that need to be considered.
- Microgrid Design: This section discusses the key design considerations for microgrids, such as the selection of microgrid components, the sizing of the microgrid, and the design of the microgrid control system.

Section 4: Microgrid Operation – This section discusses the key operational considerations for microgrids, such as the development of a microgrid operating plan, the training of microgrid personnel, and the monitoring and evaluation of microgrid performance. Microgrid control systems monitor and operate the microgrid to assure that it is operating safely and efficiently, and that it is meeting the needs of the installation. Microgrid control systems typically perform the following functions:

- Load balancing ensures that the load is evenly distributed across the microgrid. This helps to prevent overloading of the microgrid and improves efficiency.

- Frequency and voltage regulation ensures that the microgrid operates at the correct frequency and voltage. This is important for the safe and reliable operation of the microgrid and the equipment that it powers.
- Islanding allows the microgrid to isolate itself from the main power grid during a power outage. This is important for the safety of the microgrid and the main power grid and the people who work on it.

This section also highlights microgrid cybersecurity. Microgrids are vulnerable to cyberattacks, just like any other computer network. It is important to implement cybersecurity measures to protect microgrids from cyberattacks. Cybersecurity measures for microgrids may include:

- Network security measures protect the microgrid's network from unauthorized access (e.g., firewalls, intrusion detection systems, and access control lists).
- Endpoint security measures protect the microgrid's devices from malware and other threats (e.g., antivirus software, firewalls, and patch management).
- Operational security measures protect the microgrid's operations from human error and insider threats (e.g., training personnel on cybersecurity best practices and implementing procedures for responding to cyberattacks).

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Section 5: Microgrid Financing and Regulations – The microgrid design process can be lengthy and involves financing as well as regulations and regulatory approvals. This section starts with a discussion of Unified Facilities Criteria (UFC) for Resilient Installation Microgrid Design (in draft UFC 3–550–04). The regulation and regulatory approvals process is then described, starting from the scope of the microgrid, legislative actions, microgrid-related policies and programs, and regulation of microgrids. A discussion of financing strategies is then presented, including Utility Energy Service Contracts (UESC), Energy Savings Performance Contracts (ESPC), and Power Purchase Agreements (PPA).

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Section 6: Future of Microgrids – The future of microgrids is discussed with microgrid planning, trends in microgrid technology, and challenges and opportunities. This section concludes the primary report content, which provides an overview of the resilient installation microgrid design process. The process consists of the following key steps:

- Needs assessment
- System design
- System modeling and simulation
- System implementation
- System operation and maintenance

By following these steps, installations can design and implement resilient microgrids that meet their energy and water needs, reduce their risks, and improve their mission readiness.

Section 7: Additional Topics – including standards, regulations and examples including military facilities in the United States, Europe, and Asia. Case studies by implementing section are then provided: government, residential, and commercial. The case studies provide information on the microgrid architecture, components, design considerations, and control and operation of these microgrids.

Glossary:– quickly jump to the glossary at any time by clicking the rightmost lightbulb marked "G."

Resources – quickly jump to the resources section at any time by clicking the grounding symbol on the right side of the footer. This appendix provides a list of resources that can be used to learn more about microgrids. The resources include websites, articles, and reports.

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1 Introduction to Microgrids and IEWP process

1.1 What is a Microgrid?

The Department of Energy (DOE) defines a microgrid as a group of interconnected loads and distributed energy resources (DERs)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 and island mode (Ton and Smith 2012). Additionally, the Department of Defense (DoD) commissioned MIT Lincoln Laboratory (MIT-LL) to conduct a microgrid study in 2012, which defined "a DoD installation microgrid as an integrated energy system consisting of interconnected loads and energy resources which, as an integrated system, can be islanded from the local utility grid and function as a stand-alone system" (Van Broekhoven and Judson 2012) (see Figure 1).

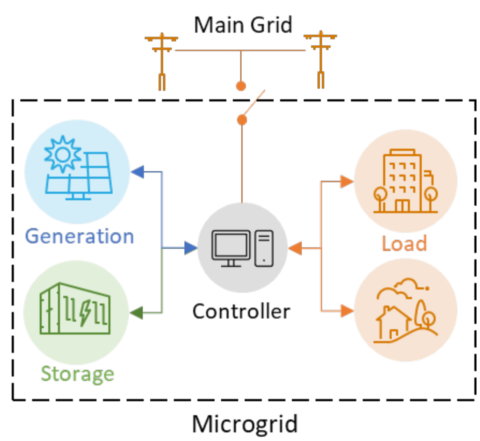

Figure 1. Components of a Microgrid

Unified Facilities Criteria (UFC) 3–550–04, Resilient Installation Microgrid Design, outlines the primary objective of networked standby power systems (e.g., microgrids), which is to deliver resilient, ride-through power to installation operations during extended contingencies resulting from commercial service failure, natural disaster, or cyber-attack. Microgrid systems deliver contingency power to loads inside a facility, a facility cluster, several facilities on one or more feeders, across substations, or an entire installation campus. Islanded operation is a fundamental characteristic of all microgrid designs. A microgrid's primary benefit is its ability, as a bounded system, to disconnect from the commercial grid during an emergency and deliver resilient, ride-through power with optimized off-grid endurance (UFC 3–550–04 2024).

These criteria provide guidance on microgrid technical requirements, performance metrics to inform design, sequence of operations, commissioning and validation, and sustainment. UFC 3–550–04 is not intended to govern microgrid research, development, or emerging technology.

A microgrid is also a self-contained power grid that can operate independently of the main electrical grid. Microgrids typically consist of a variety of DERs, such as solar panels, wind turbines, and diesel generators. They may also include energy storage systems and demand-response devices. A microgrid must have the capability to detect an outage from the utility and then isolate to operate independently.

Microgrids can operate in two modes: grid-connected mode and island mode. In grid-connected mode, the microgrid is connected to the main grid and can draw power from it. This grid-connected mode is sometimes used to reduce energy consumption costs from the utility provider, using off-site power to charge the Battery Energy Storage Systems (BESS) and supplying power to nonessential loads.

In island mode, the microgrid is disconnected from the main grid and relies on its own DERs to generate a stable grid signal and provide power to loads. This mode can be used to power mission critical loads for a predetermined amount of time or indefinitely if the BESS, DERs and loads are appropriately sized.

1.2 Key Features of Microgrids

Microgrids are known for three defining features:

- **Distributed energy resources**: Microgrids are powered by DERs, which are small-scale power generators that are located close to the end users. This makes microgrids more resilient to grid outages, as they are not reliant on a single, centralized power source. These DERs may be powered by a renewable resource with inverters, stationary, or mobile synchronous generators.
- **Islandability**: Microgrids can operate in island mode, which means that they can disconnect from the main grid and continue to provide power to their customers. This is important for critical infrastructure that needs to have a reliable source of power. It is important to keep in mind that to island the microgrid it must be shut off to safely disconnect from the larger grid. Therefore certain buildings that require "flickerless" transitions will need individual battery systems to keep them online through the transition to islanded mode.
- **Controllability**: Microgrids are typically equipped with a control system that allows them to be operated and managed in an efficient and secure manner. This control system can be used to optimize the operation of the microgrid's DERs and to assure that the microgrid meets the needs of its customers. The control system can also provide a means to deploy the most cost-efficient energy source to reduce operations costs, which is sometimes used to justify its cost.

Microgrids can be configured in a variety of ways, depending on the specific needs of the installation. Some common microgrid architectures include:

- **AC microgrids**: These microgrids use alternating current (AC) to transmit and distribute electricity. AC microgrids are the most common type of microgrid.
- **DC microgrids**: These microgrids use direct current (DC) to transmit and distribute electricity. DC microgrids are becoming more popular due to their advantages in efficiency and reliability.
- **Hybrid microgrids**: These microgrids combine AC and DC components. Hybrid microgrids offer the best of both worlds, combining the efficiency and reliability of DC microgrids with the flexibility and compatibility of AC microgrids.

The following sections describe key components of microgrid design and operation.

1.2.1 Electrical One-Line Diagrams

Electrical one-line diagrams play a vital role in the design, analysis, and maintenance of electrical systems, serving as a visual representation that encapsulates the complex network of components, connections, and interrelationships within a power system. These diagrams provide a clear and concise overview of the system's architecture, including transformers, generators, circuit breakers, switches, relays, loads (such as buildings with building numbers and equipment), and other critical elements. By depicting the flow of power, signal paths, and protective devices, one-line diagrams enable engineers, technicians, and operators to comprehend the system's configuration at a glance, facilitating effective troubleshooting, maintenance, and fault detection. This visual representation is particularly invaluable during system modifications, expansions, or upgrades, as it guides decision-making, aids in risk assessment, and ensures that changes adhere to safety and regulatory standards.

Beyond their operational significance, electrical one-line diagrams are essential for communication and collaboration among multidisciplinary teams. Engineers, planners, and stakeholders can collectively analyze and evaluate the system's performance, efficiency, and reliability, aiding in the optimization of load distribution, voltage regulation, and power factor correction. Additionally, these diagrams provide a foundational blueprint for complying with industry regulations and codes, enabling effective coordination of protection and control schemes. As electrical systems become increasingly intricate and interconnected, one-line diagrams act as a unifying visual tool that bridges the gap between technical complexity and practical understanding, enhancing both the efficiency of daily operations and the long-term sustainability of power infrastructure.

Prior to starting a microgrid project on existing electrical infrastructure it is key to have a one-line diagram of the area/region proposed to provide a good starting point for the pre-design phase. Some of the key data contained in a one-line diagram are: Line kV rating, breaker interruption and full load rating, transformer nameplate information and type of connections (Wye/Delta), and system protection and metering information such as Current Transformer and Potential Transformer ratios and ratings. Notes about potential configurations, what switches are normally open or normally closed also add value.

1.2.2 Supervisory Control and Data Acquisition

Supervisory Control and Data Acquisition (SCADA) systems are a cornerstone of modern power system operation, providing real-time monitoring, control, and data management that are indispensable for ensuring the reliable and efficient functioning of complex electrical networks. These systems enable operators to remotely supervise various aspects of power generation, transmission, and distribution, from voltage levels and load demand to equipment status and operational parameters. By offering a comprehensive and intuitive overview of the entire power grid, SCADA systems empower operators to swiftly detect anomalies, respond to contingencies, and optimize system performance in near real time. This heightened situational awareness translates into enhanced grid stability, reduced downtime, and improved decision-making, bolstering the resilience of the power infrastructure against disruptions and ensuring continuous and uninterrupted power supply to end consumers.

Furthermore, SCADA systems play a pivotal role in predictive maintenance and asset management strategies. By continuously collecting and analyzing data from sensors and remote terminals, these systems facilitate the early identification of potential equipment failures or performance degradation. Such proactive monitoring allows utilities to schedule maintenance activities strategically, minimizing unplanned outages and extending the operational life of critical assets. The ability to integrate SCADA data with advanced analytics and machine learning algorithms further amplifies its utility, enabling utilities to transition from reactive maintenance to a more cost-effective and resource-efficient predictive maintenance paradigm. As the power industry evolves toward greater automation and integration of renewable energy sources, SCADA systems stand as a linchpin in realizing a sustainable, resilient, and technologically advanced power grid. SCADA systems are discussed in detail in Section 2.

1.2.3 Relays and Coordination Studies

Coordination studies, arc flash analysis, and other protection studies are integral components of power system planning and operation, serving as critical tools to enhance safety, reliability, and overall system performance. Coordination studies focus on optimizing the protective devices, such as circuit breakers and relays, across the power network to verify that they operate in a coordinated and sequential manner during faults or abnormal conditions, thus improving reliability. By establishing well-defined protection zones and time-current characteristics, these studies prevent cascading failures, minimize outage durations, and isolate faults promptly, safeguarding equipment and personnel from potentially hazardous situations.

Arc flash analysis specifically delves into the assessment and mitigation of arc flash hazards, which can lead to catastrophic consequences if not properly managed. This analysis quantifies the potential energy release during an arc flash event, determining the associated incident energy levels and required personal protective equipment for workers. By understanding these hazards and implementing preventive measures, such as reconfiguring equipment, using remote operation, or implementing arc-resistant designs, power system operators can significantly reduce the risk of arc flash incidents and mitigate potential injuries or fatalities. Collectively, these studies assure the integrity of the power system, prevent costly disruptions, uphold regulatory compliance, and most importantly, prioritize the safety and well-being of workers and the surrounding community.

1.2.4 Phasor Measurement Units

PMUs have emerged as indispensable tools in the operation of modern power systems, offering a new dimension of real-time visibility and dynamic monitoring that was previously unattainable. PMUs provide high precision, synchronized measurements of voltage and current phasors across the grid, enabling operators to precisely analyze the dynamic behavior of the system. This real-time synchrophasor data allows for rapid detection and analysis of power oscillations, frequency deviations, and other disturbances that can impact the stability and reliability of the power network. By offering a detailed view of system dynamics, PMUs empower operators to make informed decisions swiftly, enabling them to take timely corrective actions to prevent cascading failures and maintain grid stability.

Furthermore, PMUs play a pivotal role in the integration and management of renewable energy resources. As renewable energy sources such as wind and solar power introduce greater variability and uncertainty into the grid, PMUs provide real-time insight into the interaction between these resources and the existing power infrastructure. This information enables operators to optimize power dispatch, manage voltage fluctuations, and verify grid synchronization, enhancing the efficient and seamless integration of renewable energy into the power system. With their ability to deliver accurate, synchronized data across a wide geographic area, PMUs are transforming power system operation from a reactive to a proactive mode, facilitating adaptive control strategies, improving grid resilience, and ultimately supporting the transition to a more sustainable and resilient energy future.

1.3 Benefits of Microgrids

Microgrids can provide a number of benefits, including:

- **Improved resilience**: Microgrids can be designed to withstand extreme weather events.
- **Increased reliability**: Microgrids can provide backup power during grid outages.
- **Improved efficiency**: Microgrids can help to improve the efficiency of energy use by allowing DERs to be optimally dispatched.
- **Cost Savings**: Depending on the cost of electricity, overall cost savings and cost surety are potential benefits.

Some of these key concepts are discussed below in greater detail.

Resilience: Per The National Association of Regulatory Utility Commissioners (NARUC), resilience is the robustness and recovery characteristics of utility infrastructure and operations, which avoid or minimize interruptions of service during an extraordinary and hazardous event (Commissioners 2022). The California Public Utilities Commission (CPUC) defines resilience as the ability to mitigate the impact of a large, disruptive event by any one or more of the following mechanisms (CPUC 2020) (see Figure 2):

- Reducing the magnitude of disruption;
- Extending the duration of resistance;
- Reducing the duration of disruption;
- Reducing the duration of recovery.

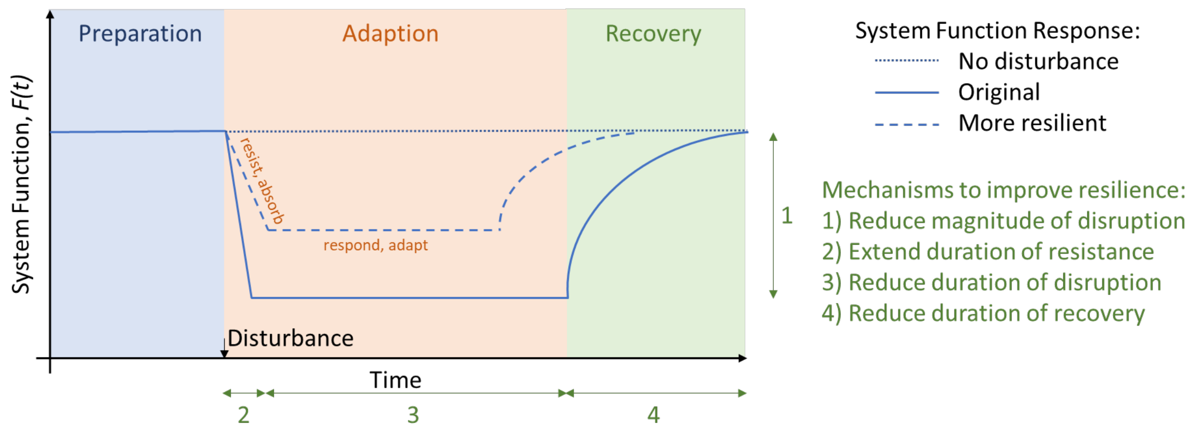

Figure 2. Resilience Trapezoid (CPUC 2020)

Reliability: Per the DOE, reliability is the ability of a power system to withstand instability, uncontrolled events, cascading failures, or unanticipated loss of system components. However, reliability also has to do with total electric interruptions – complete loss of voltage, not just deformations of the electric sine wave (Kirby 2004). Reliability does not cover sags, swells, impulses, or harmonics. Reliability indices typically consider such aspects as:

- the number of customers;
- the connected load;
- the duration of the interruption measured in seconds, minutes, hours, or days;
- the amount of power (kVA) interrupted;
- and the frequency of interruptions.

Power reliability can be defined as the degree to which the performance of the elements in a bulk system result in electricity being delivered to customers within accepted standards and in the amount desired. The degree of reliability may be measured by the frequency, duration, and magnitude of adverse effects on the electric supply. There are many indices for measuring reliability. The four most common are referred to as System Average Interruption Frequency Index (SAIFI), System Average Interruption Duration Index (SAIDI), Customer Average Interruption Duration Index (CAIDI), and Momentary Average Interruption Frequency Index (MAIFI), defined in IEEE Standard 1366-2012, below:

- **SAIFI.** The average frequency of sustained interruptions per customer over a predefined area. It is the total number of customer interruptions divided by the total number of customers served.
- **SAIDI.** Commonly referred to as customer minutes of interruption or customer hours and is designed to provide information as to the average time the customers are interrupted. It is the

sum of the restoration time for each interruption event times the number of interrupted customers for each interruption event divided by the total number of customers.

- **CAIDI**. The average time needed to restore service to the average customer per sustained interruption. It is the sum of customer interruption durations divided by the total number of customer interruptions.
- **MAIFI.** The total number of customer momentary interruptions divided by the total number of customers served. Momentary interruptions are defined in IEEE Std. 1366 as those that result from each single operation of an interrupting device such as a recloser.

In addition to the benefits described above, microgrids can offer numerous additional energy and equity benefits, summarized below from (Kerby and Hoffman, Microgrid Resource 2023).

- **Access**: Microgrids can provide access to locally generated, clean energy for remote communities off the grid. Microgrids can also provide access to clean energy for communities whose utility generation mix relies on polluting fossil fuel generators.
- **Affordability**: Microgrids can reduce the cost of electricity for local consumers by reducing transmission losses through local generation as well as providing an alternative to utility-provided electricity. Renewable-based microgrids can also provide additional cost savings over fossil-fuel-based microgrids, especially in remote locations with limited accessibility. These savings can reduce local energy burden and prevent shutoff notices for utility nonpayment.
- **Energy Efficiency**: Microgrids often incorporate DERs, such as solar panels and wind turbines, which can be more efficient than traditional power generation methods. Also, because power is generated and consumed locally, transmission losses are minimized.
- **Environmental Impact**: Microgrids with renewable generation sources can replace the need for backup diesel powered generators or polluting peaker plants, providing local air quality improvements and health benefits.
- **Flexibility and Scalability**: Microgrids can be designed to meet specific needs and can scale up or down in response to changes in demand or available resources. This flexibility makes them a great fit for a wide range of applications, from small rural communities to large industrial complexes.
- **Grid Support**: Microgrids can provide services to the larger grid, such as frequency and voltage regulation, load balancing, and congestion management. These services can improve the stability and efficiency of the broader power system.
- **Job Creation and Economic Development**: The design, installation, and operation of microgrids can create local jobs and stimulate economic development. Furthermore, by providing reliable power, microgrids can support the growth of businesses and industries.

- **Local Control and Autonomy**: Microgrids offer local control over energy resources. Users can tailor their power supply to meet their specific needs, preferences, and values, such as prioritizing reliability, cost-effectiveness, or sustainability.
- **Resilience**: Microgrids provide resilience to grid outages, whether the result of local grid conditions, extreme weather events, or public safety power shutoffs. By automatically disconnecting from the main grid during these events, a microgrid is able to provide uninterrupted access to electricity, especially important for critical infrastructure such as hospitals and community gathering spaces, where power interruptions can have severe consequences.
- **Robustness**: Robustness is the ability for a system to meet the energy demand at each time-step. Robustness is another important adequacy measure for both grid-connected and islanded microgrids (Pecenak, et al. 2020). In other words, how likely is the system able to meet its intended loads when required.
- **Social Impact**: Microgrids provide an alternative to traditional, utility-provided electricity. This can allow microgrids to serve as a community asset, not only providing energy independence, but allowing for wealth creation, community ownership, and community building.

1.4 Applications of Microgrids

The following microgrid use cases are reproduced from (Zinaman, et al. 2022).

- **Facility-Level**: A microgrid designed for an individual customer (e.g., a data center) connected to a central utility system for enhanced service quality and resilience. Microgrid assets would be located "behind" the utility meter. Such microgrids can be owned and operated by the customer, utility (i.e., under a fee-for-service arrangement), or a third-party microgrid developer, or some combination thereof.
- **Campus-Level**: A microgrid serving a single- or multi-owner contiguous set of facilities (i.e., a campus) typically behind-the-meter of a utility grid. These systems may serve customer load on a full-time basis and/or be designed to provide backup islanding services. DoD bases, universities, and airports are common sites for campus-level microgrids. Utilities may or may not be involved in campus-level microgrid operation beyond the point of common coupling.
- **Public Purpose**: A microgrid that serves one or more customers designed specifically to provide uninterrupted service to critical infrastructure and vitally important community assets. Government- or ratepayer-funded investments in these microgrids are common due to the social values associated with maintaining critical services during power outages.
- **Remote**: A fully operational microgrid serving an electrically isolated community without connection to a larger electricity grid. Remote microgrids are a "one-stop shop" for all

services, from provision of energy to maintaining stability and power quality. These are already common for service to islands, geographically remote, or rural settings.

- **Community**: A microgrid serving energy to two or more different properties nested within the service territory of a utility. Community microgrids can operate independently from the grid but are otherwise connected to the utility network through a point of common coupling (PCC). They are a means to increase local energy independence and resilience.
- **Non-Wires Alternative (NWA) / Anchor**: A type of community microgrid operating a feeder segment or substation balancing area to provide non-wires alternative services as a primary use, while simultaneously offering partial or full resiliency services to customers during utility grid outages.
- **Temporary**: Feeder segments or substations configured to be island microgrid hubs with all hardware installed except generation. Portable generators are staged at islanding point by truck, rail, boat, or helicopter, and configured to plug into feeder segment or substation microgrid hubs when needed. Temporary microgrids are a resilience-only application (i.e., no value-stacking opportunities), but do provide flexibility for where microgrids can be quickly deployed and is thus a form of "flexible resilience."
- **Networked**: A prospective future microgrid application in which sub-service-territory balancing areas, substations, feeder segments, or transformers act as clustered and nested microgrids, maximizing reliability and resilience among them. Most likely, this use case would consist of a series of community microgrids that also provide NWA characteristics in order to justify their investment.
- **Utility Pilot**: Utilities sometimes receive special regulatory approval to build-own-operate microgrids because of their novel and unique nature for the jurisdiction and the need to foster learning in the utility and regulatory environment. Realistically, a utility pilot will attempt to pursue one of the above use cases.

1.5 Challenges of Microgrids

Microgrids are a promising new technology that have the potential to improve the reliability, resilience, and efficiency of the electric grid. However, there are still some challenges that need to be addressed before microgrids can be widely deployed. (Kerby and Hoffman, Microgrid Resource 2023) summarize these challenges:

- **Cost**: Microgrids can be expensive to install, especially if they are large or use a lot of renewable energy sources. Upfront and operation costs should be considered alongside savings from reduced transmission, distribution, and utility costs; protection from market volatility; and the value of resilience.
- **Complexity**: Microgrids are complex systems that require careful planning and design. They can be difficult to operate and maintain, especially in remote or harsh environments. Process

checklists aid in design, implementation, and training. Lessons learned are also valuable for planning and design resources. Third-party service providers can also support this task.

- **Vulnerability to Cyberattacks**: Microgrids can be connected to the internet, which make them vulnerable to cyberattacks. Sensors and protection equipment—such as SCADA Systems—control, collect, and store real-time microgrid operational data to maintain efficient and safe microgrid operation.
- **Intermittency of Renewable Energy Sources**: Microgrids that rely on renewable energy sources, such as solar and wind, are intermittent—they do not produce power all the time. This can lead to power outages if the demand for power exceeds the supply. Using long-duration battery storage as well as maintaining generator backups for emergency use can lessen these impacts. Microgrids are also capable of "shedding" noncritical loads to lessen demand in times of reduced generation supply.
- **Limited Scalability**: Microgrids are limited in their ability to scale up to meet the needs of large populations. Most microgrids are limited to 10-15 MW or 20-25 MW for larger campus-wide microgrids. Microgrids of greater scale are not yet practically available as communication requirements also scale with microgrid capacity. This is a focus of research and will take time to resolve.
- **Skilled Workforce and Vendor Support:** The sophisticated technology underpinning microgrids demands a highly skilled workforce for effective operation and maintenance. Recruiting and training personnel, as well as engaging reliable third-party service providers, is vital for addressing both routine maintenance and unexpected system issues. This reliance on specialized human resources further emphasizes the need for comprehensive support and continuous training initiatives.
- **Lack of Standards**: There are no universally accepted design or hardware standards for microgrids; this can make it difficult to design, install, and operate them. For the most recent standards applicable to DoD see UFC 3-550-04: Resilient Installation Microgrid Design. Standards and regulations will vary based on your jurisdiction.
- **Resistance from Utilities**: Utility companies may resist the development of microgrids, as they could see them as a threat to their business. State regulators continue to challenge this paradigm. More states are beginning to adopt legislation facilitating microgrid development (CA, CT, ME, MA, HI, and Puerto Rico have such legislation).
- **Regulatory Hurdles**: There can be regulatory hurdles to the development of microgrids, such as obtaining permits and licenses. While regulators work to reduce these hurdles, state energy offices provide guidance and resources to navigate the local regulatory landscape.
- **Public Acceptance**: There may be public opposition to the development of microgrids due to concerns about safety, environmental impact, and cost. Microgrids can support the U.S. goal of a decarbonized power sector by 2035. Effective communication and educational resources can also be paramount to public acceptance.
- **Technology Risk**: The technology for microgrids is still evolving, and there are some challenges that need to be addressed before microgrids can be widely deployed. As of 2022,

there were nearly 700 microgrid installations across the U.S. with a combined capacity of 4.357 GW (U.S. Department of Energy Office of Energy Efficiency & Renewable Energy n.d.). Standards organizations work to reduce this risk, as do regulators.

1.6 IEWP Process

Prior to implementing a microgrid, the preparatory process requires an Integrated Energy Water Plan. The Installation Energy Water Plan (IEWP) process is a systematic approach to planning for the energy and water needs of Army installations and facilities (Army 2020). The IEWP process helps the Army to identify and implement energy and water efficiency measures, renewable energy technologies, and other solutions to reduce its energy and water consumption, costs, and environmental impacts.

The IEWP process is based on the following principles:

- **Integration**: The IEWP process integrates energy and water planning to assure that both resources are considered together in all aspects of planning and decision-making.
- **Sustainability**: The IEWP process promotes sustainable energy and water practices that meet the needs of the present without compromising the ability of future generations to meet their own needs.
- **Resilience**: The IEWP process helps the Army to build resilient energy and water systems that can withstand and recover from disruptions.

In pursuing the IEWP goals, the Office of the Chief of the Army Reserve (OCAR) has stated the importance of strategies that consider the following:

- Provide solutions that increase efficiency and reduce energy and water consumption.
- Provide cost-effective alternatives to generators (e.g., storage, photovoltaics, demand-side management).
- Invest in solutions that improve existing energy and water infrastructure and reduce installation risk.
- Leverage alternative funding to support project implementation.
- Review the operations and maintenance (O&M) requirements of recommended solutions.
- Review the environmental implications of recommended solutions.

The IEWP process consists of the following steps:

1. **Establish goals and objectives**: The first step in the IEWP process is to establish goals and objectives for energy and water efficiency, renewable energy, and sustainability. These goals and objectives should be aligned with the Army's overall mission and goals.
2. **Assess current and future needs**: The next step is to assess the Army's current and future energy and water needs. This assessment should consider factors such as the size

and type of installations, the number of people living and working on installations, and the Army's mission requirements.

3. **Identify and evaluate potential solutions**: Once the Army has assessed its current and future needs, it can begin to identify and evaluate potential solutions to meet those needs. Potential solutions may include energy and water efficiency measures, renewable energy technologies, and other solutions.
4. **Develop and implement a plan**: Once the Army has identified and evaluated potential solutions, it can develop and implement a plan to achieve its energy and water goals and objectives. The plan should include specific actions, timelines, and budgets.
5. **Monitor and evaluate progress**: The final step in the IEWP process is to monitor and evaluate progress toward achieving the Army's energy and water goals and objectives. This evaluation should identify areas where the Army is making progress and areas where improvement is needed.

Figure 3 illustrates the IEWP process:

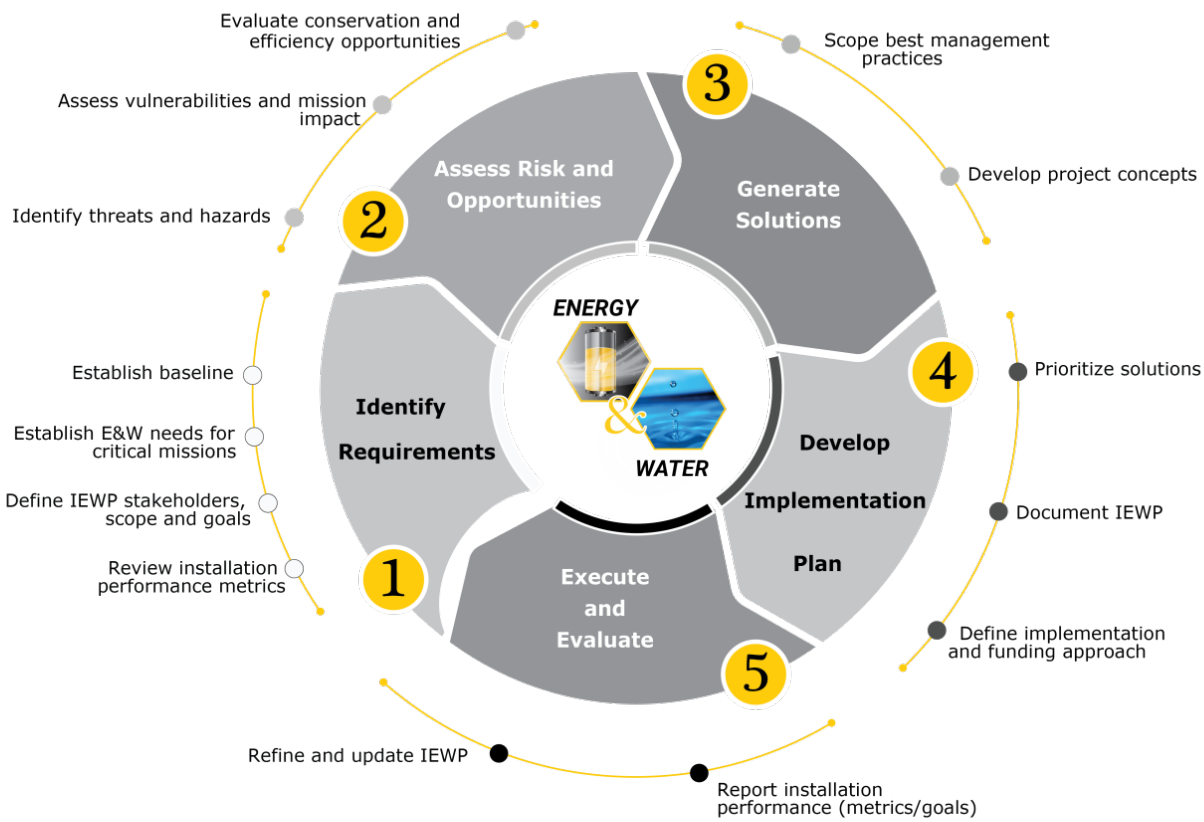

Figure 3. IEWP Process Flowchart (Smith, et al. 2022)

The IEWP process offers several benefits to the Army, including:

- **Reduced energy and water consumption,** which can lead to significant cost savings.
- **Increased energy and water security** by reducing its reliance on fossil fuels and other external sources of energy and water.
- **Reduced environmental impacts** by reducing its greenhouse gas emissions and other pollutants.
- **Improved mission readiness** by ensuring that it has reliable access to energy and water.

The IEWP process is an important tool for the Army to achieve its energy and water goals and objectives. By following the IEWP process, the Army can reduce its energy and water consumption, costs, and environmental impacts, while also improving its energy and water security and mission readiness.

Once the IEWP process is complete, the microgrid planning process can begin. This too requires a list of preparatory tasks that are recommended, but not always completed, such as undergrounding the overhead lines, coordination studies along with fault calculations, and one-line diagrams of the production facility.

2 Microgrid Components

2.1 End-Use Loads

End-use loads are the devices and appliances that consume electricity in a microgrid. These loads can be classified as either critical or noncritical.

- **Critical loads**: are those that must be powered at all times, such as hospitals, data centers, and emergency services.
- **Noncritical loads**: are those that can be interrupted during a power outage, such as warehouses and parking structures.

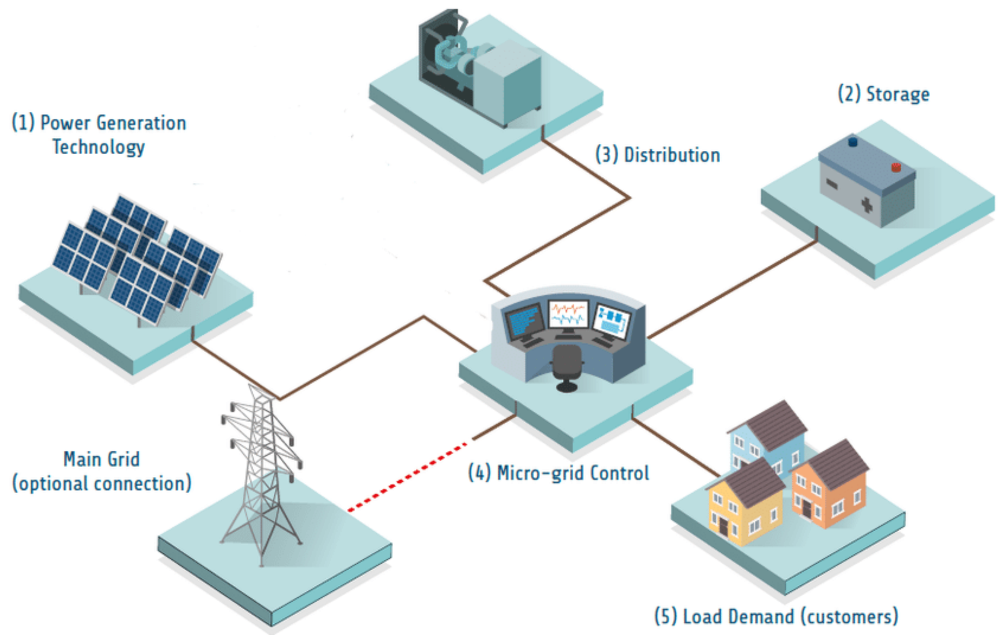

Figure 4. Distributed Energy Resources Components of a Microgrid (Eales, et al. 2019)

The type of end-use loads in a microgrid will determine the size and configuration of its DERs (Figure 4). For example, a microgrid with many critical loads will need to have a larger and more diverse set of DERs than a microgrid with mostly noncritical loads. See

The Army's critical load requirements for microgrids vary depending on the specific mission and installation. However, there are some general principles that apply to all microgrids.

- Mission critical loads must be prioritized. Not all critical loads are created equal. Some loads are more essential than others and must be prioritized in the event of a power outage. For example, a command and control facility is more critical to the mission than a barracks building.
- Microgrids must be able to island from the main grid. This means that they must be able to operate independently from the main grid in the event of a power outage. This is important for assuring mission continuity.
- Microgrids must be able to support critical loads for a sustained time period. The length of time that microgrids must be able to support critical loads will vary depending on the mission and installation. Army Directive 2020-03 states "The Army will sustain critical missions by being capable of withstanding an extended utility outage for a duration set by the senior commander or higher headquarters based on timeframes to accomplish, curtain, or relocate the critical mission(s). When the duration of the critical mission(s) has not be stipulated, the Army will plan to sustain energy and water for a minimum of 14 days" (ARMY DIR 2020-03 2020).

Critical loads for microgrids in the Army are determined on a case-by-case basis depending on an installation's infrastructure, mission, and tenants. These critical loads must be continuously powered in order to maintain critical mission functions during a power outage. They can include, but are not limited to:

- Command and control facilities
- Communication systems
- Medical facilities
- Weapon systems
- Security systems
- Data centers
- Communication towers
- Fuel storage facilities
- Ammunition storage facilities
- Airfield lighting systems
- Radar systems
- Missile defense systems
- Food Storage and Dining Facilities
- Emergency Shelter Space

The Army is currently developing and testing microgrids at a number of installations. These microgrids are being used to support a variety of critical loads, including command and control facilities, communication systems, and medical facilities.

2.2 Local Generation

Local generation is the process of generating electricity from renewable energy sources or other DERs that are located close to the end users. This makes local generation more resilient to grid outages, as it is not reliant on a single, centralized power source.

There are a number of different types of local generation that can be used in microgrids, including but not limited to:

- **Solar photovoltaic (PV) panels**: Solar PV panels convert sunlight into electricity using the photovoltaic effect.
- **Wind turbines**: Wind turbines convert wind energy into electricity using kinetic energy.
- **Diesel generators**: Diesel generators combust fossil fuels to generate electricity. They are often used a backup power source for individual buildings when the main grid is not available.

2.2.1 Solar Photovoltaics

The fundamental component of a PV system is the solar cell, made of a semiconducting material that varies depending on panel type. Individual solar cells are arranged in a grid pattern and wired together to form a PV module. PV modules are typically assembled within an aluminum frame and layered from top to bottom: front glass, front encapsulant, solar cells, back encapsulant, and back layer, which are laminated together and then connected to a junction box containing all the wiring for the module. PV modules are positioned side by side and wired together to form a panel. Many connected panels form a PV array, the largest unit of a PV system. The relationship between cell, module, and panel is shown in Figure 5 (Kerby, Hall, et al. 2023).

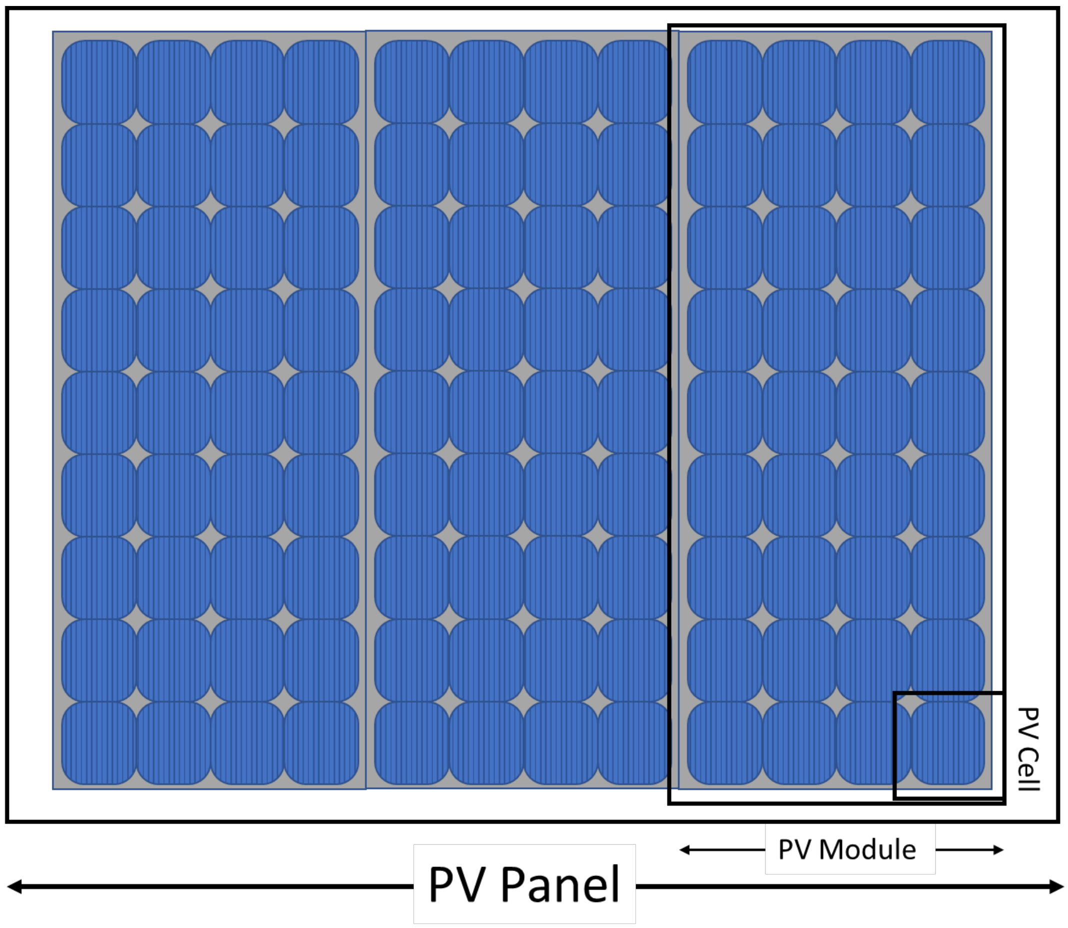

Figure 5. Relationship between solar cells (single units), modules (36 cells), and panels (three modules).

One of the fundamental characteristics of PV generation is that it is highly variable. Solar arrays only generate electricity when sunlight provides irradiance on the surface of the panel, which varies based on time of day, season, location, and tilt angle of the panel. The closer to the equator, the higher the magnitude of solar irradiation as well as the duration that a panel generates electricity. As the seasons change, so to do the sunlight hours; the summer typically brings longer days and higher PV generation than the short winter days of low irradiance. This effect is depicted in Figure 6 (Honsberg and Bowden n.d.). Therefore, to achieve a microgrid that solely relies on PV for battery charging the PV capacity has to be several times the size of the average critical load.

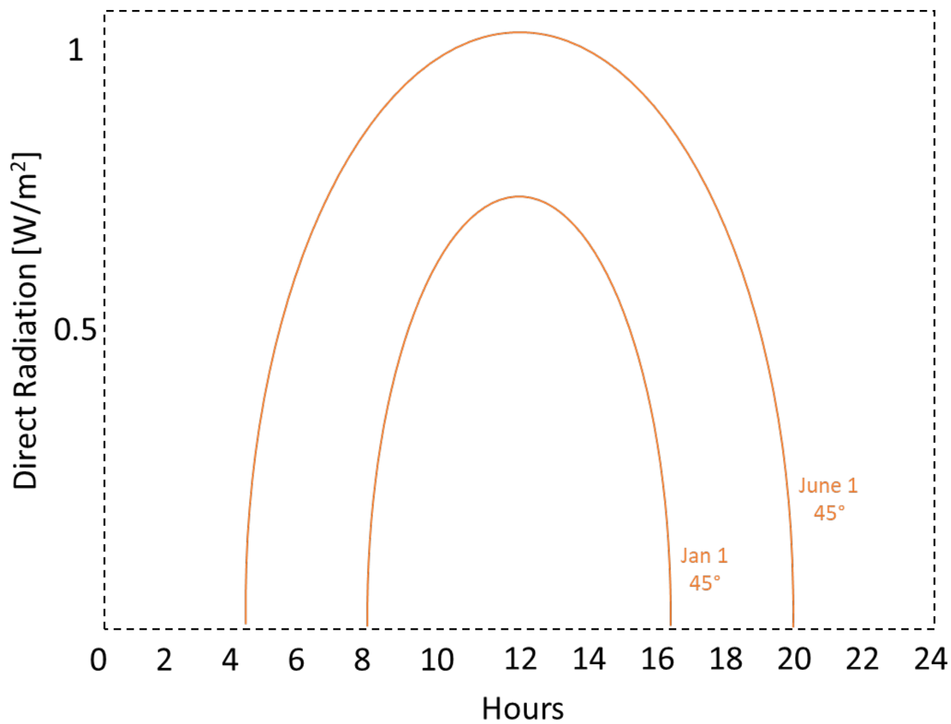

Figure 6. Approximate intensity of direct radiation throughout the day for Jan 1st and June 1st at 45° latitude, not accounting for weather effects such as cloud cover.

2.3 Energy Storage

Energy storage is the process of storing electricity for later use. This can be important in microgrids, as it can serve as a buffer for variable renewable energy sources, such as solar and wind. Energy storage can also be used to provide backup power during grid outages.

There are a number of different types of energy storage that can be used in microgrids, including:

- **Battery energy storage systems (BESS)**, the most common type of energy storage. They are relatively inexpensive and can be used to store a large amount of electricity.
- **Fuel cells** convert hydrogen and oxygen into electricity using electrochemical energy. Fuel cells are similar to batteries except they require a continuous supply of reactants.
- **Compressed air energy storage (CAES)** systems store electricity by compressing air and storing it in underground caverns and releasing that pressure when needed.
- **Flywheel energy storage (FES)** systems store electricity by rotating a flywheel and converting that rotational energy into electricity when needed.

The type of energy storage in a microgrid will depend on the specific needs of the microgrid. For example, a microgrid that needs to provide backup power for a long time period will need to use a different type of energy storage than a microgrid that needs to store excess output of a solar PV system for utilization later in the day.

Table 1 describes the different services that BESS can provide, organized into the following categories: bulk energy, ancillary, transmission, distribution, and customer services.

Table 1. Benefits of battery energy storage systems (Balducci, et al., 2018)

Category	Service	Value/Description
Bulk Energy	Capacity or Resource Adequacy	A battery energy storage system (BESS) is dispatched during high-demand events to supply energy and assist in providing power to the grid, referred to as shaving peak energy demand. The BESS reduces the need for high-polluting power plants dedicated for peak energy events and other peaking resources.
	Energy Arbitrage	A BESS operator can trade in the wholesale energy markets by buying energy during off-peak low-price periods and selling it during peak high-price periods.
Ancillary Services	Regulation	A BESS operator responds to an area control error to provide a corrective response to all or a portion of a control area. These responses correct differences between load and generation.
	Load Following	The power output of a BESS is regulated within a prescribed area in response to changes in the grid such as system frequency, tie line (transmission circuit) loading, or the relation of these to each other. This maintains certain grid characteristics such as the scheduled system frequency and/or established interchange with other areas to stay within predetermined limits.
	Spinning/Non-Spinning Reserve	Spinning reserve represents energy generation capacity that is online and capable of synchronizing to the grid within 10 minutes. Non-spinning reserve is off-line generation capable of being brought onto the grid and synchronized to it within 30 minutes.
	Frequency Response	The BESS provides energy to maintain frequency stability on the grid when it deviates outside the set limit, thereby keeping generation and load balanced within the system.
	Flexible Ramping	Ramping capability is provided in real time to meet the forecasted net load to cover upward and downward forecast error uncertainty.
	Voltage Support	Voltage support provides reactive power onto the grid to maintain a desired voltage level.
	Black Start Service	Black start service is the ability of a generating unit to start without an outside electrical supply. Black start service is necessary to help assure the reliable restoration of the grid after a blackout.
Transmission Services	Transmission Congestion Relief	Use of a BESS to store energy when the transmission system is uncongested and to provide relief during hours of high congestion.
	Transmission Upgrade Deferral	Use of a BESS to reduce loading on a specific portion of the transmission system, thereby delaying the need to upgrade the transmission system to accommodate load growth or regulate voltage.
Distribution Services	Distribution Upgrade Deferral	Use of a BESS to reduce loading on a specific portion of the distribution system, thereby delaying the need to upgrade the distribution system to accommodate load growth or regulate voltage.
	VAR Control	Volt–amperes reactive (VAR) is a unit used to measure reactive power in an alternating current (AC) electric power transmission and distribution system. VAR control manages the reactive power, usually attempting to get a power factor near unity.

Category	Service	Value/Description
	Conservation Voltage Reduction	Use of a BESS to reduce energy consumption by reducing feeder voltage.
Customer Service	Power Reliability	Power reliability refers to using a BESS to reduce or eliminate power outages to customers.
	TOU (time of use) Charge Reduction	Reducing customer charges for electric energy when the price is specific to the time (season, day of week, time of day) when the energy is purchased.
	Demand Charge Reduction	Use of a BESS to reduce the maximum power draw by electric load in order to avoid peak demand charges.

2.3.1 Safety Considerations for Lithium-Ion Batteries

Lithium-ion batteries have a number of safety risks, including:

- **Thermal runaway**: a self-sustaining chain reaction that can lead to the release of heat, gases, and flames. Thermal runaway can be caused by a number of factors, including overcharging, overheating, and internal defects.
- **Flammable gases**: lithium-ion batteries can release flammable gases during thermal runaway. These gases can ignite and cause a fire.
- **Electrical shock**: lithium-ion batteries can produce high voltages, which can pose a risk of electrical shock.

Take the actions listed below to address safety concerns and manage the risks associated with lithium-ion and lead acid batteries.

- Odor, heat, or bulging of the battery are signs of battery degradation. Promptly disconnect the battery, leave the area, and call safety personnel if any of these safety hazards are observed (UMassAmherst 2020).
- Protect lithium-ion batteries from physical damage, overcharging, and excess heat, as each of these conditions can lead to thermal runway. Excess heat, a hissing sound, or bulging batteries are warning signs of thermal runaway. If possible, disconnect the battery from its power source and extinguish battery fires with a class ABC or BC fire extinguisher. If it is not possible to take either of these actions, IMMEDIATELY evacuate the area, because these fires can spread very quickly.
- Do not charge or discharge batteries past the manufacturer's specified voltages.
- In the case of portable batteries, disconnect batteries from the charger once fully charged.
- Do not store lithium-ion batteries at full charge; discharge the batteries to a 50 percent state of charge before storing them.
- To prevent damage caused by self-discharge, recharge stored batteries to a 50 percent state of charge at least every 6 months.

There are a number of safety measures that can be taken to mitigate the risks associated with lithium-ion batteries, including:

- Using a **battery management system (BMS)**: a BMS monitors the battery and prevents it from operating outside of safe limits.
- Using appropriate **fire protection measures**: this may include installing fire suppression systems and fireproof enclosures.
- **Proper installation and maintenance**: BESS should be installed and maintained by qualified professionals.

There have been a number of lithium-ion battery safety incidents in recent years, which are tracked on UL's Lithium-Ion Battery Incident Reporting page to raise incident awareness and prompt analysis (Lithium-ion Battery Incident Reporting n.d.).

These incidents highlight the need for continued research and development into BESS safety. Lithium-ion batteries are a safe technology when properly designed, installed, operated, and maintained. However, there are safety risks associated with lithium-ion batteries, such as thermal runaway, flammable gases, and electrical shock. Safety measures can be taken to mitigate these risks, such as using a BMS, appropriate fire protection measures, and proper installation and maintenance.

2.4 Microgrid Monitoring and Control System

The microgrid monitoring and control system (MCS) is responsible for monitoring the operation of the microgrid and controlling the flow of electricity. The MCS typically consists of a number of sensors and actuators that are used to collect data and send commands to the microgrid's DERs. A critical component of any microgrid, the MCS allows the microgrid to be operated and managed in an efficient and secure manner, optimizes the operation of the microgrid's DERs to assure that it meets the needs of its customers, and verifies it is able to respond to grid outages.

Also referred to as a microgrid energy management system (EMS), this system includes decision-making strategy modules, which convey optimized decisions to the generating, storing, and loading units via DERs-load forecasting, supervisory, control, management, and data collecting modules. The primary goal of the microgrid management is to maintain microgrid balance over all variations in weather and load demands. Basically, a microgrid EMS has two primary subsystems: monitoring system and control system.

2.4.1 Monitoring Systems

The MCS verifies the current operational state of all devices and oversees their functioning to guarantee safety and stability. It is crucial to keep the monitoring system updated. The system should be maintained to assure real-time operation within the microgrid using both software and hardware components.

Supervisory Control and Data Acquisition system

A commonly used microgrid monitoring system is the SCADA system, which monitors various building types (residential, commercial, and industrial). A SCADA system consists of two main elements: a hardware setup for gathering, transmitting, controlling, and managing data, and a software infrastructure for storing, processing, displaying, optimizing, and precisely administering information. An example is shown in Figure 7.

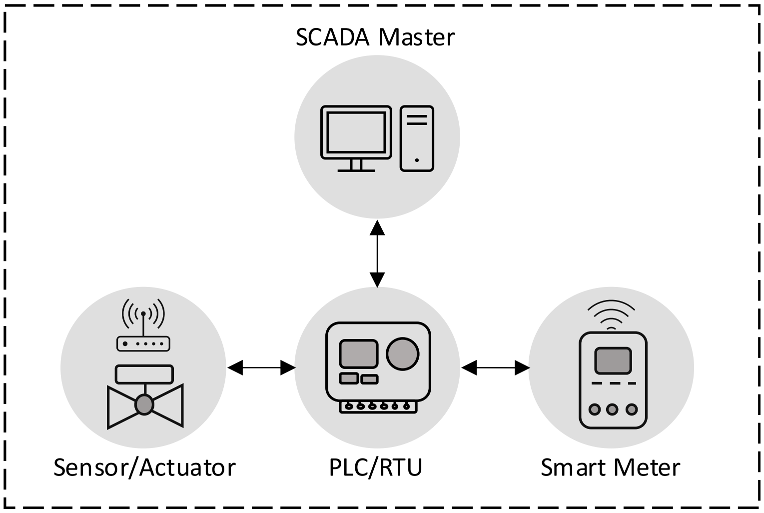

Figure 7: A SCADA monitoring system for microgrid

There are three major elements for SCADA hardware:

- **Remote Terminal Unit (RTU)** to collect status data for the SCADA system.
- **Communication Platform** to enable the creation of connections for data exchange among devices.
- **Programmable Logic Controller (PLC)** to guarantee the correct functioning of the microgrid in both grid-connected and island operational modes.

A crucial element within the SCADA system, the Human-machine interface (HMI), plays a vital role in supervision and management. The conventional arrangement of the SCADA system involves a server-client structure, where the primary SCADA application functions on the server, and the HMI operates on the client side. The HMI can be configured to display numerous parameters in real time depending on the needs of the user; a simplified depiction of an HMI is shown in Figure 8.

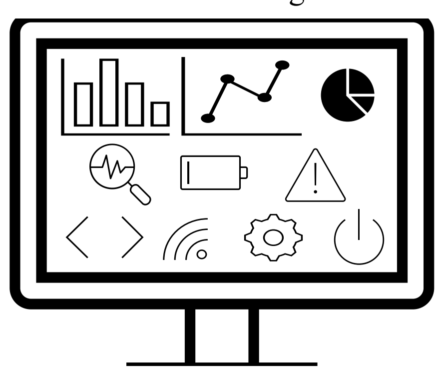

Figure 8. Human-Machine Interface (HMI)

Internet of Things-Enabled Monitoring System

The Internet of Things (IoT) refers to the concept of connecting everyday objects, devices, and machines to the internet and enabling them to communicate, exchange data, and perform tasks without requiring direct human intervention. These connected objects can range from household appliances and wearable devices to industrial machinery and vehicles.

IoT involves embedding sensors, actuators, and communication technologies into these objects, allowing them to gather and transmit data, receive instructions, and interact with other devices and systems. The data collected from these devices can be analyzed to gain insights, monitor status, automate processes, and make informed decisions.

The reliability, stability, security, and ecological sustainability of microgrids are all assured through the utilization of IoT. The rise in popularity of IoT technologies is attributed to their advancement and application in small and medium-sized grid (SMG) contexts. Essential IoT technologies include two-way connectivity, automatic recovery, decentralized operation, and intelligent metering. An adaptable and intelligent EMS must oversee and manage all variables within SMGs in real time.

The efficiency of an EMS in a microgrid has a significant boost as data is gathered and assessed from energy sources through IoT. Furthermore, utility companies can enhance their operational functions, including expediting outage investigations, fine-tuning load distribution, optimizing voltage levels, detecting faults, reducing service expenses, and expediting service restoration. Moreover, the application of IoT technology in areas like smart homes, BESS, EVs, charging stations, and fluctuating energy demand enhances the adaptability and reliability of SMGs.

The EMS of a microgrid incorporates diverse sensors to gather data (such as current, voltage, power, and temperature). These data are promptly analyzed to identify the best control approach, considering present factors like occupancy, energy usage and generation, and weather conditions. The data is then archived for future analysis, especially for developing predictive control methods. In the current era, an intelligent microgrid revolves around electronic communication networks, digital billing mechanisms, and intelligent metering. As we move toward the era of 5G, the intelligent microgrid will feature automated distribution as well as secure management of DERs.

Monitoring system with cloud computing

The application of cloud computing in microgrid monitoring systems brings numerous benefits to the management, efficiency, and reliability of these localized energy distribution networks. Cloud-based monitoring enhances the real-time visibility, analysis, and control of microgrid operations. Cloud computing can be applied specifically to microgrid monitoring systems via:

- **Real-time data acquisition**: Cloud-connected monitoring facilitates the continuous capture of up-to-the-minute data from diverse sensors, intelligent meters, and devices within the microgrid. This data encompasses metrics such as energy consumption, generation levels, battery status, grid voltage, and more. Cloud platforms enable seamless integration of these data streams into a centralized repository.

- **Consolidated data storage**: Cloud computing supplies a scalable and secure environment for housing extensive volumes of operational microgrid data. This centralized data storage enables effortless access, retrieval, and historical analysis which is pivotal for making well-informed decisions and optimizing microgrid performance over time.
- **Data analysis and visualization**: Monitoring systems hosted in the cloud can harness advanced data analysis and visualization tools, tapping into computational resources for processing data, identifying trends, and generating insights. Visualizing the data through user-friendly dashboards empowers operators and stakeholders to comprehend microgrid performance and pinpoint avenues for enhancement.
- **Remote supervision**: Cloud-based systems allow microgrid operators to remotely oversee system components. This remote oversight capability is vital for assuring optimal operation and swiftly addressing any emergent issues.
- **Identification of anomalies and issuance of alerts**: Cloud computing streamlines the implementation of algorithms designed to detect anomalies. These algorithms continuously scrutinize incoming data against anticipated patterns. Whenever deviations or anomalies are detected, the system can generate alerts or notifications, equipping operators to take immediate action to prevent disruptions.
- **Flexibility and scalability**: Monitoring systems hosted in the cloud can adapt seamlessly to accommodate increased data volumes and additional sensors or devices. This flexibility proves invaluable as microgrid installations evolve and expand to encompass more components or integrate novel energy sources.
- **Integration with advanced technologies**: Cloud platforms offer the computational muscle required for advanced technologies like machine learning and artificial intelligence. These technologies can anticipate energy demand, optimize energy allocation, and even unearth concealed correlations within the data, bolstering the microgrid’s efficiency.
- **Backup and redundancy**: Cloud-based systems provide inherent backup and redundancy mechanisms. In situations involving local hardware failures or outages, data stored in the cloud remains both accessible and secure. This redundancy guarantees continuous monitoring and operation of the microgrid.
- **Data security and adherence to regulations**: Cloud service providers often implement robust security protocols and possess certifications for regulatory compliance. This safeguards sensitive microgrid data against unauthorized access or breaches.
- **Collaborative efforts and reporting**: Cloud-hosted systems facilitate effortless collaboration among stakeholders. Different users, such as utility operators, grid managers, and maintenance teams can access identical data and collaborate on monitoring and management tasks. Cloud platforms can also generate reports and summaries detailing system performance automatically.

By utilizing cloud computing to monitor microgrids, operators can elevate the effectiveness, dependability, and overall functioning of microgrid systems. This approach also allows them to take advantage of the scalability, security, and advanced analytical features provided by cloud platforms. For Army microgrids, using cloud computing monitoring services will depend on policy and case-by-case design.

2.5 Control Systems

Microgrids possess control capabilities that are distinct from those found in other segments of the distribution network. Effectively governing microgrids can therefore be a challenge due to their dual operational roles. Consequently, distinct management systems are frequently devised for each mode of operation. Balance must be maintained among energy generation, consumption, and storage within the microgrid, ensuring consistent and efficient performance. Approaches to microgrid control include:

- **Centralized control**: makes decisions for the entire microgrid based on real-time data. It determines the best possible functioning of different components, such as generators, storage units, and loads, with the objective of meeting energy demands while minimizing costs and maximizing efficiency. An example of centralized control is depicted in Figure 9.

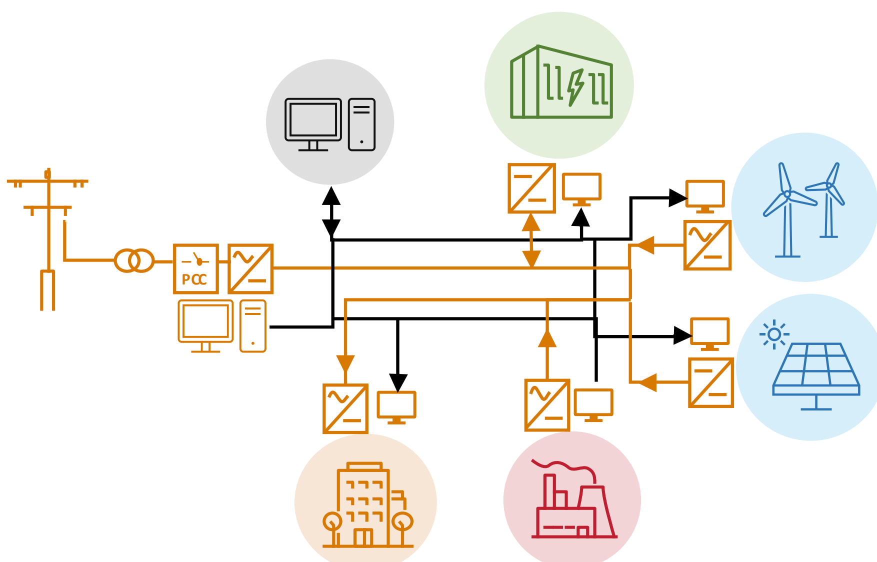

Figure 9 Architecture of Centralized Control (DC Power Line: Orange, Communication Line: Black)

- **Decentralized control**: partitions the microgrid into distinct zones or segments, each governed by its own controller responsible for managing local elements. These local controllers communicate with each other to achieve the overall objectives, enhancing resilience and adaptability.
- **Hierarchical control**: combines aspects of both centralized and decentralized strategies. It establishes multiple tiers of control, with higher levels making strategic choices and lower

levels executing these decisions at the component level. This strategy strikes a balance between globally optimizing performance and responding effectively to local dynamics.

- **Load following control**: aligns energy generation with the immediate load demand within the microgrid. This technique ensures that the microgrid remains in equilibrium by adjusting generation levels in response to fluctuating demands.
- **Power dispatch control**: efficiently manages the allocation of power from diverse energy sources, like solar panels, wind turbines, and generators, to fulfill the microgrid's energy needs. Factors such as cost and environmental impact should be considered.
- **Voltage and frequency regulation**: to assure stable voltage and frequency levels within the microgrid. This stability is critical to sustaining the quality of power supplied to connected loads.
- **Demand response**: modifies patterns of energy consumption in response to signals from the microgrid controller or grid operator. This approach aids in balancing supply and demand, particularly during peak periods, as well as optimizing energy expenses.
- **Priority-based control**: assigns varying priorities to different components and loads within the microgrid. During periods of high demand or limited supply, this control mechanism ensures that critical loads take precedence, while noncritical loads may be reduced. This supports the Army's goals of providing mission assurance to critical facilities.
- **Islanding and reconnection control**: in situations of grid outages, microgrids can isolate themselves (islanding) and operate autonomously. Reconnection control manages the seamless transition of the microgrid back to the main grid once power is restored.
- **Manual control**: a 'maintenance mode' or otherwise manual control along with manual procedures document. Having robust manual control procedures and training the energy manager on how to use them is a good fallback since it's difficult to anticipate every scenario when developing the microgrid control program.
- **Forecast-based control**: employs predictive models to estimate future energy generation and consumption. This insight informs proactive decisions regarding energy distribution and storage management.
- **Fuzzy logic control**: a controller within a fuzzy-control system intends to introduce a middle range between zero and one by dissecting logical challenges into smaller, more achievable segments. Fuzzy logic approaches show promise addressing the parameters of microgrid systems.

These techniques for microgrid control serve as the basis of microgrid administration and have evolved over time to address a range of challenges. As microgrid technology advances, these established methods remain necessary, even as more sophisticated control strategies emerge.

2.6 Utility Interconnection

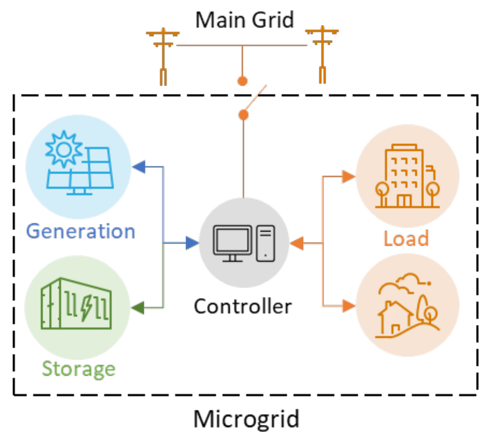

Figure 10. Microgrid and Grid Interconnection

Utility interconnection is the process of connecting a microgrid to the main grid. This allows the microgrid to both import electricity when needed and export electricity when generated in excess of local loads (Figure 10).

Utility interconnection is important for microgrids, as it allows them to participate in the electricity market as well as provide backup power during grid outages. The process of utility interconnection can be complex and time-consuming, so it is important to plan for it early in the development of a microgrid.

The interconnection application process may differ depending on the intended use of the microgrid and the utility service territory of the system. For example, large-scale commercial systems intended to export generated electricity may require more robust and lengthy study processes to assure grid stability is maintained. In general, the following information is required to submit an interconnection application (Energy Trust of Oregon 2016):

- System size, technology type, and technical specifications;
- Location, or Point of Interconnection ;
- Desired use case (such as on-site consumption only or net metering);
- Proof of site control; and
- One-line diagram of system.

The IEEE Standards Association (IEEE SA) continues to develop standards and recommended best practices for the interconnection of DERs onto the electric grid. While standards adoption is not uniform across the U.S., the IEEE Distributed Energy Resources (DER) Standards Collection provides best practices for safely and effectively connecting and utilizing DERs. Relevant standards are as follows (IEEE Standards Association 2021):

- **IEEE 1547**: Foundational interconnection requirements for DERs, originally published in 2003, with updates IEEE 1547-2018, IEEE 1547a-2020, IEEE 1547.1-2020 and more underway.
- **IEEE 2030**: provides guidelines for smart grid interoperability, power and communication best practices, originally published in 2011 with updates IEEE 2035.5-2018.
- **IEEE 2800-2022**: Standard for interconnection and interoperability of inverter-based resources (IBR) interconnecting with associated transmission electric power systems.

- **IEEE P2418.5**: standard for blockchain in energy, including transactional energy model for energy trading between DERs and electric utilities.

The interconnection process may involve additional components, such as:

- **Substations**, used to step up or step down the voltage of electricity.
- **Switchgear**, used to connect and disconnect different parts of the microgrid.
- **Metering**, used to measure the amount of electricity that is being generated, consumed, and exported by the microgrid.

The specific components in a microgrid will depend on the size and complexity of the microgrid. However, all microgrids will have some of the components listed above.

3 Microgrid Planning and Design

Microgrid planning and design is crucial to assure reliable, efficient, and sustainable energy for communities, campuses, military installations, and remote areas. These stages involve evaluating energy needs, selecting suitable technologies such as renewable sources and storage systems, and integrating them to meet current and future demands. Effective planning and design are essential for building a microgrid that improves energy security, supports environmental goals, and offers economic benefits. For Army energy managers, focusing on straightforward, actionable steps in microgrid development is key to achieving operational readiness and sustainability objectives. Section 3 covers topics that are relevant to microgrid development:

- **Microgrid Planning**: this section discusses the importance of developing a comprehensive microgrid plan. The plan should identify the microgrid's goals and objectives, as well as the technical, economic, and environmental factors that need to be considered.
- **Microgrid Design**: this section discusses the key design considerations for microgrids, such as the selection of microgrid components, the sizing of the microgrid, and the design of the microgrid control system.

3.1 Microgrid Planning

It is important to develop a clear understanding of the microgrid's primary mission and objectives. Use conclusions from IEWP reports to identify and understand the critical mission needs of the installation. This will help to inform the design and implementation of the microgrid. The microgrid should be designed to be flexible and adaptable to changing conditions while meeting mission needs. This includes the ability to operate in island mode (i.e., independently of the main power grid) and to operate in parallel with the main power grid. The microgrid should be integrated with the existing energy infrastructure at the installation. This will help to ensure that the microgrid can operate efficiently and reliably. It is important to develop a comprehensive microgrid operating plan and to train personnel on how to operate the microgrid safely and effectively.

The microgrid development process typically involves the following steps:

- **Identify the goals and objectives of the microgrid**: determine the purpose of the microgrid, the loads that will be served by the microgrid, and the desired level of reliability.
- **Assess the needs of the microgrid**: identify the DERs that will be used to power the microgrid, the energy storage that will be needed, and the control system that will be used.
- **Perform a risk assessment of the DERs**: assess the risks to each source of power to the microgrid. This risk assessment should evaluate each fuel source used in the microgrid. For example reliance on natural gas poses seismic risks as lines may be shut off during earthquakes. Delivery schedules, seasonal and hourly variability and causes of the initial outage should all be considered when evaluating DER reliability.
- **Develop a design for the microgrid**: specify the size and configuration of the DERs, the energy storage, and the control system.
- **Estimate the cost of the microgrid**: consider the costs of the DERs, the energy storage, the control system, and the construction of the microgrid. The labor associated with acquiring an interconnection agreement with the utility, permitting, cybersecurity accreditations, energy modeling, and safety testing must also be considered.
- **Develop a business plan for the microgrid**: identify the revenue streams for the microgrid, the operating costs, and the financial projections for the microgrid.
- **Obtain the necessary approvals**: obtain the necessary permits, licenses, and agreements.
- **Deploy the microgrid**: construct, commission, and operate the microgrid, including black start testing.

The microgrid planning and development process is complex and requires a good understanding of the microgrid's needs and goals. It is also important to have a qualified team in place to manage the microgrid planning process.

3.1.1 Site Selection

Site selection is the process of choosing a location for a microgrid. This is an important step in the development of a microgrid, as it affects the cost, performance, and reliability of the microgrid. There are many factors that need to be considered when selecting a site for a microgrid, including:

- **Load demand**: the site should be located in an area with a high demand for electricity. This will help to assure that the microgrid is economically viable.
- **DER resources**: the site should be located in an area with good DER resources, such as solar and wind. This will help to reduce the cost of the microgrid.

- **Grid interconnection**: the site should be located near the main grid. This will make it easier to connect the microgrid to the grid.
- **Environmental impacts**: the site should be selected in a way that minimizes the environmental impacts of the microgrid.

The site selection process should be conducted carefully to assure that the best possible site is chosen for the microgrid. Often, the microgrid controller is located in an existing building. To effectively integrate the microgrid controller and associated equipment, a site survey of the selected building should be conducted.

Prior to a site survey visit, it is recommended to review satellite imagery of the facility to familiarize oneself with the general layout, areas for potential PV, whether lines are overhead or underground, where the building's transformer is located, and the building's number and address (Hoffman 2019).

Data is essential. Load data at 15-minute resolution from the local utility, utility bills, and utility rate, including any demand charges, is a great first step. On-site data options include the building EMS energy use files, or to use a clamp-on amp meter at the main panel to measure the full building load. Request one-line diagrams of the building's wiring.

For the site survey itself, it is important to gather and document all electrical infrastructure:

- Take pictures of the building(s), transformer, distribution lines (if overhead), switchgear, generator, electrical panels, and nameplate data on all devices; name and save files of all digital photos to correspond with other data about each building and piece of equipment.
- Generator: manufacturer, kVA rating, age (if known).
- Fuel Storage: check generator to confirm fuel storage capacity.
- Transformer: kVA rating, primary voltage, secondary voltage.
- Distribution System: voltage level, overhead or underground.
- Uninterruptable power supply (UPS) total kW in building.
- Switchgear or automatic transfer switch information.
- Proposed equipment site diagram.

3.2 Microgrid Design

The microgrid should be designed to meet the specific needs of the installation by considering its energy load, critical loads, renewable energy resources, and energy storage components. The microgrid should be designed to be reliable and resilient by considering the potential risks to the microgrid and designing mitigation measures to reduce those risks. Risks include cyber threats, natural disasters, and other physical human threats such as sabotage or terrorism. Finally, the microgrid should be designed to be cost-effective by considering the initial cost of the microgrid, long-term operating and maintenance costs, and potential revenue streams, such as load shedding or time of use management (i.e., energy arbitrage, the process of buying electricity at a low price and selling electricity when the price is higher). The following stages describe the microgrid design process.

3.2.1 System Sizing

System sizing is the process of determining the size and configuration of the microgrid's DERs. This is a critical step in the design of a microgrid, as it ensures that the microgrid can meet the needs of its customers. The system sizing process typically involves the following steps:

- **Identify the loads**: The first step is to identify the loads that will be served by the microgrid. This includes both critical and noncritical loads.
- **Estimate the load demand**: The next step is to estimate the demand for electricity from the loads. This can be done by using historical load data, typically captured by meters, or by conducting a load survey by taking inventory of connected loads and documenting their usage.
- **Select the DERs**: The third step is to select the DERs that will be used to meet the load demand. This includes considering the type, size, and cost of the DERs.
- **Model the microgrid**: The fourth step is to model the microgrid to simulate its operation. This can be done using a software simulator or by using a spreadsheet model. The purpose of modeling the microgrid is to identify cost benefits and optimize the system.
- **Optimize the system**: The final step is to optimize the system to minimize the cost of meeting the load demand. This can be done by using a mathematical optimization algorithm.

The system sizing process is complex and requires a good understanding of the microgrid's loads, DERs, and operating environment. It should be considered the critical next step after site selection, as it assures that the microgrid can meet the needs of its customers.

3.2.2 Pre-Design and Design

In tandem with system sizing, pre-design processes and surveys should be completed, such as identifying the existing and future conditions on the network. Any existing production plants should be considered, such as hydro or PV. The typical time for pre-design studies is 3-4 weeks. To facilitate this process, have someone on-site with expertise in microgrid design; this can save on both time and costs of later design stages. Note that the most important step is the survey, and money spent on pre-design is time saved on expertise.

The microgrid design stage begins by identifying the physical network. This includes medium voltage (MV) and low voltage (LV) cables, substations, communications, protection, generator controls, and transfer switches. Excel-based calculators can be used to size cables, transformers, substations, conduits, and pipes. The design process typically takes three to four weeks. See the Resources section of this document for more information.

3.2.3 Coordination and Transient Studies

Coordination is important to validate the microgrid design. The point of delivery can supply the short-circuit value of substation (i.e., maximum kVA), after which fault studies can be conducted for arc flashes and short circuits. Coordination studies for MV and LV should be conducted, the relay in the substation needs to be coordinated, and on-load testing with specific instruments to simulate fault should be completed. Transient studies focus on islanding and black start, LV and MV network sizing.

4 Microgrid Operation

The microgrid operating plan should define the roles and responsibilities of microgrid personnel, as well as the procedures for operating the microgrid in different modes (e.g., island mode, parallel mode). Microgrid personnel should be trained on how to operate the microgrid safely and effectively. This training should include both classroom instruction and hands-on training. The microgrid should be monitored and evaluated on a regular basis to identify areas for improvement. This monitoring and evaluation should include collecting data on microgrid performance, identifying potential problems, and implementing corrective actions as needed. O&M should be considered in the design phase of a project. Typical O&M procedures as well as cybersecurity considerations are described below.

4.1.1 Operation and Maintenance

O&M is the process of keeping a microgrid operating properly. This includes tasks such as:

- **Monitoring the microgrid**: monitor the microgrid's operation to verify that it is operating properly. This involves real-time data collection and analysis to optimize energy production and consumption.
- **Troubleshooting problems**: troubleshoot and repair problems with the microgrid as quickly as possible. This refers to the process of identifying, diagnosing, and resolving issues or malfunctions that can occur within a microgrid system.
- **Performing preventive maintenance**: perform preventive maintenance on the microgrid to keep it operating properly. This is a proactive and scheduled approach to maintaining and servicing the microgrid's components and systems to prevent potential issues, reduce the risk of failure, and assure the continued reliability and efficiency of the system.
- **Energy management**: efficiently managing energy resources within the microgrid can include renewable energy sources (solar panels, wind turbines), energy storage (batteries), and backup generators. This involves scheduling and dispatching energy sources to meet demand and minimize costs.
- **Load balancing**: ensure a balanced distribution of electrical load across the microgrid to prevent overloads and maintain system stability. Load balancing may involve load shedding or shifting during peak demand periods.

- **Grid integration**: coordinate with the main utility grid when the microgrid is interconnected. This includes managing grid interactions for importing or exporting electricity, ensuring grid stability, and adhering to regulatory requirements.
- **Cybersecurity**: implement cybersecurity measures to protect the microgrid from cyber threats and ensuring data integrity and system security.
- **Testing and validation**: regularly test the microgrid's components and systems to validate their functionality and response during various scenarios, including grid outages and emergencies.
- **Training and personnel**: provide training for operators and maintenance personnel to verify they have the necessary skills and knowledge to manage and troubleshoot the microgrid effectively.
- **Emergency preparedness**: develop and implement emergency response plans and protocols to address unexpected events, such as severe weather, equipment failures, or cyberattacks.
- **Compliance**: ensure compliance with relevant regulations, standards, and safety codes governing microgrid O&M.

The O&M process is important for ensuring the reliable operation of the microgrid. It is important to have a qualified O&M team in place to manage this process. There are various maintenance philosophies that sit on the spectrum, from "run to failure" to "diagnostic overkill," described below:

- **Time-Based Maintenance (TBM)**: routinely scheduled preventive maintenance to prevent future equipment problems. Conducted to keep equipment operational and to extend the life cycle of the equipment.
- **Reliability-Centered Maintenance (RCM)**: reactive maintenance, focusing resources on bad actors by running equipment until it breaks. This requires fewer upfront resources but is usually more expensive in the long-term due to more frequent part replacement, cascading failures leading to more expensive repairs, and overtime costs to restore system operation when equipment fails during nights or weekends.
- **Condition-Based Maintenance (CBM)**: predictive maintenance, evaluating equipment condition while in service to indicate when repairs are needed.
- **Improvement-Based Maintenance (IBM):** proactive maintenance activities focus on improved operating standards by identifying the root cause of potential failures and establishing and maintaining acceptable operational standards for the potential root cause.
- **Total Productive Maintenance (TPM)**: a holistic maintenance philosophy that focuses on maximizing equipment effectiveness and involving all stakeholders in the maintenance process. TPM aims to improve overall operational efficiency, reduce defects, and enhance the skills and knowledge of maintenance teams.

- **Risk-Based Maintenance (RBM)**: considers the criticality of equipment and the potential consequences of failures. Maintenance efforts are directed toward high-risk components that could have significant safety, environmental, or operational impacts if they fail.

The choice of maintenance philosophy for a microgrid depends on factors such as microgrid's size, complexity, criticality, available resources, and budget constraints. Often, a combination of these philosophies may be employed, with different approaches applied to various components within the microgrid. The goal is to achieve a balance between reliability, cost-effectiveness, and operational efficiency while assuring uninterrupted power supply and system resilience. Figure 11 depicts an O&M decision tree to guide these conversations.

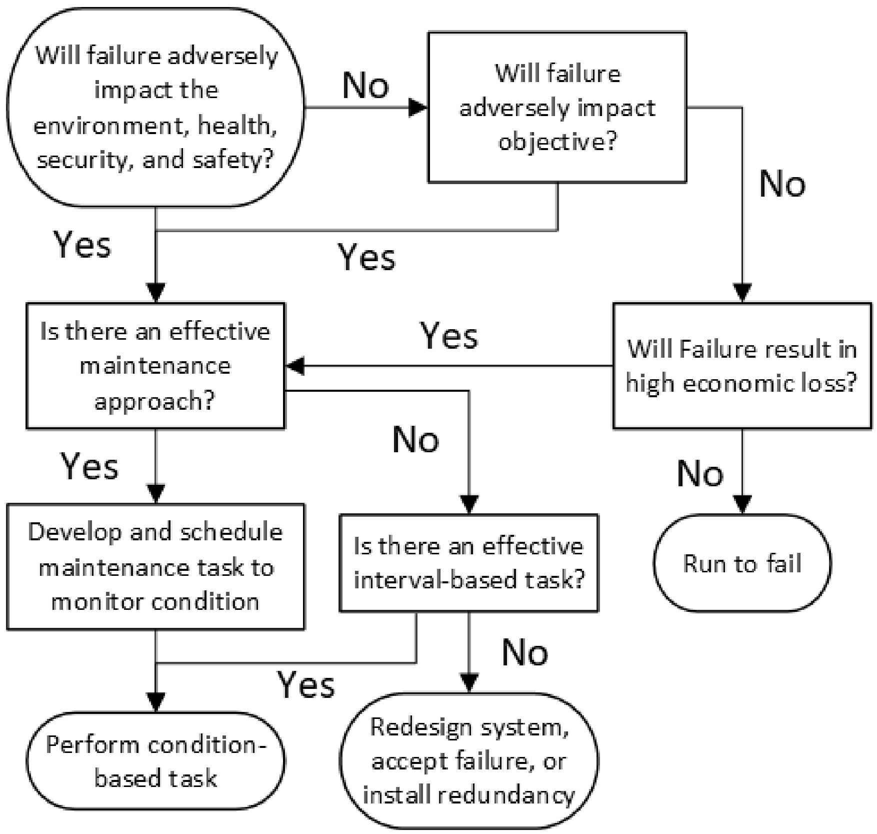

Figure 11. Operations and Maintenance Decision Tree

Several critical challenges to effective O&M of microgrids are identified as (National Renewable Energy Laboratory 2018):

- **Lack of qualified personnel:** there is a shortage of qualified personnel with the skills and experience necessary to maintain microgrids.
- **Limited budgets:** microgrid operators often have limited budgets for maintenance, which can make it difficult to implement best practices.

- **Complexity of microgrid systems:** microgrid systems can be complex, which can make it difficult to develop and implement effective maintenance plans.

To address these challenges, the study recommends that microgrid owners take the following steps:

- **Partner with qualified maintenance providers:** microgrid operators can partner with qualified maintenance providers to help them develop and implement effective maintenance plans.
- **Invest in training for microgrid operators:** microgrid operators should be trained on how to perform routine maintenance tasks and how to identify and respond to potential problems.
- **Use technology to improve maintenance efficiency:** there are many technologies that can help microgrid operators improve the efficiency of their maintenance operations.

Energy Storage Maintenance Requirements

At the 6-month interval, it is recommended to perform the following maintenance activities for energy storage devices (Hoffman 2019):

- **ESS Container**: Inspect/Clean (approximately 1 hour)
    - Enter the enclosure, inspect for obvious signs of problems such as water or dirt ingress and vermin. Clean as necessary.
- **ESS Batteries**: Inspect (approximately 10 minutes per bank)
    - Open battery cabinets, inspect for obvious visual problems such as discoloration, signs of overheating, and condensation.
- **Cooling System:** Check coolant level (approximately 5 minutes)
    - Visually inspect coolant reservoir bottle and add coolant, if low.
- **ESS Air Filters**: Inspect (approximately 1 hour)
    - Look at the transformer bay air filters, replace if necessary.
- **Fire Suppression System**: Requires certified suppression installer (time estimate varies)

At the 1-year interval, recheck the cooling system's coolant level. Open the reservoir cap and take a sample for analysis. Physical, chemical, and thermal characteristics should be monitored to ensure the coolant operates within the system as designed. Many original equipment manufacturers offer analysis as a part of their maintenance contracts. Additionally, multiple independent labs specialize in industrial fluids analysis.

4.1.2 Microgrid Cybersecurity

Microgrid cybersecurity involves protecting microgrid systems from cyberattacks, which pose a growing threat to their reliability and operational integrity. A successful cyberattack on a microgrid can disrupt power generation, compromise mission-critical operations, and potentially cause widespread power outages. For Army installations, microgrid cybersecurity is not just a technical concern. It is a mission-critical imperative that ensures energy resilience and operational continuity.

One critical component of cybersecurity for Army systems, including microgrids, is obtaining an Authority to Operate (ATO). An ATO is a formal declaration by an approving authority that a system, network, or application meets the Army's cybersecurity requirements and is authorized for use within its environment. Obtaining an ATO is crucial for any network-connected software or system, as it ensures compliance with stringent cybersecurity policies and mitigates risks to Army operations.

There are several different ways to improve microgrid cybersecurity. These include:

- **Physical security** is the first line of defense against cyber attacks. Monitoring the microgrid for suspicious activity can help identify and respond to cyberattacks quickly.
- **Compliance with Army Cybersecurity Frameworks** ensure all microgrid components and software comply with Army-specific cybersecurity frameworks, including Risk Management Framework (RMF) guidelines. RMF is integral to achieving an ATO. Obtaining an ATO is a lengthy process that should be started early in the design stage.
- **Using strong passwords** can help protect microgrids from unauthorized access.
- **Keeping software up to date** with software and firmware updates. This can help protect microgrids from known vulnerabilities. Unpatched systems area significant risk and a common target for cyber attacks.

Microgrid cybersecurity is an important part of the operation of microgrids. It is important to take steps to protect microgrids from cyberattacks. The North American Electric Reliability Corporation, Critical Infrastructure Protection (CIP) set of standards also provides guidelines for Critical Cyber Assets that may be applicable to Microgrid Assets.

5 Microgrid Financing and Regulations

The microgrid design process can be lengthy, and involves system sizing, financing, regulations and regulatory approvals, planning and deployment, and O&M plans, all of which are described in this section.

5.1 Financing

Financing is the process of raising money to fund the development of a microgrid. This can be a challenge, as microgrids can be expensive to develop. There are many ways to finance a microgrid, including:

- **Public-Private-Partnerships** : a public and private entity partner are bound by a contract to purchase the power at a fixed cost over a long duration of time. The private entity owns the microgrid and is responsible for operating and maintain it.
- **Government grants**: governments often offer grants to help fund the development of microgrids.
- **Appropriated funds**: government dollars that are earmarked for energy projects. Includes the military construction programs like the Energy Resilience and Conservation Investment Program (ERCIP) and annual appropriated O&M dollars such as the Energy/Utilities Modernization Fund, among others.
- **Private investment**: private investors can be a source of funding for microgrids.
- **Cooperative financing**: microgrids can be financed through cooperative financing, where the customers of the microgrid contribute to the funding.

The financing process for a microgrid will depend on the specific project. However, it is important to start the financing process early in the development of the microgrid. The most common financing programs include:

- **Utility Energy Service Contract (UESC)**: a multi-year contract for energy management services established between a federal agency and its designated utility provider. The contract's primary objective is to achieve quantifiable reductions in energy or water consumption, as well as measurable decreases in demand.
- **Energy Savings Performance Contract (ESPC)**: enables federal agencies to secure energy savings and enhancements to facilities without initial capital expenses or requiring specific appropriations from Congress. An ESPC represents a collaborative venture between an agency and an energy service company (ESCO).
- **Power Purchase Agreement (PPA):** governed by the Federal Energy Management Program (FEMP)'s Renewable Energy Procurement (REP) program. FEMP offers agencies expert support, advice, and education to aid in the execution of UESC/ESPC/PPA initiatives that meet high technical standards, adhere to legal requirements, and represent a favorable arrangement for the government.
- **Enhanced Use Lease (EUL):** a DoD program that allows military installations to lease underutilized land and facilities to private entities in exchange for cash or in-kind consideration that benefits the installation. This authority is codified under 10 U.S.C. § 2667 and is designed to support mission readiness while leveraging private investment for infrastructure improvements.

These four financing programs are introduced in detail below.

5.1.1 Utility Energy Service Contract

A UESC stands as a limited-source agreement connecting a federal agency with a serving utility to secure energy management services. These services encompass enhancements in energy and water efficiency, alongside reductions in energy demand. The Energy Policy Act of 1992 (codified as 42 USC. § 8256) empowers and encourages federal agencies to engage in utility incentive programs that foster such improvements, and is open to all customers of the utility.

UESCs offer an efficient avenue for federal agencies to contract a wide array of energy management services accessible through local utilities. The utility partner evaluates opportunities, and devises and executes desired energy conservation measures—ranging from lighting upgrades to renewable energy installations and combined heat and power (CHP) systems. They might also provide financing for the project. The agency can utilize a combination of appropriations and financing to fund the endeavor, offering practical flexibility. UESCs are suitable for projects of any scale.

Since the inception of the FEMP's Utility Program, federal agencies have allocated billions of dollars in total investment value to UESC projects, enhancing their facilities. Figure 12 below illustrates how the cost savings and payments flow in a UESC program.

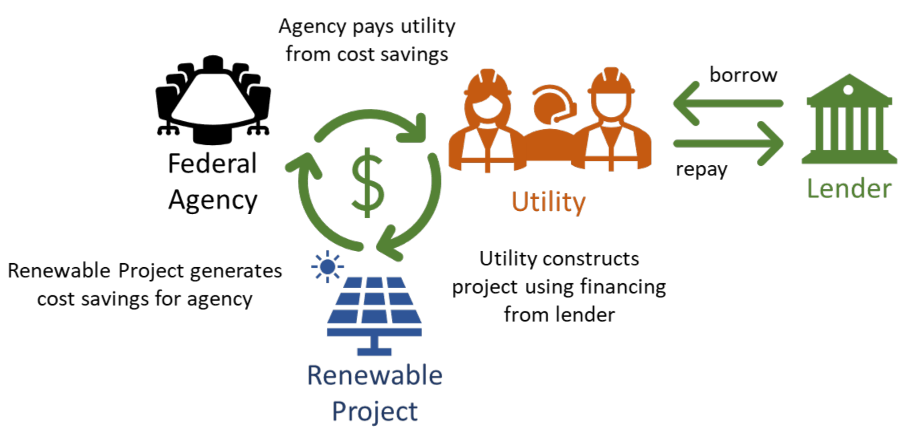

Figure 12. Cycle of Cost Savings and Payments for UESCs

The process for procuring UESC includes five phases:

- **Phase 1 - Acquisition planning**: the installation is advised to get in touch with their land holding command's (LHC) UESC point of contact. Per the DCS G-9 guidance, each LHCs must appoint a command UESC program manager (Department of the Army Guidance for Implementation of a Utility Energy Service Contract 2022). Multiple contracting offices are available to assist installations in the contracting acquisition process. The United States Army Corp of Engineers (USACE), the Defense Logistics Agency (DLA), and the United States Mission and Installation Contracting Command (MICC) can potentially support installations. These resources can provide guidance to the installation regarding the distinct procurement processes associated with UESCs.

- **Phase 2 - Utility selection and preliminary assessment:** the Installation chooses a utility and proceeds to carry out a preliminary assessment. If multiple utilities provide utility energy services (like gas and electric companies), the Federal Acquisition Regulations (FAR) require that agencies conduct a market analysis of the qualified utilities. Each interested utility is evaluated, and the agency chooses the one offering the best value for the government. This selection process involves notifying all utilities about the opportunity, assessing their responses, and ultimately choosing a single utility to undertake the PA.
- **Phase 3 - Project development**: the installation collaborates with the utility to develop a detailed investment grade audit to finalize a task order. This task order encompasses explanations of the energy conservation measures (ECMs), benchmarks, and financial timelines. It outlines projected savings, detailed costs, and the agency's payment structure.
- **Phase 4 - Project implementation and construction**: At this stage, a UESC project follows a pattern similar to a construction effort. The project design is typically between 40%–70% completed before the award is granted. The design must be completely finished, and all submissions need to be reviewed and endorsed by the agency before the utility can commence construction. Additionally, in alignment with 42 USC. § 8253(f)(5), energy-consuming equipment and control systems need to be commissioned and functioning according to the design specifications before being accepted. Government acceptance takes place when the implemented measures are prepared for advantageous use and operation.
- **Phase 5 – Post-acceptance performance**: the utility provides the agreed-upon savings and equipment performance as outlined in the contract and carries out the commissioning activities detailed in the performance assurance plan. Meanwhile, the agency oversees the UESC, ensures that the anticipated performance of ECMs is achieved, and fulfills the services specified in the contract.

For FAQs about the UESC program and a template agreement between a federal agency and a utility company, see the Resources section .

5.1.2 Energy Savings Performance Contract

An ESPC offers federal agencies the opportunity to secure energy savings and enhance their facilities without the need for initial capital expenses or special appropriations from Congress. An ESPC represents a collaboration between an agency and an ESCO.

Since the introduction of DOE's indefinite-delivery, indefinite-quantity (IDIQ) ESPCs in 1998, federal agencies have utilized the ESPC contracting framework to notably curtail energy expenses, operational costs, and advance toward federal sustainability objectives.

FEMP extends expert support, guidance, and training to federal agencies to facilitate the implementation of ESPC projects that stand out for their technical proficiency, legal soundness, and overall value for the government. This involvement by FEMP is rooted in the legislation authorizing federal ESPCs, which also designates FEMP as the federal entity responsible for establishing and offering services to enable all agencies to successfully execute ESPC projects.

FEMP is properly authorized by law to define appropriate procedures and approaches for use by federal agencies concerning the ESPC program. ESPC program structure is shown in (Figure 13). This is delineated in 42 USC. § 8287(b)(1)(A); 10 C.F.R. § 436.30(a).

Figure 13. The Energy Savings Performance Contract Structure of ESPC

Similar to UESC, the ESPC process also includes five phases:

- **Phase 1 - Acquisition planning**: Multiple contracting offices are available to assist installations in the contracting acquisition process. The USACE, DLA, and MICC can potentially support installations. These resources can provide guidance to the installation regarding the distinct procurement processes associated with ESPCs.
- **Phase 2 - ESCO selection and preliminary assessment**: the agency chooses an ESCO to move forward with project planning. This selection procedure involves informing all IDIQ ESCOs of the opportunity, assessing the responses received from ESCOs, and narrowing down the choices to two or more ESCOs. From there, the agency selects a single ESCO to conduct an initial assessment.
- **Phase 3 - Project development**: the agency collaborates with the ESCO to formulate and finalize a task order. This task order encompasses explanations of the ECMs, benchmarks, and financial timelines, outlining projected savings, assured savings, detailed costs, and the agency's payment structure.
- **Phase 4 - Project implementation and construction**: At this stage, an ESPC project closely resembles any standard construction effort. The IDIQ ESPC of the U.S. DOE incorporates the Federal Acquisition Regulations clauses, FAR Part 41 (FAR 2025), typically found in any government construction project.
- **Phase 5 - Post-acceptance performance**: The ESCO fulfills the agreed-upon savings and equipment performance, as stipulated in the contract, and carries out the annual measurement and verification tasks outlined in the measurement and verification plan. Meanwhile, the agency oversees the ESPC, ensures compliance with guarantees, and carries out the services outlined in the contract.

For FAQs about the ESPC program and a template for ESPC acquisition plan is included in the Resources section.

5.1.3 Power Purchase Agreement

In a PPA, a third-party developer sets up, possesses, and manages an energy system on the property of a customer. The customer then procures the generated electricity from the system over a specified timeframe. A PPA offers the customer the benefit of accessing consistent and often cost-effective electricity without any initial expenses. In turn, the system owner capitalizes on tax credits and earns revenue from selling electricity. While typically associated with renewable energy systems, PPAs can also be employed for various energy technologies, including CHP.

Throughout the duration of the PPA, the developer and its investors possess the equipment. Typically, the developer initiates the process by securing temporary financing, planning, and obtaining permits, often incurring minimal or no expenses for the customer. The equipment installation might be carried out internally by the developer or by an external contractor.

The electricity produced by the energy system is subsequently procured by the customer at a rate that commonly falls below the retail rate charged by the utility, leading to immediate savings. The PPA rate typically experiences an annual increase of 1%–5% throughout the contract period (known as a price escalator), to accommodate gradual declines in system operational efficiency, operating and maintenance expenses, and rises in the retail electricity rate. PPAs generally span over extended periods, ranging from 10 to 25 years. Upon the contract’s conclusion, the customer might have the option to prolong the agreement, acquire ownership of the system from the developer, or arrange for the equipment's removal from the property.

The developer commonly establishes a distinct entity known as a special purpose entity (SPE) for every project, which assumes the role of the legal proprietor of the energy system. The primary function of the SPE is to secure financial resources through debt and equity investments for the project. Consequently, ownership of both the SPE and the project is shared between the developer and the investor(s). This approach allows for project-level investments, shielding investors from potential risks tied to the developer’s other projects. Additionally, it mitigates the developer’s exposure to risks in case the project faces defaults or other complications. Figure 14 displays the structure of PPA.

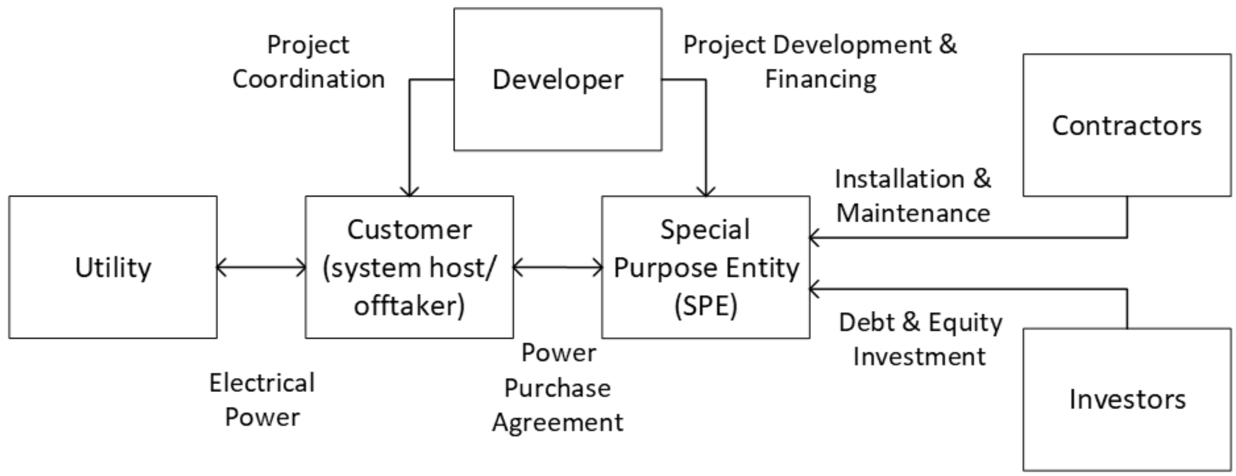

Figure 14. Power Purchase Agreement Structure

Note that for a PPA to be a viable option, the project needs to be located in a region or jurisdiction that permits third-party ownership of energy generation equipment. Certain state regulations constrain non-utility entities in regulated markets, restricting their ability to sell electric power.

FAQs about the PPA program and sample documents for PPAs can be found in the Resources section.

5.1.4 Enhanced Use Lease

An EUL is a valuable tool for Army energy managers, enabling installations to form public-private partnerships with developers or utility companies to address critical infrastructure needs. By leasing underutilized land, facilities, or resources to private entities for a specified period, installations can unlock significant opportunities for mission-aligned improvements. In return, the Army receives compensation through cash payments, infrastructure enhancements, or services, often directly supporting operational readiness and energy resilience. EULs are highly flexible, making them adaptable to a wide range of projects, including energy systems like microgrids, housing developments, or commercial ventures. These partnerships provide a strategic approach to leveraging private investment for enhancing installation capabilities while maintaining a focus on the Army's mission.

5.2 Regulation and Regulatory Approvals

Microgrid regulation is the process of developing and enforcing regulations for microgrids. These regulations are important to assure the safety, reliability, and security of microgrids. The specific regulations for microgrids will vary from country to country. However, there are some common principles that are typically included in microgrid regulations. These principles include:

- **Safety**: microgrids must be designed and operated in a safe manner.
- **Reliability**: microgrids must be able to provide reliable power to their customers.
- **Security**: microgrids must be protected from cyberattacks and other security threats.

Microgrid regulation is an important part of the development and deployment of microgrids. It is important to have clear and consistent regulations in place to assure the safety, reliability, and security of microgrids. Regulatory approvals are the permissions that are required from government agencies to develop and operate a microgrid. These approvals can be complex and time-consuming to obtain. The specific regulatory approvals that are required will depend on the location of the microgrid and the type of microgrid. However, some common regulatory approvals include:

- **Building permits**: required to construct the physical infrastructure of the microgrid.
- **Utility interconnection agreements**: required to connect the microgrid to the main grid.
- **Environmental permits**: may be required to protect the environment from the impacts of the microgrid.

The regulatory approval process can be a challenge, but it is important to obtain the necessary approvals before developing a microgrid.

State energy offices and Public Utility Commissions (PUCs) are tasked with developing programs, policies, rules, and regulations for microgrids. DoD has Unified Facilities Criteria (UFC 3-550-04) requirements on resilient installation microgrid design for the Army. Many states are actively working to promote the deployment of microgrids to enhance resilience and achieve various policy objectives, including clean energy integration, expanded electricity access, cost reduction, and support for underserved communities. The urgency of these efforts is influenced by several factors:

- **Reliability**: evaluating the frequency, duration, and scale of power outages, as well as the impact on service quality.
- **Resilience**: evaluating threats to utility service and whether microgrids can protect customers and infrastructure from physical or cyber threats.
- **Customer Engagement**: identifying the types of customers interested in microgrids, including residential, municipal, commercial, and industrial customers.
- **Market Structure**: considering entities participating in the microgrid market, standardized interconnection agreements, and potential regulation of community-owned microgrids.

- **Utility Involvement**: determining whether utilities can own and operate microgrid components, how multi-customer microgrids should be managed, and their access to wholesale markets.
- **State Policy Goals**: aligning microgrid development with state objectives such as clean energy, affordability, and resilience.

PUCs play a crucial role in defining and regulating microgrids. They establish conditions and classifications for microgrid operators, determining whether microgrids fall under public utility regulations. For example, in the District of Columbia, the Public Service Commission issued proposed rules governing microgrid development. These rules classify multiple customer microgrids as public utilities, requiring them to obtain certificates and adhere to cost-of-service rate regulation as do investor-owned utilities.

PUCs have also explored rate recovery mechanisms for microgrid energy and services. The challenge lies in determining who benefits from microgrids and how to allocate costs in a fair way. During outages or emergencies when a microgrid operates in isolation, only those within its footprint benefit from its services, raising questions about compensating ratepayers for services they do not receive. PUCs nationwide are actively assessing the costs and benefits of microgrids compared to other reliability and resilience investments, such as additional generation, transmission, distribution capacity, or grid hardening practices. The aim is to assure fair and efficient regulation of microgrids while avoiding cost-shifting.

To assist states and PUCs, the National Association of State Energy Officials (NASEO) and the NARUC have created a framework for developing state-level policies, programs, or regulations related to microgrids. The framework provides background information, examples from different states, and guidance for stakeholders interested in understanding and engaging with microgrid-related policy and regulatory initiatives.

The framework is organized into several sections:

- **Section I**: Provides background information on microgrids, definitions, and the role of the framework as a resource for state energy offices and PUCs.
- **Section II**: Offers an overview of existing State Energy Office and PUC efforts related to microgrids, including factors such as resilience threats, market structure, and legislative activity.
- **Section III**: Discusses the needs of state energy offices and PUCs when scoping and launching microgrid policies, programs, projects, or regulatory actions, emphasizing stakeholder engagement and technical assistance.
- **Sections IV and V**: Presents existing state programs and regulatory initiatives as examples to guide the development of microgrid policies and programs or regulations. These sections are designed to help state energy offices and PUCs determine the steps needed for their specific circumstances.

Overall, the framework aims to support the safe, reliable, and affordable deployment of microgrid projects to meet state policy goals and requirements.

Microgrid programs and regulations often originate from state legislation, involving appropriations and definitions. Implementing these initiatives can take several years due to complexity and stakeholder input solicited through workshops, public comments, and other avenues. Stakeholder engagement is vital to capture the needs of diverse energy system stakeholders. For example, investor-owned utilities differ from states with vertically integrated markets and restructured electric utilities. These differences impact microgrid ownership and operation. Consumer-owned utilities face unique challenges, such as educating members and overcoming financial constraints, but can benefit from microgrids by reducing transmission costs and enhancing resilience. Each stakeholder group plays a role in shaping programs and regulations.

5.2.1 Legislative Actions

Legislative actions significantly influence the development of microgrid programs, policies, and regulations. Governors and legislatures often direct state energy offices to explore microgrid initiatives, and these actions are indispensable due to the growing legislative interest in microgrids. As of the time of writing, 21 states and Puerto Rico have substantive microgrid laws or mentions of microgrids in their legislation.

Legislative efforts can encourage microgrid development by:

- Establishing a standard statewide microgrid definition.
- Appropriating funding for grant programs and technical assistance.
- Creating state green or resilience banks to fund projects, including microgrids.
- Setting interconnection, standardization, and microgrid tariffs.
- Integrating microgrid considerations into other state policies.

Legislation plays a crucial role in shaping State Energy Office and PUC activities, requiring the setup of grant programs, microgrid tariffs, or regulatory proceedings. Collaborative efforts among legislators, state energy offices, and PUCs are important for defining action plans and addressing barriers to microgrid deployment.

Examples of legislative impact include California's SB 1339 (CPUC 2025), which directed the CPUC to develop microgrid standards and incentives. Colorado passed legislation (CGA 2022) (CGA 2022)to advance microgrid deployment and resilience. Oregon has the Oregon Community Renewable Energy Grant Program (ODOE n.d.), and HB 3378 aims to study microgrid development and adoption (OSL 2023). North Carolina's SB 509 created a revenue fund to support clean energy microgrid projects through technical assistance (NCGA 2021). State leadership goals, such as renewable energy standards, can also drive microgrid-related actions.

State energy offices, governors, and organizations like NASEO-NARUC can influence legislation by advocating for supportive policies and energy plans. Examples of microgrid initiatives advancing without legislative activity include Wisconsin's Critical Infrastructure Microgrids and New Jersey's Town Center Distributed Energy Resources microgrid program (NJIT 2014). North Carolina's Department of Environmental Quality used data and mapping tools to identify potential sites for resilience projects (SEPA 2025), highlighting the importance of data analysis in microgrid planning.

5.2.2 Policies and Programs

Legislative actions often result in the allocation of funds for state energy office-driven microgrid programs, including grants, incentives, road maps, and feasibility studies. State energy offices take the lead in these statewide initiatives by engaging stakeholders and analyzing data from various sources, such as utilities, private sector entities, local governments, and communities.

These initiatives, like road maps and feasibility studies, serve to:

- Identify ideal microgrid locations;
- Evaluate factors such as cost, energy sources, battery storage, and engineering design;
- Highlight deployment challenges and regulatory/policy structures;
- Consider project costs and viability;
- Assess community and environmental impacts;
- Align microgrid development with state priorities, such as decarbonization and resilience; and
- Identify key stakeholders for consultation.

For example, Wisconsin's Office of Energy Innovation's Critical Infrastructure Microgrids and Community Resilience Centers Pilot Grant program awarded feasibility study grants to 15 entities, including tribal governments, utilities, and nonprofit groups (PSC Wisconsin n.d.). These studies help gather critical information before investing in project development. The Kentucky Office of Energy Policy led a study conducted by the Smart Electric Power Alliance, "Regional Microgrids for Resilience" (SEPA 2021), which collected data on demographics, critical infrastructure, natural hazards, and utility-related metrics in the region.

6 Future of Microgrids

The future of microgrids is bright. Microgrids have the potential to improve the reliability, resilience, and sustainability of the electric grid. As the technology for microgrids continues to evolve, microgrids are likely to become more widespread in the future.

6.1 Trends in Microgrid Technology

The technology for microgrids is constantly evolving. There are numerous technologies being developed that have the potential to improve the performance and reliability of microgrids, as well as to implement decentralized energy solutions. Some of the most promising new microgrid developments include:

- **Renewable energy integration**: microgrids are increasingly incorporating renewable energy sources such as solar panels, wind turbines, and energy storage systems.
- **Distributed energy resources**: DERs are becoming more efficient and affordable. This is making it possible to develop microgrids that are powered by a wider range of DERs.
- **Energy storage**: energy storage is becoming more cost-effective. Storage systems enhance grid stability and enable energy resilience to provide backup power during outages.
- **Microgrid control systems**: microgrid control systems are becoming more sophisticated. Advanced software and algorithms enable efficient energy dispatch, load management, and seamless transitions between grid-connected and island modes.
- **Hybrid microgrids**: hybrid microgrids combine multiple DERs, such as solar, wind, and fossil fuels, to provide reliable and cost-effective power. These systems optimize energy generation based on resource availability and demand.
- **Microgrid as a Service (MaaS)**: MaaS models are emerging, allowing organizations to adopt microgrids without upfront capital costs. Third-party providers design, build, operate, and maintain microgrids under long-term contracts.
- **Cybersecurity and resilience**: with the growing digitization of microgrids, there is an increased focus on cybersecurity to protect against cyber threats and assure the resilience of microgrid operations.
- **Microgrid standards**: the development of international and national standards specific to microgrids is advancing, providing guidelines and best practices for design, operation, and safety. See the latest revision of IEEE Std. 1547, which covers inverter-based resources and provides guidelines around islanding.
- **AI and IoT integration**: artificial intelligence and the Internet of Things are being leveraged to optimize microgrid operations, predict energy demand, and improve energy efficiency.
- **Grid-forming inverters**: these inverters can serve as independent black start resources, restoring the grid from outages without relying on a strong grid connection. This enhances overall system reliability.
- **Small modular reactors**: nuclear technology has the potential to provide a large impact on the microgrid industry. Small modular reactors are non-greenhouse gas-emitting energy resources that occupy a much smaller footprint than a solar array, with the tradeoff of

operating with radioactive materials. The design is being evaluated by the Nuclear Regulatory Commission to ensure safety considerations drive the development of this technology.

- **Electric Vehicles**: EVs have the potential to become portable BESS to be used during emergencies to provide critical infrastructure with temporary power. Note that they are also a load burden as they require energy to function in an emergency.

The trends in microgrid technology are constantly evolving. It is important to stay up-to-date to assure that microgrids can be developed and deployed in a way that meets the needs of their customers.

6.2 Microgrids for Critical Infrastructure

Microgrids can provide power to critical infrastructure, such as hospitals, data centers, and military bases. These microgrids are designed to be able to operate independently of the main grid so that they can provide power during grid outages. The duration that a microgrid is required to operate while islanded from the main grid can be determined on a case-by-case basis or by requirements in that industry. It is also important to note that utility interconnection agreements may have provisions for critical infrastructure to reduce restoration times by having either standby crews or priority restoration to reduce the duration of islanded operation.

Microgrids for critical infrastructure are becoming increasingly important, as the demand for reliable power in critical infrastructure continues to grow. These microgrids can help to assure that critical infrastructure is able to continue operating even during major disruptions to the power grid.

6.3 Microgrids for Disaster Resilience

Microgrids designed to be able to operate during and after natural disasters are typically located in areas that are prone to natural disasters, such as hurricanes, earthquakes, and floods. Microgrids for disaster resilience are becoming increasingly important to assure communities can recover from natural disasters more quickly and easily, as the frequency and intensity of extreme weather events continue to increase.

BESS and diesel generators have both been proven to provide stable power during outages, however diesel generators have been disincentivized at a federal level due to emissions that contribute to adverse health impacts from poor air quality.

Microgrids for disaster resilience are often paired with emergency response planning for outages. For instance, it is often critical to ensure refrigerators remain powered to store perishable foods and medicine, and that batteries for medical equipment remain charged. It is important to define the critical assets and assign comprehensive roles and responsibilities before and during such events.

6.4 Challenges and Opportunities

Developing and implementing a microgrid can be challenging. Some of these challenges include:

- **Cost**: microgrids can be expensive to develop and deploy.
- **Regulation**: microgrids are subject to a variety of regulations, which can make it difficult to develop and deploy them.
- **Technology**: the technology for microgrids is still evolving; variation in capabilities between manufacturers can lead to high costs and lack of standardization.

However, microgrids also provide many benefits, including:

- **Reliability**: Microgrids can provide reliable power during grid outages.
- **Resilience**: Microgrids can be designed to withstand extreme weather events.
- **Sustainability**: Microgrids can be powered by renewable energy sources, which can help to reduce greenhouse gas emissions.

It is important to consider both the challenges and opportunities of microgrids when making deployment decisions, as both are constantly evolving.

7 Additional Topics

7.1 Standards and Regulations

Microgrid standards and regulations are the rules and guidelines that govern the design, construction, operation, reliability, safety, security, and interconnection of microgrids. This section identifies key standards and regulations in the U.S. and internationally.

7.1.1 United States

IEEE 1547: this is a standard for interconnecting DERs, including microgrids, with the electrical power system. It covers various aspects of DER interconnection, including safety, power quality, and protection.

IEEE 2030: provides guidelines for the integration of renewable energy sources and DERs into the power grid, which is relevant to microgrid design and operation.

IEEE 1547.4: focuses on the design, operation, and integration of microgrids into the distribution system, addressing control strategies, protection, and communication.

IEEE 1547.6: provides testing procedures and requirements for microgrid controllers, assuring their reliability and functionality.

UL 1741: a safety standard for inverters, converters, controllers, and interconnection system equipment used in renewable energy and microgrid applications. Compliance with this standard is often required for microgrid components.

NFPA 70, National Electrical Code (NEC): the NEC contains electrical installation requirements that may apply to microgrid components and their interconnection with the grid.

NEMA MG 2: offers guidelines for the design and application of motors and generators, essential components of many microgrids.

State-specific regulations: many U.S. states have developed their own regulations and guidelines for microgrids, often in collaboration with PUCs. These regulations can vary significantly from state to state.

Federal Energy Regulatory Commission (FERC) Orders: FERC has issued various orders and rules related to microgrids and DERs, including FERC Order No. 2222, which addresses the participation of DER aggregations in wholesale energy markets.

7.1.2 International

IEC 61850: an international standard for the communication and integration of protection and control equipment in electrical substations and microgrids.

IEC 62257: a series of international standards that provide guidelines for the design and implementation of microgrids in developing countries, focusing on off-grid and rural electrification.

IEC 62559: a standard series that provides requirements for the design, installation, and operation of microgrids.

ISO 50001: a standard regarding energy management systems, which can be applied to microgrid operations to improve energy efficiency and sustainability.

IEC 61508: a standard for functional safety of electrical, electronic, and programmable electronic safety-related systems, which may apply to safety-critical aspects of microgrids.

IEC 61400: this standard covers the design and safety of wind turbines, which are often integrated into renewable energy microgrids.

IEC 62443: a standard series that provides a cybersecurity framework for industrial automation and control systems, including those used in microgrid control.

Microgrid standards and regulations are an important part of the development and deployment of microgrids. It is important to be aware of the relevant standards and regulations when designing, constructing, and operating a microgrid. When planning and implementing microgrids, consulting with experts and regulatory authorities in your specific region is essential to ensure compliance with applicable standards and regulations.

7.2 Case Studies

7.2.1 U.S. and U.S. Government Microgrids

Fort Hunter Liggett, USAR, California

Source: (interview with Jarrod Ross, November 27, 2024)

Fort Hunter Liggett (FHL), a prominent U.S. Army Reserve installation, has become a benchmark for microgrid development, showcasing innovative approaches to energy resilience and sustainability. Initiated in 2008, the FHL microgrid aimed to address the installation's historical energy reliability issues. FHL's leadership recognized the potential of microgrids to enhance energy independence while supporting the Army's broader energy security and environmental goals. This case study examines the development, implementation, and lessons learned from the FHL microgrid project.

Background and Implementation

In 2010, FHL was designated as a Net Zero Energy demonstration site, reflecting its commitment to energy efficiency, renewable energy integration, and sustainability. This designation underscored the Army's intent to use FHL as a model for achieving energy independence and resilience, aligning with broader goals to reduce reliance on traditional energy sources and enhance mission readiness. This recognition catalyzed funding and support for microgrid development and complementary projects, such as heat pump installations and building efficiency upgrades.

Electrification and demand reduction were central to FHL's resilience strategy, enabling the installation to reduce dependence on fossil fuels and optimize energy usage. By transitioning HVAC and domestic hot water systems to efficient heat pumps and implementing advanced building controls, the installation significantly lowered its energy demand and use. These efforts complemented the microgrid by ensuring that reduced and more predictable energy loads could be effectively managed during islanded operations, maximizing the capacity of on-site renewable generation and storage systems.

The microgrid development process at FHL began with the installation of solar arrays and small-scale battery storage systems. By 2015, the first three phases of solar installations were completed, providing 3 megawatts (MW) of renewable energy capacity. These projects were funded through various appropriated funds. The initial energy storage system was a 1 MW/1.25 MWh battery that was primarily used for peak shaving. The battery was insufficient at the time to support mission critical infrastructure on the installation during outages on its own. Subsequent ERCIP projects expanded the microgrid's capabilities, adding 3.75 MW of solar, a 2.5 MW/5MWh BESS, and a SCADA system to integrate and automate operations.

FHL is planning to leverage a UESC to address critical gaps in its microgrid infrastructure and operations. This contract will repair the original 3 MW solar array, incorporate upgrades to enhance water resiliency, and install an additional 4 MW/4 MWh BESS. Additionally, the UESC addresses a major challenge for the installation by funding ongoing O&M for the microgrid's components and controller. Unlike appropriated funds, which do not address O&M needs, the long-term nature of the UESC ensures that FHL has the resources and contractual framework necessary to maintain and optimize its microgrid systems.

Challenges and Technical Innovations

The development of FHL's microgrid was marked by significant challenges, many of which stemmed from the complexity of managing multiple interconnected projects over nearly two decades. A major structural challenge was the reliance on appropriated funding, which does not provide project-specific O&M funding for sustaining energy projects post-installation. While this approach is common for energy conservation and water conservation measures, it proved particularly problematic for FHL's microgrid, which requires ongoing technical expertise and support to remain operational. Without sustainment funding, the installation struggles to address maintenance needs for critical components, which are critical for the microgrid's functionality and resilience.

One of the best examples of this was the lack of proper maintenance for the initial 3 MW solar array installed between 2012 and 2015. The contractor responsible for O&M failed to address key deficiencies, leading to the solar array becoming non-operational by 2017. Despite quarterly inspection stickers from maintenance service providers, critical systems were left unrepaired, illustrating systemic failures in contractor oversight and accountability.

Manpower shortages added another layer of complexity to the microgrid's development and operation. The lack of a dedicated engineering department at FHL hindered the installation's ability to review and approve project designs, verify contractor performance, and address O&M gaps. These staffing challenges also affected ancillary systems critical to the microgrid, such as the wastewater treatment plant, which lacked certified operators to bring it fully online. This shortage of skilled personnel created bottlenecks in project implementation and exacerbated maintenance and operational issues, further complicating efforts to achieve energy resilience.

FHL's experience with the their contracting agency highlights significant frustrations stemming from a disconnect between the installation's needs as a customer and the execution of contracts by that agency. As the contracting authority they are responsible for overseeing design, award, and project commissioning, yet it often failed to ensure contractors delivered high-quality results. For instance, the installation encountered issues where project managers prioritized closing out contracts and issuing positive reviews for contractors, even when punch list items were incomplete or unresolved. This misalignment of incentives allowed contractors to focus on meeting minimal requirements to secure payment, often leaving the installation with incomplete or non-functional systems.

The lack of technical expertise within their contracting agency compounded these problems. Field inspectors frequently lacked the practical knowledge to assess the functionality of microgrid components and often relied on checking specifications against design documents rather than evaluating operational performance. This gap in understanding created delays and forced installation staff to step in and advocate for corrections. One notable example was the failure of the contracting agency to address persistent communications issues within the SCADA system, leaving the installation unable to complete critical endurance tests. Furthermore, the contracting agencies personnel often left projects in limbo during critical periods, such as leaving unresolved requests for contract extensions during testing phases. This lack of accountability and technical rigor hampered the microgrid's development and underscored the need for better alignment between contracting authorities and installation requirements.

This experience illustrates the necessity of involving installation staff, who better understand operational requirements, more directly in the contracting process. It also highlights the importance of improving training for contracting personnel to ensure they can effectively manage and commission advanced energy systems like microgrids.

The lack of consistency in planning and execution across the various projects also posed significant challenges. With different contractors, funding sources, and timelines, ensuring alignment and integration of all components into a cohesive system required constant oversight and adaptation. These challenges underscore the importance of long-term planning, robust contract management, and sustained funding for microgrid initiatives, especially for complex, multi-phased efforts like those at FHL.

Operational Insights and Resilience Strategies

The microgrid's operational design ensures that critical infrastructure remains functional during grid outages. The SCADA system dynamically manages energy generation, storage, and load prioritization, although challenges remain to fully automate operations. When a power outage occurs, the microgrid transitions into island mode through a carefully programmed sequence of events designed to maintain stability and prioritize mission critical loads.

When utility power is lost, the SCADA system detects the interruption and initiates the disconnection of FHL's electrical distribution system from the utility grid by opening the recloser. This isolates the installation from the broader utility network, preventing back-feeding and ensuring safe operation. Simultaneously, the system transitions the battery storage from a grid-following mode to a grid-forming mode, allowing the microgrid to stabilize voltage and frequency on the installation's backbone. The microgrid then sequentially energizes the distribution backbone before selectively reconnecting loads based on a priority list. Critical facilities are brought online first, followed by additional loads as resources allow. The system monitors solar generation throughout the day, using excess production to recharge the battery and gradually adding more loads until the battery's charge or solar output is sufficient.

However, the microgrid's current communication system has introduced challenges to these operations. Initially configured as a point-to-point network, the SCADA communications infrastructure was reconfigured into a mesh network to improve efficiency and speed. This change aimed to create a more robust system by enabling multiple paths for data transmission, reducing bottlenecks, and increasing system reliability. Unfortunately, the reconfiguration caused unexpected failures, including difficulties maintaining stable communication between SCADA components. This issue has disrupted the seamless coordination of operations, preventing the microgrid from executing overnight endurance tests or managing day-two operations autonomously. While efforts are underway to resolve these communication problems, they have highlighted the complexity of integrating advanced technologies into operational systems and the importance of rigorous testing and validation during commissioning.

Lessons Learned and Broader Implications

The FHL microgrid underscores the importance of comprehensive planning, stakeholder engagement, and adaptability in large-scale energy projects. Key lessons include the critical role of contractor oversight, the necessity of aligning project design with long-term O&M requirements, and the value of integrating complementary infrastructure upgrades. Moreover, FHL's experience highlights the importance of tailoring microgrid solutions to site-specific conditions, such as climate and load requirements. The project's successes and challenges provide valuable insights for other military installations and organizations pursuing similar energy resilience initiatives.

Additionally, the experience at FHL demonstrates a critical need for training personnel to better manage Military Construction (MILCON) projects, including those funded through ERCIP. Comprehensive training provided by resources like the Construction Engineering Research Laboratory (CERL) could equip staff with the technical knowledge needed to oversee design, commissioning, and integration of complex microgrid systems. Finally, future projects must prioritize ongoing maintenance, incorporating robust O&M strategies and funding from the outset to ensure the long-term functionality and resilience of these critical systems.

Conclusion

The FHL microgrid represents a significant achievement in advancing energy security and sustainability for military installations. While the project faced numerous hurdles, including infrastructure limitations and operational, contractual, and manpower challenges, its innovative design and strategic implementation have positioned FHL as a leader in microgrid technology. The lessons learned from FHL's journey offer a road map for other installations seeking to enhance resilience and efficiency through microgrid solutions. As the Army and other organizations continue to pursue energy independence, FHL's microgrid serves as a model for the integration of renewable energy, advanced controls, and comprehensive planning in achieving mission resilience.

Marine Corps Air Station (MCAS) at Miramar, California

From: (Black & Veatch 2022), (Cohn, Lisa 2023), (Correspondence with Mick Wasco, S-4 Public Works Division, 2023).

MCAS Miramar, located in San Diego, California, houses over 15,000 service members and their families. The mission of MCAS Miramar is to maintain and operate air station facilities and property while providing services, material support, and training venues that promote combat readiness and support the missions of the 3rd Marine Aircraft Wing and other tenants aboard the installation.

The MCAS microgrid was developed in a joint venture between Black & Veatch and Schneider Electric. The microgrid is designed to operate for 21 continuous days with on-site fuel supply. The MCAS Miramar microgrid utilizes 50% on-site renewable energy and includes Tier 4 clean burning diesel and natural gas generators, in compliance with the state Air Pollution Control District regulations, supplying cleaner burning generation than what the local grid would typically provide.

The microgrid includes four generators:

- 6.5 MW diesel and natural gas-fired power plant,
- 3.2 MW of landfill gas power acquired through a PPA,
- 2 MW of solar PV,
- 2 MW diesel facility backup generator with electrical paralleling capability to the microgrid.

Landfill gas comes from a separate power plant operated by a third party, Opal Fuels. The power plant consists of two engines that use methane gas collected from the garbage at the landfill.

The microgrid is designed to operate in both island and grid-connected modes. Miramar has completed several black start exercises and microgrid islanding tests. The microgrid controls are programmed to perform fast load shedding and can also be operator-directed. The system will further be developed with California Energy Commission funds to shed air conditioning loads as a less disruptive load management measure. Economic programming in grid-connected mode involves energy optimization, peak shaving, and demand-response operations.

In partnership with the CPUC and San Diego Gas and Electric, the microgrid is enrolled in multiple demand-response programs; the Emergency Load Reduction Program and a site-specific innovative tariff called the Miramar Summer Generation Incentive. In the Summer of 2022, both programs were called up for 10 days of grid support, yielding MCAS Miramar over $400,000 in incentives.

MCAS Miramar is currently building a large-scale energy storage system as an additional DER asset to the microgrid. This asset will provide stability in island mode, allow for greater renewable penetration in the system, as well as enhance the system's peak shaving capability.

USAG Kwajalein, Atoll, Marshall Islands

Source: (U.S. Army n.d.), (Cohn 2018)

Approximately 1,300 U.S. Government military service members, DoD Civilians, and Contractor Americans inhabit the two islands of Kwajalein and Roi-Namur. Each island in the USAG-KA is operated by a separate utility reliant on diesel generators, and power is distributed to military facilities via government-owned and operated infrastructure. The microgrid project at U.S. Army Garrison Kwajalein (USAG-KA) on Meck Island consists of 2.4 MW solar and 2 MW / 3 MWh Li-Ion BESS. The integrated and distributed microgrid control network is designed to prioritize the most efficient and reliable asset at any given time, which is expected to reduce diesel consumption by 55%. The microgrid project was complemented by a series of lighting upgrades to LEDs, expected to reduce lighting costs by 64%. The combined microgrid and energy efficiency project is estimated to save $2.2 million annually over the 20-year performance period.

Pele United States Army Reserve Center, Tutuila Island, American Samoa

Source: (Bradford, Ashley 2021)

Tutuila Island is the main island in American Samoa, a U.S. territory since 1900 in the south-central Pacific Ocean. Tutuila is home to 50,000 people with an Army Reserve presence of 275 soldiers and civilians. Funded through ERCIP, this microgrid contains a 325 kW roof-mounted PV array, a 150 kWh BESS, and incorporated an existing 300 kW generator. The system provides an estimated annual savings of $124,000 through reduced energy use and demand. The energy specialist at the 9th Mission Support Command attributes the success of the project to partnering with other staff sections up-front to coordinate cybersecurity, environmental assessments, and conducting numerous planned blackouts to test the system. "Through programmed blackouts… we conducted full-scale testing of emergency energy generation systems, infrastructure, and equipment. We learned a lot about what worked well and what did not work well with the center's generator set-up and utility to inform our decisions.""

Fort Carson, IMCOM, Colorado

Source: (Interview with Sean Bogren, Installation Energy Manager, December 3, 2024)

Fort Carson's microgrid journey began in 2012 when the installation was selected for the Smart Power Infrastructure Demonstration for Energy Reliability and Security (SPIDERS) program. This initiative aimed to enhance energy resilience through cutting-edge microgrid technologies, integrating renewable energy, battery storage, and advanced controls to allow for independent operation (islanding) during grid disruptions.

By 2013, the SPIDERS Phase 2 project showcased a successful 72-hour operational demonstration. The microgrid supported critical operations using a combination of a 1 MW PV array, diesel generators, and electric vehicles equipped with vehicle-to-grid (V2G) capabilities. This milestone validated the microgrid's ability to provide energy resilience and meet mission-critical needs in a controlled environment.

Following the conclusion of the SPIDERS program in 2014, the microgrid was transitioned to Fort Carson for long-term management. However, the system was handed over without a dedicated O&M contract or clear strategies for sustaining operations. Over time, challenges arose, including the proprietary nature of the control systems, lack of firmware updates, and limited training for installation personnel. These factors gradually undermined the system's functionality.

The installation continued to expand its renewable energy capabilities, commissioning a 2 MW PV system in 2016 to complement the microgrid. Despite these efforts, by 2020 the proprietary microgrid components had become obsolete, with no further vendor support or software updates, rendering the system effectively inoperable or "bricked". Attempts to revitalize the system were deemed too costly and not aligned with mission priorities.

In parallel, Fort Carson pursued other energy resilience measures. In 2018, a 4.25 MW/8.5 MWh lithium-ion battery was installed under an ESPC, primarily for peak shaving and energy cost reduction. While the battery added value, its limited cycle life and dependency on accurate peak predictions restricted its utility for broader resilience goals. By 2022, a 1 MW flow battery was installed, offering enhanced daily cycling capabilities and longer operational life.

Lessons Learned from the Fort Carson SPIDERS project

The Fort Carson microgrid project offers a wealth of insights into the challenges and opportunities associated with developing resilient energy systems. One of the most critical takeaways was the importance of incorporating sustainable O&M agreements. The lack of ongoing O&M support for the SPIDERS microgrid contributed to its decline, as the Army did not have the expertise or resources to maintain the system independently. Future projects must ensure O&M agreements are in place, whether through the original vendor or a trained third-party contractor, to safeguard long-term functionality.

Vendor and technology selection also proved to be a significant vulnerability. The microgrid relied on proprietary technology, which became a liability when the vendor ceased support and discontinued firmware updates. This left critical components inoperable, effectively rendering the system "bricked." Future designs should prioritize open-source solutions or work with established vendors with a proven track record of longevity to minimize such risks.

The system's design also highlighted the importance of aligning infrastructure with mission priorities. The microgrid connected buildings without strategic consideration for their operational importance during emergencies. Future projects should focus on grouping facilities logically, ensuring the system can prioritize mission-critical loads when needed.

As a demonstration project, the SPIDERS microgrid underscored the limitations of temporary initiatives. Demonstration projects often lack scalability and long-term viability, as they are designed primarily for testing rather than sustained operation. Fort Carson's experience emphasizes the need to plan for transitioning successful pilot projects into fully operational systems with lasting value. Without dedicated funding or a plan for post-demonstration operations, the SPIDERS microgrid was abandoned once its initial purpose was fulfilled. Transition plans and long-term funding mechanisms are essential to ensure such investments continue to deliver value beyond the testing phase.

Integration challenges further complicated the microgrid's effectiveness. The system was not well-integrated with Fort Carson's existing robust energy infrastructure, which already featured triple redundancy and underground distribution. This diminished the microgrid’s perceived value. Future resilience projects must complement existing systems and address specific gaps rather than duplicating capabilities. While Fort Carson's robust utility infrastructure helped mitigate the impact of external grid disruptions, the microgrid’s inability to adapt to evolving needs ultimately limited its utility. Projects must remain flexible and scalable to meet both current and future demands.

By addressing these lessons learned, future microgrid projects can achieve greater resilience, sustainability, and operational value, ensuring they contribute meaningfully to the mission goals of installations like Fort Carson.

Community Microgrid, Adjuntas, Puerto Rico:

Source: (Rapin 2023), (De La Garza 2023)

In 2017 hurricane Maria left many in the center of Puerto Rico without power for 11 months. Even before Maria, Puerto Ricans dealt with an unreliable electricity system while paying nearly double the U.S. average price of electricity. The majority (97%) of the electricity supply comes from centralized fossil fuel power plants, largely in the southern part of the island, which burn coal and natural gas imported from the U.S. mainland.

In Adjuntas, seven local buildings now house rooftop solar, interconnected to form Puerto Rico's first community microgrid project. This $2 million, 700-panel project brings resilient electricity to 14 local businesses, expected to be able to run for 10 days in an outage using paired energy storage.

The business connected to the community microgrid include a pharmacy, a hardware store, a bakery, and Irizarry's pizza shop, among others. During Hurricane Maria, Irizarry spent $15,000 on diesel in the six months he was without power to remain open. The pizza shop was the only restaurant in Adjuntas able to continue serving customers in the wake of Maria. The new microgrid brings resilience and essential services, storing insulin in commercial freezers, preserving food, charging laptops, phones, and more.

The project was led by Casa Pueblo in partnership with the solar-energy focused Honnold Foundation, as well as local business owners, the University of Puerto Rico Mayagüez, and others.

USAG Italy, Vincenza Caserma Ederle Microgrid

Source: (Correspondence with Gregory Vallery, 207th MIB-T Brigade Engineer, 2023)

The Caserma Ederle Microgrid was initiated in 2006, integrating two 1.5 MWe diesel gensets (cogeneration) into an existing centralized boiler plant/CHP and the Installation's electrical medium voltage (20kV) distribution system that, at the time, consisted of 32 substations with remotely actuated MV and LV switchgear. Distributed rooftop solar systems in excess of 1 MWe were added through the years. Caserma Ederle consumed a peak electrical load of over 7 MWe, so having the remote capability to shed noncritical loads was essential during islanded operations.

The microgrid design and deployment process highlighted the importance of early and close coordination with all stakeholders, including the Italian government, national and local electrical utility providers, and the local community. The unique requirements of the Italian energy grid and the evolving regulatory environment influenced the selection of microgrid technologies and systems to meet specific needs of the installation. A thorough feasibility study was required to assess the technical, economic, and regulatory feasibility of microgrid implementation in Vincenza. An important stage in this process was the development of a comprehensive microgrid operating plan that included training personnel on how to operate the microgrid safely and effectively. Italy has a high share of renewable generation, and the growing community of local microgrid developers provide valuable support and expertise. The diesel gensets have since failed, so the Ederle Microgrid is not currently operational, but the diesel gensets are pending replacement under an awarded ERCIP project.

USAG Italy, Vicenza Caserma Del Din Microgrid

Source: (Correspondence with Gregory Vallery, 207th MIB-T Brigade Engineer, 2023)

The Caserma Del Din Microgrid was designed in 2008-2010, leveraging lessons learned for the Ederle Microgrid. Del Din became operational in 2013 and consisted of three 2.6 MWe bi-fuel diesel/natural gas cogeneration units integrated into a centralized hot water and chilled water plant that included thermal chilled water storage, integrated into the installation's electrical medium-voltage (20kV) distribution system that consisted of 16 substations with remotely actuated MV and LV switchgear. Distributed rooftop PV systems over 3.5 MWe were added through the years. Del Din has a peak electrical load of over 4 MWe, so the Installation has the remote capability to shed noncritical loads and operate in island mode, supporting all electrical and thermal loads. The microgrid initially operated in island mode for over a year, pending upgrades of the electrical grid from the utility provider to support the Del Din installation. Del Din will be adding BESS and hot water thermal storage to the central energy plant under an awarded ERCIP project.

Other U.S. & U.S. Government examples:

- University of California, Davis: this microgrid is used to provide power to the university's campus. It is powered by a variety of DERs, including solar PV, wind turbines, and natural gas generators.
- Brooklyn Navy Yard: this microgrid is used to provide power to the Brooklyn Navy Yard, a former shipyard that has been converted into a mixed-use development. It is powered by a variety of DERs, including solar PV, wind turbines, and battery storage.

7.2.2 International Microgrids

Corn Island, Caribbean, Nicaragua

Source: (MKG Gobel 2021), (Solartia: Positive Energy 2019)

In July 2019, the largest hybrid microgrid in Latin America was officially inaugurated on Corn Island, 70 km off the Caribbean coast of Nicaragua. The "Caribbean Pride Solar Energy Plant" was deployed by Spain's Solartia. The 8,500 residents of Corn Island now no longer depend on diesel, and over 60 temporary and permanent jobs were created from the project. The Caribbean Pride project represents an investment of nearly 4.5 million dollars, implementing autonomous, reliable, intelligent, and replicable technology developed entirely in the region of Navarre, in pursuit of sustainability for Corn Island. The microgrid is powered by a combined solar and storage facility, consisting of a 2.1 MW PV system, a 2.2 MWh lithium-ion BESS, and two 900 kW diesel backup generators in case of insufficient PV generation. The microgrid is expected to save 30,000 gallons of diesel per month and have a payback period of only 4 years.

Siemens Campus Microgrid (Corporate Headquarters), Vienna, Austria

Source: (Siemens 2020), (Ali 2021)

Siemens corporate headquarters campus microgrid was completed in 2020, and includes 312 kW of solar, 500 kW / 500 kWh BESS, and a series of Siemens eMobility charging stations. The Siemens microgrid controller was designed to incorporate the Siemens Desigo building management system, using the Siemens IoT platform to gather data and facilitate optimization of consumption management using data analytics solutions. The controller incorporates demand-response capabilities via the building's management system to adjust heating loads during peak periods. The building was originally designed to optimize heating through a series of heat exchangers capable of recovering up to 75% of exhaust heat, which, along with partial geothermal heating, led to the building design being awarded the Gold LEED certificate as well as the EU Green Building Certificate.

Siemens has plans to use the microgrid to provide frequency support to the local grid via an aggregator, as well enable BESS market participation to provide additional revenue to the microgrid owner, Siemens Real Estate. Siemens is also planning to partner with Nokia and A1 to move the microgrid communications to a dedicated frequency range to increase the data rate and mitigate communication delays.

Taiwan Cement Group (TCC Group) Yingde Plant, Guangdong Province, China

Source: (NHOA Energy 2023)

One of the largest industrial microgrids was deployed by the NHOA Energy, and contains 8 MW solar, 107 MWh BESS, and 42 MW of waste heat recovery systems on the Taiwan Cement plant. The project is expected to store 46 million MWh and provide $2.91 million in cost savings annually. The microgrid was designed to provide peak load management as well as to provide backup for critical equipment within the cement plant that could be damaged by sudden loss of power. The project aligns with the TCC Group's carbon reduction goals, the 6-Zero Factory Guidelines set by the China Building Materials Federation, and the Guangdong Provincial Government's energy storage development policy, which provide annual subsidies for the project.

Glossary

Advanced Metering: electronic meters that have the capability to, at a minimum, measure and record regular interval use and communicate that data to a management system. Comment: an existing meter data management system requires improvement to offer automated opportunity analysis.

Black Start: the procedure wherein a microgrid operation is restored in island mode after a complete shutdown. This process involves the microgrid central controller, multiple resources, loads, and switchgear.

One-Line Diagram: provides a clear and concise overview of the system's architecture, including transformers, generators, circuit breakers, switches, relays, and other critical elements. By depicting the flow of power, signal paths, and protective devices, one-line diagrams enable engineers, technicians, and operators to quickly comprehend the system's configuration, facilitating effective troubleshooting, maintenance, and fault detection.

Centralized Control: This technique entails a central controller making decisions for the entire microgrid based on real-time data. It determines the best possible functioning of different components, such as generators, storage units, and loads, with the objective of meeting energy demands while minimizing costs and maximizing efficiency.

Curtailment Service Provider: an authorized third party that interfaces between the energy end user and the independent system operators/regional transmission operators (ISOs/RTOs) to deliver demand-response capacity and/or services. Curtailment Service Providers include utilities, energy service companies, or demand-response aggregators.

Decentralized Control: partitioning the microgrid into distinct zones or segments, each governed by its own controller responsible for managing local elements. These local controllers communicate with each other to achieve the overall objectives, enhancing resilience and adaptability.

Demand Response: modifying patterns of energy consumption in response to signals from the microgrid controller or grid operator in order to help balance supply and demand, particularly during peak periods, and optimize energy expenses.

End-Use Loads: the devices and appliances that consume electricity, such as refrigerators, washers, dryers, personal computers, and lighting.

Forecast-Based Control: employs predictive models to estimate future energy generation and consumption.

Fuzzy Logic Control: employed to develop a controller within a fuzzy-control system. This approach intends to introduce a middle range between zero and one by dissecting logical challenges into smaller, more achievable segments.

Hierarchical Control: Hierarchical control combines aspects of both centralized and decentralized strategies. It establishes multiple tiers of control, with higher levels making strategic choices and lower levels executing these decisions at the component level.

Islanding and Reconnecting Control: in situations of grid outages, microgrids can isolate themselves (islanding) and operate autonomously.

Independent System Operators/ Regional Transmission Organizations (ISOs/RTOs): independent, geographically defined, membership-based, nonprofit organizations that ensure reliability and optimize supply and demand bids for wholesale electric power. Electricity systems not operated by ISOs or RTOs are operated by individual utilities or utility holding companies.

Load Following Control: centers on aligning energy generation with the immediate load demand within the microgrid.

Metering: used to measure the amount of electricity that is being generated, consumed, and exported by the microgrid.

Microgrid: a group of interconnected loads and DERs within clearly defined electrical boundaries that acts as a simple controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate both grid-connected or island modes.

Peak Load Management: management of peak demand and consumption through advanced metering and electricity consumption controls. Participation is managed directly by the aggregator or utility, but the definition does encompass demand response.

Power Dispatch Control: efficiently manages the allocation of power from diverse energy sources, such as solar panels, wind turbines, and generators, to fulfill the microgrid's energy needs.

Priority-Based Control: assigns varying priorities to different components and loads within the microgrid. During periods of high demand or limited supply, this control mechanism ensures that critical loads take precedence, while noncritical loads may be reduced.

Reliability: the capability of an adversely effected grid or system to recover its optimal functionality.

Resilience: the capacity of a grid or system to withstand or recover from adverse impacts.

Substations: used to step up or step down the voltage of electricity.

Switchgear: used to connect and disconnect different parts of the microgrid.

Synchrophasor: uses monitoring devices, called phasor measurement units, which take high-speed measurements of phase angles, voltage, and frequency that are time-stamped with high-precision clocks. The high-speed measurements, typically taken 30 times a second, can reveal system changes undetectable through traditional monitoring systems used in the industry (PJM n.d.).

Voltage and Frequency Regulation: used to ensure stable voltage and frequency levels within the microgrid.

Resources

Introduction to Microgrids

- Microgrid Functional Use Case: Microgrid Protection – Microgrid Blackstart (Xu and Reilly 2014). https://smartgrid.epri.com/UseCases/F9 Microgrid Blackstart.pdf
- Handbook for Understanding and Engaging in Demand Response (Parker and Hoffman 2019).
- Department Of Energy Microgrid Database. https://doe.icfwebservices.com/microgrid

Microgrid Components

- Electric Grid Supply Chain Review: Large Power Transformers and High Voltage Direct Current Systems (U.S. Department of Energy Response to Executive Order 14017 2022). https://www.energy.gov/sites/default/files/2022-02/Electric Grid Supply Chain Report - Final.pdf
- First Responders Guide to Lithium-Ion Battery Energy Storage System Incidents (American Clean Power 2023). https://cleanpower.org/wp-content/uploads/2023/07/ACP-ES-Product-7-First-Responders-Guide-to-BESS-Incidents-6.28.23.pdf

Microgrid Planning and Design

- Interconnection Guidebook for Developers of Small Scale Renewable Energy Generation Systems, Energy Trust of Oregon (Energy Trust of Oregon 2016). https://www.energytrust.org/wp-content/uploads/2016/10/100908_Interconnection_Guidebook.pdf
- IEEE 1547 and 2030, The IEEE Distributed Energy Resources (DER) Collection (Bundle) (IEEE Standards Association 2021). https://www.techstreet.com/ieee/standards/the-ieee-distributed-energy-resources-der-collection-bundle?product_id=2222893
- IEEE 2800-2022: IEEE Standard for Interconnection and Interoperability of Inverter-Based Resources (IBRs) Interconnecting with Associated Transmission Electric Power Systems (IEEE Standards Association 2020). https://standards.ieee.org/ieee/2800/10453/
- IEEE P2418.5: Guide for Blockchain in Power and Energy Systems (IEEE Standards Association 2023). https://standards.ieee.org/ieee/2418.5/11217/
- Resilient Installation Microgrid Design (DoD 2024). https://www.wbdg.org/FFC/DOD/UFC/ufc_3_550_04_2024.pdf
- ProjNet Secure On Demand Design Review (NIBS 2021). http://www.projnet.com/index.php

Categorical Comparisons of Microgrid Tools, reproduced from *Energy and Water Resilience Tools Survey* (Anderson, et al. 2021). Half-filled entries represent partial functionality.

Table 2. Categorical comparisons of microgrid tools

Tools	Power Simulation	Dispatch Strategy Analysis	Cost Estimation			Load Profile Assessment	O&M Est.		DER Analysis (types)	DER Analysis (details)	Backup Genset Modeling	Battery Storage Modeling	Revenue Calculations	Design for Resilience	Design for Cost	Life-Cycle Cost Analysis
			Generators	Balance of Plant	Renewables / DERs		Generator Assets	Renewable Assets								
DER-CAM	Full	Partial	Partial	Partial	Partial	Partial	X	X	Full	Partial	Full	Full	Partial	Full	Full	Partial
ERA	X	Partial	Partial	Partial	Partial	X	Partial	X	Full	Partial	Partial	Partial	Partial	Full	X	Partial
MASCOR	X	Partial	Partial	X	Partial	Full	X	X	Partial	Partial	Partial	Partial	Partial	Full	Full	X
MCOR	X	Partial	Partial	X	Partial	Full	Full	Full	Partial	Partial	Full	Partial	Partial	Full	X	Partial
MDT	Full	X	Partial	Partial	Partial	Full	X	X	Partial	Partial	Partial	Partial	Partial	X	Full	X
Quest	X	Full	X	X	X	Full	X	X	Partial	Partial	X	Full	Full	X	X	X
ReOpt Lite	X	Partial	Partial	X	Partial	Full	Partial	Partial	Partial	Partial	Full	Full	Partial	Full	Full	Partial
Xendee	Full	Full	Partial	Partial	Full	Full	Full	Full	Full	Partial	Full	Full	Partial	Full	Full	Partial

Source: (Anderson, et al. 2021)

Microgrid Financing and Regulations

- About Utility Energy Service Contracts (Federal Energy Management Program 2023). https://www.energy.gov/femp/about-utility-energy-service-contracts
- Frequently Asked Questions About Federal Utility Energy Service Contracts (Federal Energy Management Program 2023). https://www.energy.gov/femp/frequently-asked-questions-about-federal-utility-energy-service-contracts.
- ESPC Enable Acquisition Plan Template (Federal Energy Management Program 2013). https://www.energy.gov/femp/articles/espc-enable-acquisition-plan-template
- Frequently Asked Questions (PPA Watch 2022). https://ppawatch.org/faq/
- Sample Documents for Federal On-Site Renewable Power Purchase Agreements (Federal Energy Management Program n.d.) Federal Energy Management Program. https://www.energy.gov/femp/sample-documents-federal-site-renewable-power-purchase-agreements

Video Training Materials

- Webinar: Substation, The basics of a substation configuration and its components
  - https://www.youtube.com/watch?v=E_y_tbyU7jA
- Webinar: Substations, Looking From Outside... In
  - https://www.youtube.com/watch?v=DCUwtGlEt3U
- Circuit Breaker Maintenance Fundamentals, NETA Standards - Webinar
  - https://www.youtube.com/watch?v=5iuTLD2eB_w
- Electrical Safety for Industrial Facilities
  - https://www.youtube.com/watch?v=7MjJQolGoC4
- Essential Fundamentals for Electricians and Substation Technicians
  - https://www.youtube.com/watch?v=JxFUpO1m7uY
- Electrical Safety Refresher Training and Its Importance
  - https://www.youtube.com/watch?v=eRMyL3uoIIQ
- Trip Devices & Time Curves for Low Voltage Air Power Circuit Breakers
  - https://www.youtube.com/watch?v=n-EnpE7l5tM

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