Fundamentals of Advanced Microgrid Design

Coursebook for Advancing Caribbean Energy Resilience Workshop,
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Coursebook Content

Advanced Microgrid Design Overview

Our modern society is highly dependent on the electrical grid and major outages have severe consequences. A reliable source of power is especially important for campuses (including college campuses, business parks, etc.), military bases, and other areas with critical municipal functions (such as hospitals, police, and fire stations), where public safety may be compromised by a lack of electrical power. Although backup generation is common at critical facilities, failure of backup generation resources is quite common due to lack of maintenance or insufficient fuel supplies. Advanced microgrids can be an effective solution for power delivery to critical infrastructure.

We consider a "microgrid" as an integrated energy system consisting of loads and generation operating as a coherent unit. Microgrids may operate either in parallel with, or islanded form the main electric grid, and may switch between these two states. A simple microgrid might involve minimal design effort and employ a simple design, such as only a critical load paired with a backup generator. Simple designs are typically inefficient solutions when considering all critical loads and possible threats to a given system. An "advanced microgrid" is one that is designed using Sandia National Laboratories' Energy Surety Design Methodology (ESDM), which is a systematic process to maintain or enhance the attributes of: safety, security, reliability, sustainability, cost effectiveness, and resilience. Key components of advanced microgrid design include identifying and prioritizing critical assets, defining design basis threats, and establishing performance goals.

Maintaining local power delivery during extended main electric grid outages has become increasingly important as more customers and services rely on electric power. This is highlighted in Figure 1, which shows that several of the worst blackouts in the world in terms of customer hours lost have occurred in the last 20 years.

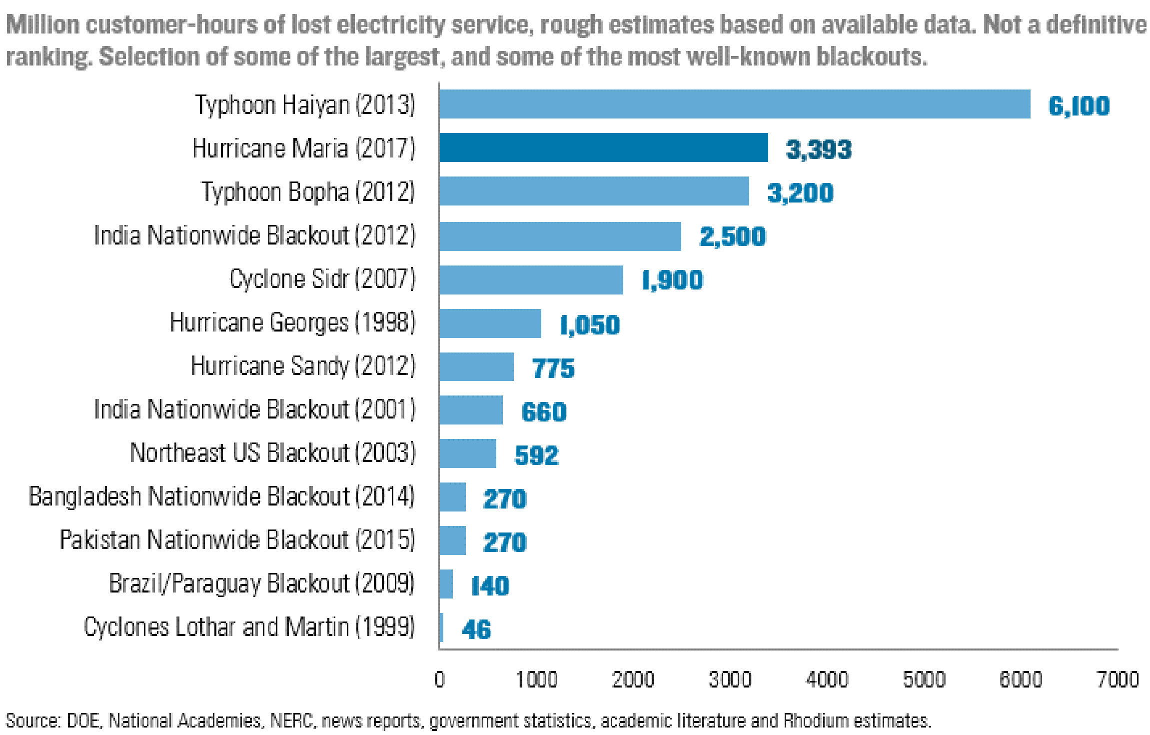


Figure 1: Major blackouts across the world.[1]

Due to interdependencies, extended power outages have cascading impacts on productivity, safety, and public health. Loss of power to a water treatment plant for an extended period will deplete reserves, impacting not only public health, but also firefighting and water for industrial uses. Outages to communications infrastructure due to lost power impacts the ability to dispatch emergency services, to coordinate mitigation efforts such as clearing

[1] Image from the Rhodium Group: https://rhg.com/research/puerto-rico-hurricane-maria-worlds-second-largest-blackout /

debris, and to communicate with customers. Traffic signal outages and an inability to pump fuel due to power outages can cripple transportation.

These issues highlight how important it is for communities to consider options such as advanced microgrids to improve the design, operation, and management of their energy system infrastructure to minimize the impacts of extended electric grid outages. Many groups, including governments, research communities, and philanthropic organizations are placing new emphasis on increasing energy security and improving energy system resilience. From our viewpoint, the need is for energy surety: energy systems that are safe, secure, reliable, and designed in a way that provides energy system operational assurance during routine and extended impact events caused by accidents, natural disasters, or intentional attacks.

This coursebook is laid out in modules. Modules 1 and 2 give an overview of the electric power systems and microgrids. These sections motivate the need for microgrids for energy surety and discuss the basic operation of microgrids. Module 3 gives an overview of the Energy Surety Design Methodology, which we suggest as best practice for designing microgrids. Modules 4, 5, and 6 describe components of the Energy Surety Design methodology, including establishing system boundaries, defining critical assets, and specifying design basis threats. These modules give a clearer understanding of the design considerations for the microgrid. Module 7 builds on this by setting quantitative performance goals for the microgrid. Module 8 is a discussion of reliability versus availability, which has implications for different types of critical loads. Finally, Module 9 describes the initial and final conceptual design phases, which consider the critical assets, threats, and performance goals to create and iterate on conceptual designs to optimize value of the microgrid.

1. Introduction to Electric Power Systems and Energy Surety

This module provides a general overview of the design and operation of the electric power grid, emerging concerns of energy reliability and security for extreme events, energy system design metrics, and how microgrids can be used to improve energy security and reliability using both smart grid and distributed and renewable energy generation and storage technologies.

1.1 Main Electric Grid

Most electric customers are served by a main electric grid. Main electric grids may span entire continents or may cover only a small island. These electric grids typically consist of the four components shown in Figure 2: generation, transmission, distribution, and customers, although smaller systems may not have significant transmission components.

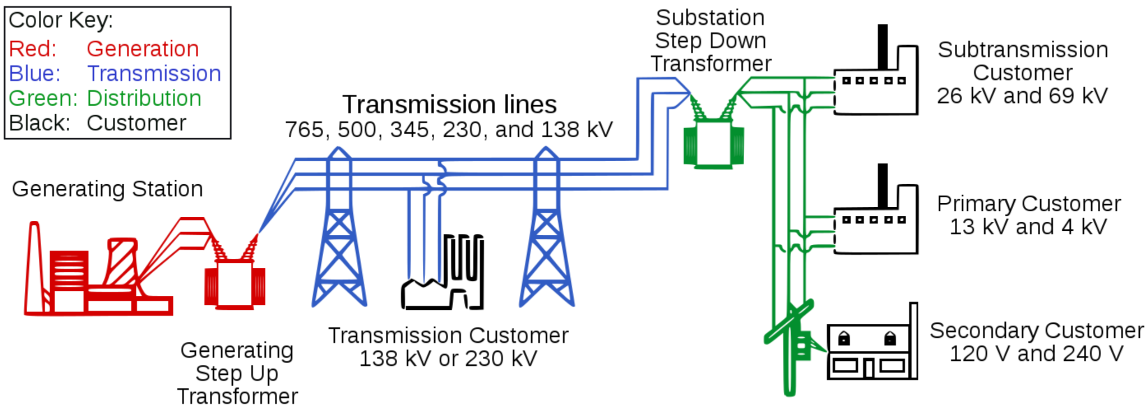


Figure 2: Basic components of an electric grid.[2]

Common types of generation include coal (~27% of worldwide generation); natural gas (~27%); nuclear (~18%); hydroelectric (~13%); wind, solar, and geothermal (~10%); biofuel (~3%); and oil (~2%) power plants[3]. Electric grids have typically been operated with large generating stations, with power generally flowing from generating station to customer load, as illustrated in Figure 2. However, the growth of renewable energy such as wind and solar is increasingly spreading out the generation. Utility-scale wind and solar plants may be connected to transmission lines at myriad locations across the electric grid, and residential and commercial solar often exist on the distribution system, with residential systems often behind the customer meter. Generation may be owned by an electric utility or may be owned by a private entity that contracts with the utility, such as through a power purchase agreement.

Transmission systems are networks of transmission lines designed to transport energy over long distances with minimal power losses. They are often complex mesh networks with multiple redundant paths which can be utilized in the event of a single node failure. Transmission lines are typically administered by a regional transmission organization or an intendent system operator. Careful attention is paid to balancing load and generation, maintaining a set frequency, and balancing the voltage between the three different phases.

Distribution systems complete the delivery of power to customers. The backbone of distributions systems is a high voltage "primary" system which, similar to transmission but at a lower voltage, transports the power closer to the customer. At or near the customers, distribution transformers reduce the voltage to customer-appropriate levels (such as 240V/120V in many North American systems). This lower voltage system is called the distribution

[2] Image from FERC report: https://www.ferc.gov/industries/electric/indus-act/reliability/blackout/ch1-3.pdf.
[3] IEA 2017 provisional electricity production by source: https://www.iea.org/statistics/electricity/

"secondary" system and connects the low-voltage side of the distribution transformer to the customer meter. Electric utilities manage distribution systems, ensuring that power is delivered to customers at safe voltage levels.

Customers can range from large industrial complexes to single-family homes. Customer voltages will vary depending on the size of the load and types of equipment used by the customer. Distribution system equipment including transformers and wires leading to the customer must be sized appropriately for the loads. A special case of customer is one that has generation behind the meter, such as a rooftop photovoltaic system. These customers will draw less load from the main electric grid when they are self-generating.

Many facets of modern society are heavily reliant on the main electric grid, and a major outage for an extended duration can have severe consequences. Several other categories of infrastructure, including water, transportation, and communications are heavily dependent on electric power infrastructure. Services including healthcare, emergency operations, command and control centers, municipal services, wastewater treatment plants, data centers, banking, and more can be affected by a loss of electric power.

Many critical facilities have individual building-tied backup generators and uninterruptible power supplies (UPS) to maintain critical loads for a short duration blackout of the main electric grid. However, these resources often have not been designed or maintained to support longer-term outages from expanding types and levels of threats and disruptions. Natural disasters such as hurricanes, floods, and tornadoes, as well as intentional attacks such as cyber or physical attacks to grid infrastructure can cause outages lasting for weeks or more. Stored fuel for generators typically lasts only a few days without external refueling from central storage sites; sites which may also be affected by the event causing the extended electric grid outage. Because of the interdependency of critical services, a loss of power in one location can adversely affect other functions or operations at other locations, potentially leading to a chain of events that could have a devastating impact on overall critical services.

1.2 Energy Surety Attributes and Associated Metrics

There are many attributes important in evaluating the value of electric power services. These attributes should be considered when making improvements to the main electric grid, but also when designing backup systems or microgrids. The six major energy surety metrics shown in Table 1 were identified based on discussions by various federal and industry working groups.

Table 1: Identified Energy Surety Metrics

Attribute	Metric
Safety	Safely supplies energy to the end user
Security	Maintains power in a malevolent environment
Reliability	Maintains power when and where needed
Sustainability	Can be maintained for necessary duration
Cost Effectiveness	Produces energy at the lowest predictable cost
Resiliency	Efficiently recovers from large-scale events

The first attribute, safety, ensures that energy is provided to the end user in a safe manner. This means that the energy system must function well even when components fail and must be developed with safety as a top concern.

The second attribute, security, makes a power system robust to various cyber and physical threats, including terrorist attacks. Threats against power systems have escalated in recent years, including increased concerns of terrorist threats. Security can be accomplished through hardening of the energy infrastructure, protecting the assets, and by having more redundancy in energy systems.

The third attribute, reliability, reflects a power system's ability to meet its mission-critical electric demands. Although it may be impossible to ever achieve 100% reliability for all buildings and functions during an extended outage, serving critical power needs for a campus, military base, or community is necessary for public support and safety. This can be accomplished in many ways, including through additional redundant power systems.

The fourth attribute, sustainability, is the ability to operate a power system not only for a long period of time, but in a manner that will not compromise the future. Sustainability can be improved with the use of renewable energy, such as photovoltaics (PV), geothermal heat pumps, and combined heat and power, as a secure onsite energy resource.

The fifth attribute, *cost effectiveness,* relates to the ability to provide high reliability and secure electric power at an affordable cost. Affordability includes evaluation of the costs of different energy infrastructure upgrade options relative to the benefits of mission assurance, higher reliability, and extended outage capability improvements.

The final attribute, *resilience,* refers to a grid that can adapt to large-scale events or disasters and remain operational in the face of adversity, thus minimizing the catastrophic consequences that affect safety, quality of life, economic activity, national security, and critical infrastructure operations. Specifically, the focus on short-term reliability needs to be replaced with a resilience approach, one that looks at the grid not strictly as a flow of electrons but as a grid that serves, interfaces with, and impacts people and societies. Put another way, it is the consequences, not the outages, that matter. Enacted properly, a resilience framework would improve upon the traditional reliability approach to grid operations and be more responsive and adaptive (that is, able to react predictively to threats and adjust operations prior to forecasted threats).

1.3 Grid Improvement Options to Address Energy Surety

There are several ways to improve the energy surety of an electric grid, including building additional transmission and distribution systems to provide energy supply redundancy; hardening transmission and distribution systems to make them more resistant to storms or attacks; or adding additional onsite energy generation and storage systems to protect critical buildings or services and critical mission functions. The focus should be on how to balance the costs and benefits of different improvement options.

Improvements should focus on the energy surety metrics. For example, the *safety* attribute can be addressed by ensuring that no new safety hazards are introduced with the interconnection of generation such as addition of renewable energy to the existing electrical system. This is often done by having renewable systems disconnect from the main grid during a power outage to avoid dangerously energizing power lines that are assumed to be deenergized. If appropriate controls and switching are in place to maintain safety, the system could instead electrically island the critical infrastructure and generation into a type of microgrid. *Sustainability* can be improved by including renewable distributed generation, such as solar or wind power, and minimizing the dependency on fossil fuels where appropriate. Because of the variable nature of many renewable energy sources, integration with other distributed generation resources including generators and energy storage systems are often needed to meet overall system reliability needs (e.g., to provide power at night when there is no solar resource).

From a *reliability, security, and cost effectiveness* standpoint, many energy system improvement options focus on integrating microgrids by utilizing some of the existing distribution system equipment. Use of existing onsite electrical distribution feeders, backup generators, and switchgear can reduce implementation costs of forming microgrids. The resulting local generation on a microgrid reduces reliance on remote substations and transmission lines and is often more secure and more easily protected (e.g., distribution system components may already exist on a military base or may be in a secured area of a business park). The increased use of onsite, locally controllable generation can be directly focused on critical mission needs, improving reliability.

Research at Sandia National Laboratories, other National Laboratories, and other research institutions has shown that microgrids often are the most cost effective and resilient solution to provide critical mission and critical services assurance for military bases or communities. The following modules in this coursebook provide specific evaluation and conceptual design guidance approaches for using microgrids to support improved energy surety and resilience.

2. Introduction to Microgrids and Advanced Microgrids

This module provides an overview of the application and use of microgrids and microgrid components. It is intended to provide background information on how microgrids are being designed to safely and reliably use distributed energy including renewable energy and storage resources to provide power for communities during extended main grid outages. In many microgrid applications, the existing main electric grid power infrastructure can be utilized with minor modifications of electrical system components to ensure worker safety and appropriate system functions and operations.

2.1 Functional Categories of Microgrids

A simple definition of a microgrid is a set of loads with local generation that can be isolated from the main electric grid. As seen in Figure 3, microgrids can be single customer solutions, may serve several customers as a partial feeder microgrid, or may encompass a full feeder or substation.

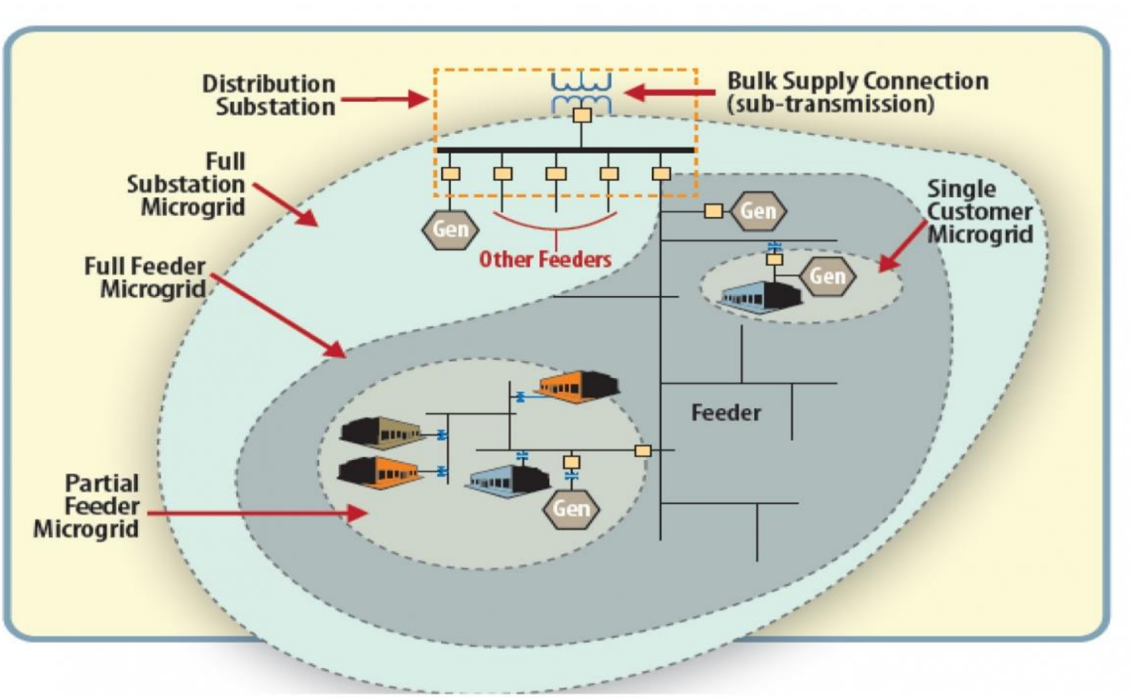


Figure 3: Illustration depicting the various possible sizes of microgrids.[4]

The basic operation of a microgrid can be separated into three main types based on (a) whether the microgrid is typically connected to the main electric grid or typically islanded and (b) if the microgrid has enough generation for sustained operation or simply short-term backup generation.

We separate microgrids into three basic types:

- Type 1: Microgrid for Backup Only
  - Operates only when the main electric grid is down
  - Generation is sized to cover critical loads only
- Type 2: Always Islanded Microgrid
  - Never connected to the main electric grid (e.g., a remote system far from the main grid)
  - Has enough local generation to cover all local load
- Type 3: Hybrid Microgrid
  - Operates grid-connected part of the time and islanded part of the time

[4] Image from: https://www.energy.gov/oe/activities/technology-development/grid-modernization-and-smart-grid/role-microgrids-helping

        - Operation mode determined by factors including costs, main grid outages, fuel supplies, etc.
    - Has enough local generation to cover all local critical loads, may have enough generation to cover all local loads

Type 1 microgrids provide backup power to critical buildings when utility power is lost by opening the point of common coupling (PCC) main breaker switch, isolating the system form the main grid. After isolation, there is startup and synchronization of generators to the critical loads served by the microgrid. While the simplest Type 1 microgrid would be one generator and one critical load, the most effective Type 1 microgrids involve multiple generators and multiple critical loads, because additional generators provide redundancy and coordinated controls will make the generators run more efficiently, resulting in efficient, reliable, and resilient backup power.

Type 2 microgrids involve simply local generation and load and are never connected to the main grid. These systems may be referred to as "off-grid." In Type 2 microgrids, it is essential to appropriately match generation and load for continuous operation. Type 2 microgrids will require larger generation resources, fuel supplies, and energy storage systems than Type 1 or Type 3 microgrids, since they must constantly operate autonomously. Although there is no switch needed for isolation from the main electric grid, Type 2 microgrids may have isolation switches to separate critical loads from non-critical loads during periods of low generation (e.g., due to a fuel shortage or a lack of wind or solar resource).

Type 3 microgrids are the most flexible option. These microgrids can operate either grid-tied or islanded from the main electric grid. Type 3 microgrids will at least have generation to cover their critical loads, and often will have generation to cover all loads. The later scenario of generation to cover all loads provides significant flexibility to respond to grid signals such as time of use pricing, demand response requests, or grid outages while maintaining reliable power for all loads on the microgrid. During times of high microgrid load, the microgrid may draw power from the main electric grid to supplement its local generation. During times of low microgrid load, it may be possible to sell power back to the main grid. Sending power back to the main grid may be particularly valuable during periods of main grid peak load and during resilience events which stress the main grid.

Generation resources on microgrids are distributed energy resources (DERs). DERs can include diesel and gas engines, microturbines, fuel cells, PV, wind, biomass, and energy storage. These local generation resources enhance reliability by providing power to the microgrid's critical resources when the microgrid is islanded. When not islanded, excess generation may be able to be sold back to the utility to offset DER capital and operation costs. DERs can also be used as peak shaving devices, operating only when the microgrid loads are large and it is desired to reduce net consumption from the utility (e.g., to minimize a capacity cost).

Site requirements will impact which generation resources are best and how the generators are able to run. For example, United States Environmental Protection Agency standards limit both NO_X emissions for diesel engines and the number of hours that diesel engines can run, which can limit their ability to supply power to serve loads except under emergency conditions – and may make diesel-only systems most appropriate for Type 1 backup-only microgrids. Renewable energy including solar and wind power, especially when paired with energy storage, is particularly attractive for Type 2 and Type 3 microgrids, though wind and solar resources vary by location and season. In many cases, a large amount of generation needs can be supplied by the renewable resources and supplemented as needed by other generation such as diesel generators or by drawing power from the main grid for Type 3 microgrids.

In this coursebook, when we mention "microgrids" we are typically referring to Type 3 microgrids.

2.2 Microgrid Capabilities and Elements

A microgrid should have capabilities designed to make it operate with flexibility and efficiency.

Some important capabilities include:

- Flexibility in placement and technologies associated with generation resources including distributed generation, renewables, and energy storage by development of plug-and-play capabilities. Plug-and-play also provides for reduction of engineering costs and increased reliability through shared use among multiple facilities within the microgrid. There may be a range of different sizes of generation resources in the microgrid.
- Complex controls including dynamic power quality control, intentional islanding, and autonomous control of generation resources. These complex controls allow the microgrid to provide high-quality power efficiently even when not connected to the main electric grid.
- System robustness through the ability of generation resources to coordinate to meet the needs of the loads. The microgrid provides for continuous operation during loss of the utility grid and compensates for loss of local generation resources by sharing loads between units.
- Efficient operations by matching total generation to the microgrid load (with a slight excess for contingencies), the generation resources are run more efficiently so only the backup generation required for the microgrid is utilized.

Microgrids are designed to distribute existing and new generation resources among buildings to meet critical energy needs. Microgrid implementation may require the following types of alterations to typical infrastructure associated with drawing power from the main electric grid:

- *Additional transformers/breakers/controls to existing generator resources (backup generators, PV, etc.)* – step up voltage levels of backup generators to designated feeder levels, if necessary, and apply microgrid monitoring and generator resource controls of voltage and power levels
- *New generation resources (generators, PV, etc.)* – add sufficient new generation resources to supply required critical microgrid load demand when the microgrid is islanded from the utility grid, assuming microgrids have enough generation such that the loss of any generation resource within the microgrid will not entail loss of load (which provides so-called 'N-1' redundancy)
- *Static switch/main breaker* – provide a main isolation device separating the microgrid from the main electric grid to allow it to change between grid-tied and islanded (note: there may be multiple isolation devices between a microgrid and the utility grid)
- *Sectionalizing switches/breakers* – can be used to isolate non-critical loads within a microgrid when limited generation is available to serve loads or to sectionalize a microgrid into zones of protection to isolate faults
- *Energy storage* – protect non-interruptible loads and provide ride-through capability until distributed generators start up; can also improve system performance, such as absorbing sudden changes in PV, so that generators limit the amount of ramping in response to PV fluctuations
- *Microgrid controls* – use a set of centralized and distributed controls to monitor and control generation resources or isolation devices (breakers, switches) to switch the microgrid between grid-tied and islanded operation, as well as deploy the generator resources efficiently to reduce fuel use by being responsive to load conditions
- *Protection* – microgrid system protection against fault conditions to isolate generation devices from the system during the microgrid operation
- *Building load reconfiguration* – in some microgrid designs, the critical load needs for a microgrid can be reduced by reconfiguring building loads to sectionalize critical and non-critical loads within the building so that the microgrid is only required to supply a portion of building loads rather than entire building loads
- *Load shedding* – in some microgrid designs, isolation devices can isolate less critical loads within a microgrid when sufficient generation is not available to meet all the load within the microgrid
- *New feeders* – in some microgrid designs, it may be more economical to install a new dedicated microgrid feeder connecting critical buildings together rather than use the existing utility grid because the amount of non-critical load far exceeds the critical load (so it would be cost prohibitive to use the existing utility grid to form a microgrid)
- *Feeder rearrangement* – in some microgrid designs, instead of installing a new dedicated microgrid feeder, it may be possible to reconfigure the connections of an existing utility feeder so that critical loads are on the microgrid feeder and the non-critical loads are on other feeders (this existing feeder can be made into a microgrid without a prohibitively large amount of generation required to meet loads).

Energy storage with fast response times can be used to keep non-interruptible loads from experiencing short outages during a microgrid's transition between grid-tied and islanded mode. Without energy storage, there may be a short outage (e.g., 10 - 60 seconds) when transitioning from grid-tied to islanded as microgrid generation resources start up and synchronize to a standard frequency. Non-interruptible critical loads, such as telecom or computer server equipment, are usually equipped with uninterruptible power supply (UPS) units to provide five or more minutes of backup power to these loads. The power is rated to ride through the time necessary for backup diesel generators to start and recharge the batteries. A microgrid could be designed to allow ride-through of all critical loads by using many UPS units, but if an entire building requires non-interruptible loads, then a larger scale energy storage unit may be most effective.

Energy storage has additional benefits of being able to help control variation in generation. The storage system can dampen the variability of solar or wind systems caused by cloud cover changes or shifts in wind. If large enough, energy storage may also be able to help address daily variability such as evening peaks in load and the diurnal cycle of PV power (i.e., no solar irradiance at night). As a rough rule of thumb, it has often been cost-effective to install some amount of energy storage when variable generation exceeds about 20% of total microgrid generation to prevent excessive ramping of other generation resources (diesel or natural gas generators, microturbines, etc.). Engineering studies considering renewable variability, cost, and the system's other generators' performance will inform the optimal balance of renewable resources with energy storage.

Building load reconfiguration refers to how the existing emergency connections of critical buildings are setup and what adjustments can be made to prioritize critical loads. Buildings with backup generation generally have an automatic transfer switch (ATS) that closes the generator onto a portion of the building loads during emergency situations. If it is determined that a larger portion of a critical building should be supplied by the microgrid, then existing switchboards and/or panelboards will have to be retrofitted or expanded to accommodate the new load requirements. Or, if a new building is added to a microgrid, it might be desired to reconfigure the building so only the critical loads in the building are connected to the microgrid to limit the amount of generation required on the microgrid.

Non-critical loads can be shed by installing remotely operable main breakers on the incoming building feeds, which will isolate these buildings when the microgrid is in islanded mode. If the microgrid is designed to handle all loads within its jurisdiction, these retrofits won't be required, but additional generation will be required to cover these additional loads.

If it is too cumbersome to create a microgrid within an existing distribution feeder system, it may be possible to reroute a portion of the non-critical loads along the existing radial distribution feeder to other feeders. This will allow the microgrid to island from the utility during power outages and supply mostly critical loads so that generation requirements are reduced. It also may be more efficient to develop a separate dedicated microgrid feeder that is attached to only critical loads, isolated from the utility by one or more PCCs, to reduce the amount of generation required for the microgrid.

2.3 Example Microgrid Sequence of Operation

Although we can not specify the exact sequence of operations associated with a microgrid without knowing the type of microgrid (e.g., Type 1, 2, or 3) and its specific configuration, including its size and the conditions upon which it will operate, it is possible to describe some generic features that most microgrids will follow.

Below is an example of a simple Type 3 microgrid, with local generation to support only its critical loads:

- The microgrid provides power to all critical mission loads within its area and isolates non-critical loads during islanding mode when utility power is lost.
- The microgrid predominantly operates grid-tied but can be isolated during main grid outages or other grid events such as high time of use rates.
- When the microgrid is isolated, generators come online to pick up loads and restore power.

- There is no energy storage on the microgrid. Any critical loads requiring UPS are assumed to be already provided for in existing buildings.
- Isolation devices remove non-critical buildings from the microgrid when it is islanded from the main grid.

Figures 4 through 7 illustrate the basic steps involved in forming an islanded microgrid from a grid-tied collection of buildings. The first step (Figure 4) illustrates a feeder with a microgrid and a PCC main breaker dividing the upstream non-microgrid portion of the feeder from the downstream microgrid portion of the feeder. The microgrid consists of a collection of critical mission buildings in blue and non-critical buildings in yellow. Some buildings have DERs attached to them. The generation resources are de-energized when the microgrid is grid-tied. Initially, the PCC is closed, allowing critical and non-critical buildings to be fed from the utility.

In step 2 (Figure 5), when the feeder loses power through a system fault that affects the feeder to which the microgrid is attached, the feeder and microgrid become de-energized. Depending on the type of fault, a main substation breaker or upstream breaker will open to isolate the feeder from the utility power (the fault may have occurred on the microgrid feeder or another upstream feeder, which affects the main substation). Next, the microgrid main breaker (PCC) opens to isolate the microgrid portion of the feeder from the main substation to prevent the generation in the microgrid from backfeeding upstream faults in the utility system for safety purposes. The PCC also sends signals to open non-critical building feeds to prevent them from connecting to the microgrid when the generation resources are started up to limit the microgrid generation to critical loads. A more sophisticated microgrid control scheme could allow non-critical loads to remain in service and only become isolated when sufficient generation is not available. During this period prior to generation resources being started (~30 seconds), the critical buildings will be without power, so any uninterruptable loads will need backup sources such as UPS units.

In step 3 (Figure 6), once the generation resources sense a loss of utility power, they start up to pick up their individual building loads. Any remaining generation capacity from these generators is available for other critical loads.

Finally, in step 4 (Figure 7), the generators are synchronized sequentially to the microgrid portion of the feeder until all the generators are on the bus and all critical buildings in the microgrid are provided with power, with each generator output increasing as they are synchronized to large loads. At this point, the amount of generation provided by the generation resources can be adjusted for more efficient utilization, either manually or through an automated process. For example, if the load does not require one or more of the DERs to be available, they can be shut off to make the other resources more fuel efficient.

When utility power is restored, the steps to undo the microgrid occur in the reverse order. When the power returns, the generation resources at each building sense that power is restored and are individually offloaded from the microgrid in a seamless fashion, preventing any load interruptions. When all critical buildings are up and running a signal is sent to the non-critical buildings to close their isolation devices and re-energize these buildings.

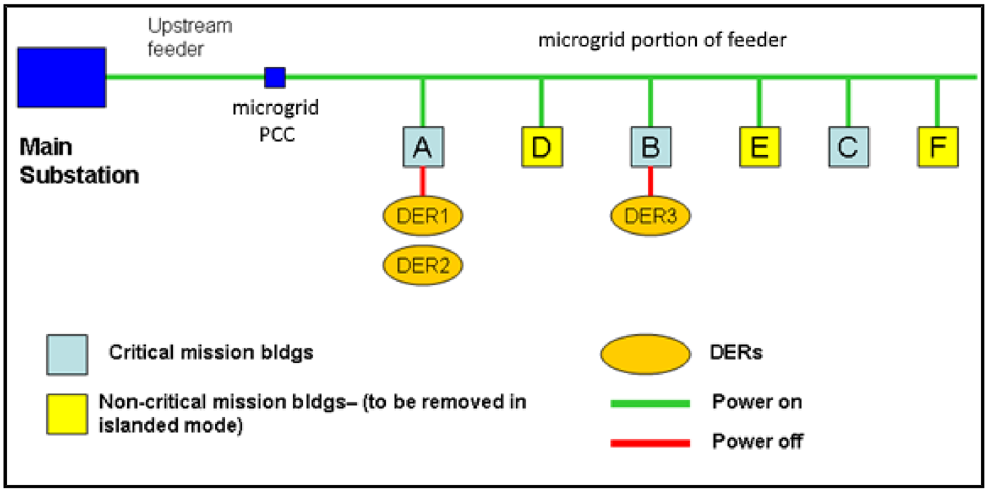


Figure 4: Step 1 – Feeder and microgrid are grid-connected (DER – generation resource such as diesel or gas generator or renewable energy).

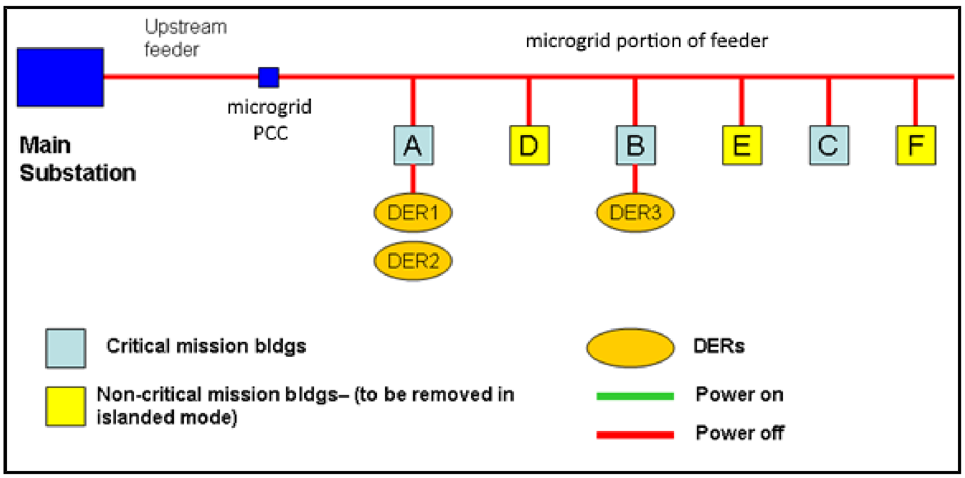


Figure 5: Step 2 - Loss of utility power deenergizes feeder and microgrid.

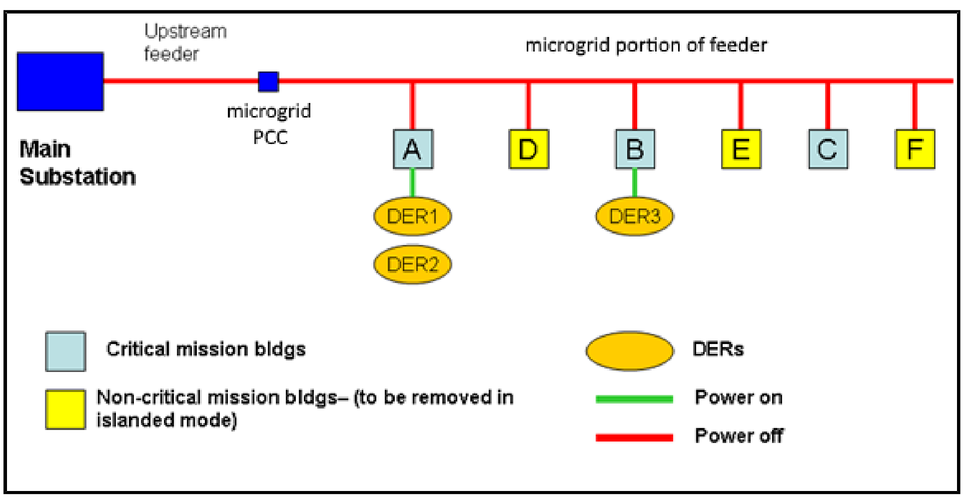


Figure 6: Step 3 – Generation resources (DERs) start up to pick up critical buildings; non-critical buildings are kept offline.

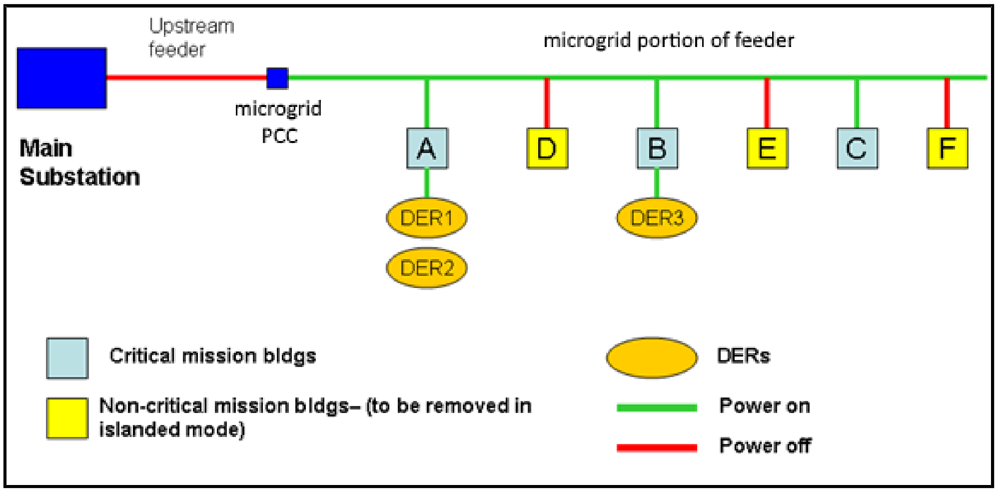


Figure 7: Step 4 – Generation resources synchronize to form microgrid supporting critical buildings.

A more detailed set of steps for the microgrid to transition from grid-tied to islanded mode and back again is listed below (note, as mentioned previously, that a microgrid may have more than one main breaker/PCC depending on the arrangement):

1. Utility power is lost, upstream fault clearing devices open to turn off power to all buildings connected to the affected feeder to which the microgrid is attached; all renewable resources automatically disconnect from the grid
2. The main breaker (PCC) senses a power loss and opens
3. The main breaker sends a signal to each building to open main breakers to non-critical loads and receives confirmation that breakers are off (15-45 seconds)
4. Each generation resource's automatic transfer switch (ATS) determines that there has been a loss of utility power
5. Each ATS starts the generation resources in isochronous mode to pick up their specific loads (30-60 seconds, depending on the generator type)
6. Microgrid controls allow each ATS to communicate its status with others
7. Voltage and frequency is measured at each ATS and communicates to other ATSs in the microgrid
8. When the voltage and frequency between two ATSs are within a window (i.e., they are in sync), the bypass switch on the ATS is closed (30-60 seconds for all generators to sync together)
9. The generators go into a frequency droop mode, in which the predetermined power and voltage setpoints are altered based on the generator size (percent droop) and are controlled by the microgrid generator controls unless the user changes the setpoints from the main microgrid control algorithms
10. All the generators will run together as long as the microgrid network provides the correct generator frequency
11. Renewable resources (if any) may reconnect to the microgrid at this point – isolation devices will reclose and be available for the microgrid
12. At some point, the utility power returns and its fault device is cleared, restoring power to the feeder with the microgrid
13. Controls are used to change the frequency of the generators to match the grid

14. When the synchronizing conditions are satisfied, the main microgrid breaker (PCC) closes, restoring grid power to the critical buildings in the microgrid from the utility
15. Generators will soft unload and eventually stop
16. The closed main breaker (PCC) sends signals to close the isolating devices and restore power to all non-critical loads.

It is also possible, in certain situations, to have a microgrid with generation resources normally operating in parallel with the utility or a microgrid which is normally isolated from the main electric grid, but which can connect to and synchronize with the main grid. The main difference between this example and a microgrid operated in parallel would be that designated generation resources would be continually operating while connected to critical load. In Step 1 (Figure 4), when utility loads become disconnected, the generation resources will continue to feed critical loads without interruption, but the rest of the steps to form the isolated microgrid will occur. There may be generation resources which are normally off in grid-tied mode but start up to be available only when the microgrid is islanded. As before, if sufficient generation is supplied to the microgrid, non-critical loads will not have to be isolated from the microgrid.

3. Energy Surety Design Methodology and Microgrids

This module provides a general overview of the Energy Surety Design Methodology (ESDM), developed by Sandia National Laboratories to improve the energy surety of energy systems, and how that methodology is utilized to evaluate the value of microgrids in site-specific applications, provide general analysis, and outline the design steps for advanced microgrids.

3.1 Energy Surety Design Metrics for Microgrids

The energy surety metrics discussed in Table 1 also apply to microgrids and have become the basis for advanced microgrid designs. We designate an advanced microgrid meeting these six ESDM attributes as an Energy Surety Microgrid (ESM). "ESM," "advanced microgrid," and simply "microgrid" are often used interchangeably in the following sections as we suggest an ESM as best practice for microgrid design. ESMs address the six energy surety metrics as described below.

The first attribute, *safety*, ensures that energy is provided to the end user in a safe manner. This means that the microgrid must be developed with safety as a top concern and must not be dangerous even during unplanned outages of either the main grid or of the local generating units. The microgrid design must ensure that interconnection of distributed generation including renewable energy systems does not compromise safety and that all human safety issues, such as electric shock hazards, are mitigated. For example, it is essential to confirm successful opening of the PCC switch to isolate the microgrid during a main grid outage before sustained operation of the microgrid DERs – unsuccessful isolation could lead to injecting power back onto main grid which is otherwise assumed to be deenergized due to the outage.

The second attribute, *security,* makes a power system more resilient to cyber and physical threats, including terrorist attacks. Threats against power systems have escalated in recent years, including both weather and intentional attack threats. As a result, cyber security standards such as encryption, firewalls, and strong password requirements must be integrated into a microgrid's command and control system. Another simple but effective way to improve security is to locate microgrid components including generators inside a secure facility, where they are harder to physically attack. Local topology and weather threats (including flood plains and wildfire risks) should also be considered when siting microgrid assets.

The third attribute, *reliability*, reflects a power system's ability to meet its mission-critical electric demands. Although it may be impossible to ever achieve 100% reliability, installing a microgrid system can significantly improve onsite reliability. Having several onsite generators not only reduces the number of possible failure nodes associated with long-distance power transmission, but also reduces single points of failure at a given site. Moreover, a microgrid configuration reduces the likelihood that the failure of any one generator will affect critical load; if a microgrid is well designed, other generators in the network will have sufficient energy to power all critical mission buildings.

The fourth attribute, *sustainability,* is the ability to operate a power system not only for a long period of time, but in a manner that will not compromise the future. Including renewable sources of distributed generation, such as solar, at a microgrid site can improve sustainability by reducing or eliminating a facility's dependency on fossil fuel resources. The ESM design process should therefore include a sustainability analysis that can predict or manage the cost of electricity generated by various fuel sources. Such an analysis should reflect resource availability (such as fuel deliveries and storage capabilities) and promote strategies such as switching to a different fuel and to minimize or eliminate dependency on depleting resources and reduce carbon emissions.

The fifth attribute, *cost effectiveness*, deals with being able to provide high reliability and secure electric power at an affordable cost. Affordability includes evaluation of the costs of different infrastructure upgrade options relative to the benefits of mission assurance, higher reliability, and extended outage capability improvements. The addition of renewable energy, for example, reduces a site's dependence on the utility grid and on diesel fuel when utility power is unavailable, which likely leads to cost savings.

Finally, to address *resilience*, the microgrid must adapt to large-scale environmental and manufactured threats while remaining operational, thus minimizing the catastrophic consequences that affect quality of life, economic activity, national security, and critical-infrastructure operations when major threat events occur. A resilience approach must look at electricity delivery not strictly as a flow of electrons but as something that services, interfaces with, and impacts people and societies. A resilience framework should improve upon the traditional reliability metrics applied to grid operations in three key ways: 1) the term resilience would be formally defined to include threats against the grid and the consequences of grid disruption; 2) the concept of resilience would include a set of metrics for measuring resilience; and 3) a resilient grid would, in contrast to a merely reliable grid, be more responsive and adaptive (that is, able to react predictively to threats and adjust to disasters before they happen). Reliability is a measure of microgrid uptime based on historical conditions, while resilience is the microgrid's ability to maintain service when encountering emerging threats.

3.2 Types of Energy Surety Design Analyses

In addition to a focus on energy surety, the ESDM specifically acts to increase resilience through a focus on analytical and performance-based design and evaluation approaches. For these approaches, one or more Design Basis Threats (DBT) are defined by the customer. A DBT is a profile of the type, composition, and capabilities of an adversary. The adversary can be natural, such as a hurricane or ice storm, or it can be manufactured, such as a cyber or physical attack on infrastructure. The DBT provides boundaries on the environment in which the system must be made more resilient. Evaluation approaches include:

> **Risk-based analyses** – Risk-based solutions include elements of reliability (or vulnerability), threat (which is defined per the DBT), and consequences. The importance (or criticality) of loads served by the system define the level of consequences. The importance of these loads is quantified during evaluation in relation to customer-defined performance goals.
>
> **Graceful degradation -** The designs chosen are made to reduce loads in a piece by piece manner, in a way that places a priority on preserving critical loads.
>
> **Reduced restoration time -** Identifies options to locate distributed energy and storage resources that support the ability to accelerate restoration of the electric system.
>
> **Reduced frequency of power outages -** A natural result of increasing resilience of the electric grid will be a system that is more robust to extreme changes in the operating environment, is impacted less by different events, and maintains power and services to most customers during events.
>
> **Mitigation of consequences to specific threat classes -** Focuses consequence mitigation efforts on identified energy system performance goals so that outage scenarios are proactively addressed.

The following elements are included in an energy surety evaluation and design:

1. Support differentiated reliabilities of loads for high-consequence, low-frequency events
2. Increase resilience to specific identified threat classes
3. Quantify resilience, reliability, and exposure of specific loads
4. Offer focused solutions
    a. For specific system infrastructure improvements (rate based)
    b. For specific load owning entities (private)
    c. For community service emergency response entities
5. Quantify resilience and reliability benefits to the solutions identified
6. Perform cost-benefit tradeoffs for the solutions identified
7. Acceptable resilience and reliability decision method metrics are related to community-identified electric system performance goals
8. Decision methods and support tools are used to help determine appropriate options.

The analysis includes the following analytical elements to help quantify options:

1. Include risk by assigning numerical values to the criticality of each load
2. Account for the uncertainty associated with the threat by assigning numeric values to the criticality of individual assets within the system with respect to specific threats and outage durations
3. Provide ranking criteria, such as power availability and cost, that can be used to analytically rank options against each other with respect to a resilience and cost tradeoff
4. Utilize a DBT to rigorously define the threat under which the evaluation takes place
5. Consider interdependencies between the electric infrastructure and other critical infrastructures (e.g., communications, transportation, physical security, emergency services).

3.3 Energy Surety Design Steps

The following steps are utilized as part of the ESDM. The same general steps are utilized in applying the ESDM to microgrids. If the steps are followed closely, at the end of the evaluation, microgrid design options can be compared directly for cost and performance benefits relative to community-identified energy system performance goals.

1. Define the boundaries of the system to be considered.
2. Identify critical loads:
    a. Identify what service the load is providing.
    b. Identify interdependencies among critical loads and other critical infrastructures.
    c. Identify physical locations (map/building).
3. Define critical infrastructure (components such as switches and transformers)
    a. Build upon the component list developed by the utility.
    b. Identify generators, storage, switches, breakers, buses, etc.
4. Obtain input for defining performance goals from the city, county business, etc.
5. Attain system status awareness (distribution, transmission, and ISO)
    a. Experience with previous events, any reports, etc.
    b. Emergency operation procedures
        i. Staging of equipment
        ii. Reconfiguring network
        iii. Protection
        iv. Recovery procedures
    c. What telemetry is available to support awareness?
    d. Future infrastructure plans
    e. Constraints (environmental, regulatory, safety, etc.).
6. Obtain stakeholder input for defining performance goals.
7. Work with city, county, etc. to create or identify the DBT document(s) that should be applied to the ESDM and identify boundaries on the maximum allowable (tolerable) consequences.
    a. Start with generic historical data
    b. Validate with stakeholders
    c. Could be multiple DBTs for hurricane, ice storms, peak heat, flood, CIP, etc.
8. Create a performance risk vector that shows the risk of each element in the grid by analyzing existing infrastructure and loads against the DBT(s). This results in baseline system response to events in the DBT relative to the preliminary system performance goals.
9. Determine what modifications to the system should be considered high-level options to enhance system performance to meet preliminary performance goals.
    a. Hardening of individual facilities, distributed and renewable generation and storage at individual facilities, networking of generation assets, etc. Combinations of all these approaches might be appropriate due to locations or other factors.

b. Further gathering of detailed electrical system information
    i. Electrical feeds (one-line, building breaker, etc.)
    ii. Electrical characteristics
        1. Daily and seasonal KW and KVAR
        2. Example profiles could include:
            a. High resolution for a few days
            b. Hourly for a year
    iii. Peak load, average load, minimum load (KW/KVAR)
    iv. Interdependencies
    v. Level of criticality
c. Identify reliability/resilience measures already in place
d. Determine any qualifications (e.g., load is critical in spring, but not summer, fall, or winter)

10. Using high-level options found in (9), engineer low-cost potential solutions and prove technical and operational feasibility as well as the ability to meet identified performance goals.
    a. This is done using best practices for safety, reliability, construction, operation, and cost.
11. For each option considered, evaluate the performance risk to make sure that system performance is appropriately enhanced, and the risks are reduced.
12. Evaluate engineered solutions and determine the cost/performance (Pareto) frontier and identify the best viable options with input from the stakeholders.
    a. The Pareto frontier compares cost and performance for multiple options to identify the most efficient and cost-effective solutions.
    b. This comparison can be done with engineering judgment if the number of cases is small.
13. Compare the respective reliabilities of baseline and engineered solution cases and costs to the system goals.
    a. If the costs and performance of the upgrades are acceptable, move forward.
    b. If the costs and performance of the upgrades are not acceptable, iterate on the process by reducing the DBT, reducing performance goals, or looking at alternative solutions.

3.4 General Energy Surety Microgrid Design Phases

In using the ESDM approach discussed above, the evaluation steps for microgrid evaluations are generally combined into three general phases. These phases include:

- Phase I: Assessment of the current energy infrastructure, including identifying critical functions, services, and loads and defining the expected threats and durations.

  This is usually accomplished by developing a project working group (PWG) by teaming with the local utility and government officials to identify critical and priority building and facility functions and, with their help, determining the expected energy demand for various outage durations (DBTs), the energy reliability required, and the energy supplies and energy storage needed.

  This essentially establishes the expected system performance goals for various outages and threats.

- Phase II: Assessment of options to reconfigure existing energy resources to enhance critical mission energy needs.

  In this phase, based on the critical and priority buildings, operations, and services identified by the PWG, a range of upgrade options are considered to meet the expected performance objectives and design threats.

  This range of system upgrade options can include preliminary costs estimates, which typically include:
    - Hardening the system to prevent outages
    - Use of additional backup generators to provide redundancy and improve utilization of backup generation

    - Networking of distributed and renewable generation resources in either campus microgrids (does not interact with the grid) or advanced microgrids (can operate either grid-tied or islanded).

- Phase III: Evaluate upgrade options and develop conceptual designs to cost effectively meet energy supply, reliability, and restoration needs.

  In this phase, preliminary information on integrating hardware improvements, control system improvements, distribution system modifications, and renewable and distributed generation resources are evaluated along with potential cost and performance benefits.

  This phase includes the use of a range of consequence modeling tools, power reliability modeling tools, and system cost and performance optimization tools to provide more detailed understanding of how the system will perform.

  The need for this step depends on the complexity of the system and the design approach. For example, optimization analyses for only a few buildings that cannot be networked, or buildings that would be hardened, do not add significant value.

3.5 Outcome of an Energy Surety Design

The outcome of an energy surety design includes two important elements. The first is a conceptual design at about a 10%–15% design level. This provides a general description of the major design and construction elements, suggestions of the best locations to enhance energy surety, and suggestions of the elements and operational scenarios to be included. This design can then be used by an architectural and engineering company to develop a detailed engineering design for construction and implementation. The second element is a cost analysis that allows the customer to evaluate the trade space between solution performance and costs, which provides the relative cost/energy system performance tradeoffs needed for community leaders and managers to estimate budgeting and funding needs and expected performance benefits.

4. Defining Energy System Boundaries

This module provides a general discussion of how to establish the initial energy system boundaries to be evaluated in the microgrid design (as discussed in the ESDM methodology steps in Module 3). This step requires deliberation and discussion of the general reasons for the microgrid, types of events and outages that should be considered, and the major critical functions and capabilities that the community needs from the microgrid during an outage. It is critical to establish the boundaries for considering the microgrid to limit the scope of critical functions and facilities to be considered, which will constrain the amount of analysis and data gathering necessary to design the microgrids.

We use the term “community” to describe the group of people considering the microgrid. A community may be as small as a few neighbors creating a small microgrid or may be as large as an entire city looking to build a large microgrid or several microgrids to serve its residents.

If final critical functions and facilities are not entirely clear, the evaluation can initially use a wider scope that will be narrowed with further analysis. This begins to establish the performance goals and objectives, range, infrastructure, and duration of the microgrid.

4.1 Energy System Boundaries, Stakeholders

Steps to define energy system boundaries include:

- Initially determine the boundaries of the size and scope of the system to be addressed.
  - Boundaries may be a campus, a military base, or a whole city/town
  - Consider the distribution system configuration – feeders, substations, switchyards, etc.
- Based on the boundaries, determine the key stakeholders who should be involved in the process:
  - City government or base/campus operators
  - Public works
  - Utilities (power, gas, water, communications)
- Identify general energy performance goals and impact of power outages
  - Operational strategies expected
  - Cost and funding mechanisms being considered
  - Types of events to consider

To further understand the energy system performance within the boundary, the following questions should be considered:

- What are likely outages – what has occurred in the past – lessons learned from past outages, what performance might be needed during an outage?
- What do those within the energy boundary (city/community/campus/base) want to be able to do during an extended outage: cover all power needs or only critical loads?
- Is this an economic development opportunity, or is this for local energy security/surety?
- What funding mechanisms are available, and do they have incentives to include certain capabilities or technologies (e.g., renewable energy)?

4.2 Module 4 Exercise

As the mayor and city council of Alphaville, consider broadly what your major goals and objectives are for an energy surety evaluation.

Alphaville

- Alphaville is a small city with a population of 30,000 residents
- It has its own city government, police, combined fire/ambulance services and a hospital
- It has a water treatment plant which is obtained from the river on the northeast corner of town, and processed by a wastewater treatment plant and discharged in the southwest corner of town
- The city is electrically served by a private utility with two substations and five feeders, both overhead (OH) and underground (UG)
- Most of the northern and central part of the city has gas services provided by a private utility

What types of services and assets do we want to provide energy surety?

For what duration of time (days, weeks, longer) do we want to provide these services and assets?

In addition to existing backup generation, what types of distribution resources should we consider (e.g., diesel, gas, generators, cogeneration, renewables like PV or wind, etc.)?

In addition to providing emergency services, do we want to consider ancillary benefits like cogeneration, providing peak shaving, selling power back to the utility, incorporating a certain amount of renewables, etc.?

What funding sources are available (federal, city, state, private purchase agreements, etc.)?

5. Prioritizing Critical Assets and Services

This module provides a general discussion of how to establish critical loads and infrastructures that need to be included in the energy surety design evaluation, as well as the opportunities for microgrid applications. This step requires integration with key stakeholders to discuss the general needs of the microgrid, rank the major critical functions and capabilities needed from the microgrid by the community during a main grid outage, and hone in on the needs for different potential outages. This process begins to further establish the system boundaries, operations, and critical infrastructures to be included in the final design.

As in module 4, we use the term "community" to broadly mean the group of people considering the microgrid, which may range from a few people to an entire city.

As part of a microgrid conceptual design assessment, we ask communities to identify critical needs, critical operations, and critical functions that they believe need to remain in operation for a range of events that could vary in severity and duration. Though actual performance goals and resilience capabilities needed for a community differ, general categories of operational performance goals and service considerations are commonly addressed. A general discussion of services that need to be considered are presented below.

5.1 Community Energy and Infrastructure System Consideration Examples

In general, a community might have different operational performance goals for a one-day outage and a five-day outage. For example, a one-day outage response or microgrid design might focus on infrastructures like:

- Operating major intersections and traffic lights
- Meeting the energy needs of the city hall, police, fire, and paramedic services
- Making sure hospitals keep operating.

This response might focus on temporary solutions that can be handled quickly and easily with portable technologies, such as portable gensets.

A five-day outage could require a focus on an additional set of needs that would not be initially identified as critical but would become critical during an extended outage. This may require consideration of not only a different set of operations and infrastructures, but also a different set of solutions. For example, a five-day outage might focus on more permanent energy solutions, or a combination of permanent and temporary solutions, that support having people stay in one place for the duration of the outage or event. This might include:

- Increasing importance of energy for critical infrastructures
  - Providing fuel or energy to hospitals whose generators might have run out of fuel
  - Operation or partial operation of water and waste water utilities, so people are not living in unhealthy conditions and firefighting is possible
  - Meeting the energy needs of businesses that provide important community services, including grocery stores, pharmacies, and gasoline stations, for at least some period each day
- Making sure city hall, emergency operation centers, police, and fire station energy needs are met
- Providing energy for shelters, schools, and community centers where people can go for assistance
- Providing energy to at-risk residents, such as those in senior housing, if possible or warranted
- Making sure energy is available for communications hubs, radio, TV, etc. so citizens can stay informed of the latest developments and information on the outage.

5.2 Community Energy and Infrastructure System Consideration Priorities

Below is a summary of community operations, infrastructures, and services that should be considered when developing microgrids for extended outages from natural disasters or other low probability but high consequence events. The categories that should be considered include:

- Critical water (for public health and firefighting), waste water (for public health) and associated treatment operations and pumping needs, as well as storm water pumping infrastructure
- Communication infrastructure for radio and TV stations, though not all would be required
- Emergency response infrastructure for police, fire, ambulance, emergency response operations center (city hall), and related emergency communications for these functions
- Community health and public safety infrastructure for hospitals, at-risk patient care centers, pharmacies, and ambulance services
- Community services, including grocery stores, gas stations, shelters, schools as shelters, etc.
- Transportation services, including operations and controls for traffic, railways, and aviation facilities as appropriate
- Other infrastructure needed to support identified major critical community or business operations.

These elements should always be considered but might not be appropriate in all cases, depending on the range of threats and the expected performance of the energy system that will support the community services and operations identified as critical by each community.

5.3 Module 5 Exercise

Assign the following general services and facilities high, medium, or low priorities. Assign each facility a category of service (e.g., grocery stores apply to the category of "Food" service) to help map facility priorities to service priorities.

	Service	Priorities (H, M, L)	#	Facilities	Priorities of Facilities (H, M, L)	Facility Category Service
1	Comm. (Radio and Phone)		1	City Hall		
2	Data Service/Internet		2	Public Works		
3	Emergency Response		3	Fire Station A		
4	Fire/Ambulance		4	Police Station A		
5	Road Clearing		5	City Radio Repeater		
6	Equipment Maintenance		6	Water Treatment		
7	Water Resource		7	Waste Water Treatment		
8	Waste Water		8	Pump Station A		
9	Flood Control		9	Pump Station B		
10	Temp. Housing		10	Senior Housing A		
11	Safety Systems		11	Affordable Housing A		
12	Police		12	Affordable Housing B		
13	Shelters		13	Hospital		
14	Hospital		14	Cell Tower		
15	Medical Supplies		15	Gas Station A		
16	Food		16	Gas Station B		
17	Fuel		17	Grocery A		
			18	Grocery B		
			19	Pharmacy A		
			20	School Shelter A		
			21	Church Shelter		
			22	Garage A		

Fill in specific services and facilities applicable to you (e.g., for your campus, city, etc.), and rank them as done for the generic services.

	Service	Priorities (H,M,L)	#	Facilities	Priorities of Facilities (H,M,L)	Facility Category Service
1			**1**			
2			**2**			
3			**3**			
4			**4**			
5			**5**			
6			**6**			
7			**7**			
8			**8**			
9			**9**			
10			**10**			
11			**11**			
12			**12**			
13			**13**			
14			**14**			
15			**15**			
16			**16**			
17			**17**			
			18			
			19			
			20			
			21			
			22			

Rank your specific facilities from highest to lowest priority. Higher-ranked facilities are critical loads that should be included in microgrid designs. Lower-ranked facilities may be non-critical loads that can be disconnected during a stress event (e.g., a grid outage), so may not need to be included in microgrid designs.

Facility	Service	Priority

6. Identification of Design Basis Threats

This module provides a general discussion of how to identify potential design basis threats (DBTs) and utilize this knowledge to evaluate which DBTs should most influence microgrid design. DBT impacts are used to develop performance objectives for system improvements that will mitigate these impacts. The DBT terminology was borrowed from the nuclear industry, where it is a comprehensive document that identifies threats a facility must withstand. The DBT then informs the design of the facility and its systems. Performance objectives are separately listed for each DBT, which is a profile of the type, composition, and capabilities of an adverse threat.

The threat can be natural, such as a hurricane or ice storm, or it can be manufactured, such as a cyber or physical attack on infrastructure. The DBT provides boundaries on the environment in which the system must be made more resilient. It is a cooperatively developed statement(s) that explains the threat (such as a hurricane, flood, or cyber-attack) and provides a basis for the design.

The module provides examples of different classes of DBTs. A given DBT will impact a system in terms of both the consequences of the threat to the microgrid, expressed as power loss, equipment loss, and economic loss, and the broader potential threats to public safety. Additionally, a given DBT will have a duration associated with how long the threat is expected to last, and how long it will take to restore the system and recover from the threat. While it is helpful, it is not necessary to determine the impacts and duration of a DBT in great detail, as in many cases the data for such an analysis may not be available. However, it is important to distinguish key threats and to attempt to rank them. It is also important to determine which key threats should be specifically designed for or prioritized and which ones can be ignored.

Natural DBTs are regional in nature. Coastal areas may be more prone to hurricane threats, while dry areas with forest cover may be more prone to forest fires. Following establishment of DBTs for a given system, overall system-wide performance goals are developed to mitigate or diminish the impacts of these threats to the system.

6.1 Example Design Basis Threats

Examples of DBTs include:

Natural Causes:

- Hurricanes – high winds and storm surges, impacts are regional and can take weeks (or more) to restore power
- Floods – impacts vary regionally and locally, usually restored within a few days
- Tornados – some people can be displaced for long periods, wider area can be restored in days
- Earthquakes – in active zones impacts can be over a wide area, can take days to weeks for restoration
- Volcanoes – can devastate a local to regional area, can take weeks to months to restore power
- Major fires – can entail evacuations of whole areas and take weeks to restore power
- Ice storms/blizzards – often result in tree damage to lines, can take out local to small regions for days until storm clears and power can be restored
- Heat waves – at risk people need support or shelter, do not usually entail large-scale power outages
- Minor fires – usually localized and impacts for short durations, local power outages only for area where fire occurs
- Landslides – take out local areas but do not cause widespread power outages

Mechanical/Operator Failures:

- Human error in operation – impact usually localized, takes out node where error occurred, does not typically impact overall system, though can cause wide-spread outages in certain conditions
- Equipment failure – rare, impact usually localized, takes out node where equipment failed, system protection usually isolates the failure to localized areas

Attacks

- Cyber-attack – impact depends on cyber protections in place, can be local to regional depending on attack, restoration depends on mitigating attack to restore the system
- Physical attack – impact depends on nature of attack and physical protections in place

6.2 Ranking Design Basis Threats

Metrics can be assigned to the design basis threats based on their likelihood, the consequence, system resilience to the event, and the duration. An example scale to rank DBTs is:

- Likelihood of event (High = 3, Medium =2, Low = 1)
- Consequences of event (High = 3, Medium =2, Low = 1)
- Resilience to the event (High = 1, Medium =2, Low = 3)
- Duration of the event (Hours = 1, Days =3, Weeks = 5)

For example, a hurricane may have a low likelihood (1), high consequence (3), the system may have low resilience to the hurricane (3), and the duration of the hurricane's impact may be weeks (5), resulting in an overall score of 12. A heat wave may have a high likelihood (3), low consequence (1), medium system resilience (2), and a duration of only hours (1), resulting in an overall score of 7. Since the hurricane has a higher impact score than the heat wave, it is found to be the higher impact DBT.

It is important for communities to develop their own DBT metric scale. The scoring listed above is a simple example and will not be appropriate in all situations. For example, communities may want to give more than 5x weight to week-long events compared to hour-long events and may have some events for which the consequences are more than 3x greater than others. The main goal is to define metrics which prioritize the most impactful DBTs.

6.3 Module 6 Exercise

The city of Alphaville is considering options to improve the resilience of their community, which has experienced 3 to 10-day power outages 4 times in the past decade due to flooding and heat waves. Additionally, there are rolling brownouts in peak summer seasons, during which portions of the city lose power for up to two hours per day (no blackouts, though increasing load demand may change this). Once, there was an ice storm that made services for senior and affordable housing impossible for a couple of days. This significantly impacted city services and public health because many people needed to be evacuated to shelters, but fuel supplies were limited, and city residents were unable to easily leave the region.

Alphaville

- Alphaville is a small city with a population of 30,000 residents
- It has its own city government, police, combined fire/ambulance services and a hospital
- It has a water treatment plant which is obtained from the river on the northeast corner of town, and processed by a wastewater treatment plant and discharged in the southwest corner of town
- The city is electrically served by a private utility with two substations and five feeders, both overhead (OH) and underground (UG)
- Most of the northern and central part of the city has gas services provided by a private utility

Using the following table, rank design basis threats to prioritize Alphaville's performance goals in addressing future threats.

Threats	Likelihood of event (H3, M2, L1)	Consequence of event (H3, M2, L 1)	System Resilience to event (H1, M2, L3)	Duration of event (Hours 1, Days 3, Weeks 5)	Overall rank scores (Total)

In the table below, fill in specific Design Basis Threats applicable to you (e.g., for your campus, city, etc.).

Threats	Likelihood of event (H3, M2, L1)	Consequence of event (H3, M2, L1)	System Resilience to event (H1, M2, L3)	Duration of event (Hours 1, Days 3, Weeks 5)	Overall rank scores (Total)

7. Performance Goals, Objectives, and Risk Analysis

This module provides a general discussion of how to establish the initial system performance goals and objectives for identified critical services and facilities against identified DBTs. The performance goals and objectives clarify requirements that the set of system improvements must meet to protect these critical services and facilities if the identified DBTs were to occur. After their initial determination, performance goals and objectives are modified and expanded as conceptual design improvements are developed and the feasibility of various options is evaluated.

The performance goals are affected both by the scope of the system being considered and by the types of DBTs considered. For example, it would be easier to implement performance goals for a small subset of buildings in a city or campus than in an entire city or campus. It would also be easier to implement performance goals to withstand minor storm damage than for hurricanes, since the impacts will be smaller and more localized. The performance goals indicate what the system is designed to do, given the designated DBT. The performance goals need to include both the scope of critical functions and facilities that need to be protected and the duration for which these assets need to be protected.

If the DBT is a hurricane, performance goals might specify that for electrical equipment in critical buildings in a flood zone to be functional, electrical service equipment must be located above the flood zone. Enough backup fuel sources, such as diesel, must be stored to ensure that the designated critical buildings can be supplied for the duration of the outages.

Performance goals can also include limiting fuel use, increasing generator equipment efficiency, incorporating a given amount of renewable resources, and lessening the impacts of noise, pollution, or CO2, in addition to ensuring the system functions reliably for the designated DBT(s) being considered for the system.

7.1 Performance Goal Considerations

When establishing performance goals, it is valuable to consider the following questions:

- What are the worst-case impacts to critical services and assets for the DBT events?
    - Consider the impact of services lost in terms of not only load, time, and cost, but also human, social, and emergency response impacts.
- How do we prioritize critical services and assets to both maximize the resilience improvements and minimize the service impacts?
- How can the broad set of resilience options considered (distributed generation, renewables, storage, hardening controls, etc.) be compatible with the existing distribution and backup systems while also improving resilience?
- What is the cost of the gained resilience? How does cost/benefit play out over short, medium, and long timescales?

Additional performance goal considerations are:

- Critical service requirements during the DBTs provide the basis for resilience improvements
- Requirements for resilience will vary depending on the importance of the asset considered:
    - Some assets may require non-interruptible power
    - Some may require hardening to the DBT such as relocating electrical equipment above the expected flood zone or protection against wind damage
    - Resilience improvements may be applied collectively to multiple local assets, or may be done individually through targeted improvements of local backup generation
- Asses existing backup systems for critical assets in terms of reliability, maintenance, fuel storage, and supply chains to determine if they adequately meet the needs for the DBT
- The overall goal is to provide the most cost-effective and sustainable set of targeted resilience improvements that address the critical service impacts expected by the DBT.
    - Cost-effective must consider not only direct costs such as equipment and loss of load, but also indirect human and social impacts including public health and safety.

7.2 Performance Risk Analysis

It is important to evaluate the ability of the energy system to meet the defined extended outage performance criteria. This is typically done using a risk-informed performance assessment. Described in this section are simple performance parameters used to defined performance risk in a way that has been valuable to previous analyses. However, this definition of performance risk may need to be modified based on the specifics of the microgrid being considered to best address the true performance of that microgrid. For example, the equations below reference percent of critical buildings served. For certain applications, the percent of people receiving a critical service (e.g., clean water, cell phone signal, etc.) may be a better metric.

We have generally based energy system performance risk assessment on how well the energy system can meet critical infrastructure functions and services during a given power outage. Based on this approach, we define the performance risk $\boldsymbol{PR}$ for a given outage as a function of the critical buildings and loads served and the length of time they can be met by the energy system. The performance risk, $\boldsymbol{PR}$, defined as:

$$\boldsymbol{PR = 1 - \left(CBS \times CLS \times RG \times \frac{Da}{Dn}\right)},$$

$\boldsymbol{CBS}$ = Percent of critical buildings served – critical buildings with backup power systems. If few buildings are served, then consequences and risks will be high.

$\boldsymbol{CLS}$ = Percent of critical loads served – weights serving the defined critical loads for the critical services and buildings. If minimal loads are covered, the consequences and risks will be high.

$\boldsymbol{RG}$ = Reliability of generation – weights the maintenance of backup generators. Low maintenance lowers reliability and the risks will be high.

$\boldsymbol{\frac{Da}{Dn}}$ = Ratio of generator fuel availability versus outage duration. If the generator fuel tank is small, and/or the ability to refuel the generator is low, then the risks can increase for longer power outages, unless renewable or other energy resources are available.

Based on customer outage evaluations for some major natural disasters, we have found that typically when backup power systems can meet 85% or more of the critical buildings and loads served for 85% or more of the outage duration, the overall power system can adequately provide power to support critical community services and functions without significantly impacting overall public health and safety. For energy systems that meet less than 70% of the critical buildings and loads served for less than 70% of the outage duration, the community health and safety become increasingly stressed. Therefore, in general we have quantified energy system performance risk notionally as:

Low Performance Risk – $\boldsymbol{PR} < 0.30$

Medium Performance Risk – $0.30 < \boldsymbol{PR} < 0.50$

High Performance Risk – $\boldsymbol{PR} > 0.50$

7.3 Resilience Enhancements to Improve Performance

We evaluate improved resilience as both the reduced impact of the event and the reduced recovery time to return to normal operation after the event. Specifically, the system impact (SI) of the event is the time integral of the "typical" system performance (TSP) minus the actual system performance (SP):

$$SI = \int_{t0}^{tf} \left[TSP(t) - SP(t)\right] dt.$$

Similarly, the total recovery effort (TRE) is the time integral of the recovery effort:

$$TRE = \int_{t0}^{tf} \left[RE(t)\right] dt.$$

Improved resilience will minimize both the system impact and the total recovery effort, as illustrated in Figure 8.

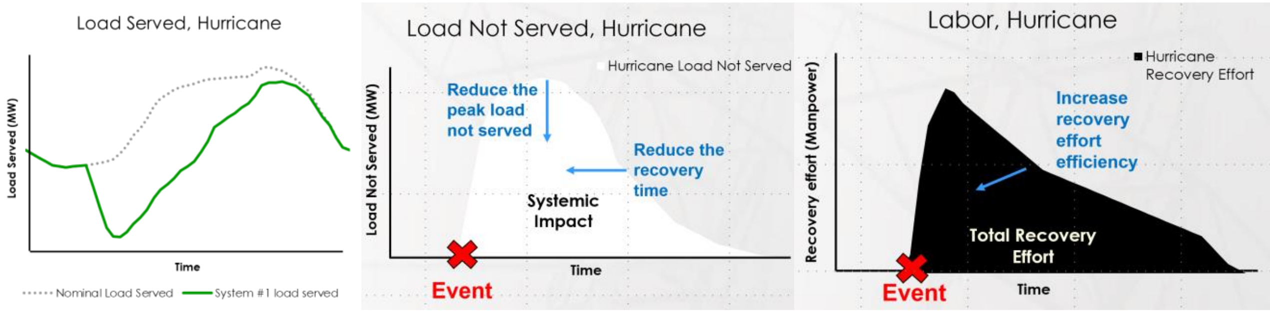


Figure 8: Hypothetical impact of a hurricane, showing (left) normal load and actual load served, (center) load not served, and (right) labor required for recovery. Blue arrows and text indicate the goals of resilience to reduce system impact and total recovery effort.

7.4 Module 7 Exercise 1

Based on the critical assets and facilities determined for the city of Alphaville, develop an initial set of performance goals and objectives to meet energy requirements. Include the critical services, facilities, businesses, and industrial areas that will need to have power maintained, how this power will be maintained, and how much power will need to be maintained.

Alphaville

- Alphaville is a small city with a population of 30,000 residents
- It has its own city government, police, combined fire/ambulance services and a hospital
- It has a water treatment plant which is obtained from the river on the northeast corner of town, and processed by a wastewater treatment plant and discharged in the southwest corner of town
- The city is electrically served by a private utility with two substations and five feeders, both overhead (OH) and underground (UG)
- Most of the northern and central part of the city has gas services provided by a private utility

Duration of services required to meet DBT, including differences in requirements for longer term outages such as shelter in place, food, water, gas, medical supplies, etc.:

Requirements for electric power reliability, redundancy, and power quality:

Requirements for backup power sources and fuel supplies:

Additional site- or community-specific goals and objectives:

7.5 Module 7 Exercise 2

Using the data in the fuel use table on the next page, estimate the generator fuel use per day and generator tank storage capability in days based on building peak demand values and the generator fuel use table on the next page.

Building Name	Peak Demand (kW)	Backup Generator Size (kW)	Generator Use (%)	Fuel Tank Size (gal)	Estimated Fuel Use (gal/hr)	Estimated Fuel Use (gal/day)	# Days of Fuel Available
City Hall	75	150		200			
Police Station	15	60		120			
Fire Station A	30	30		60			
Fire Station B	150	200		100			
Warehouse	30	60		80			
Police HQ	100	100		500			
Pump 1	75	300		200			
Example	**100**	**200**	**50**	**300**	**7.7 (from fuel use table –50% use)**	**184.8 (7.7*24)**	**1.6 (300/184.8)**

Equipment Generator Fuel Use Table

	Fuel Used (gal/hr) Based on % Loading			
Gen Rating (kW)	**25%**	**50%**	**75%**	**100%**
20	0.6	0.9	1.3	1.6
30	1.3	1.8	2.4	2.9
40	1.6	2.3	3.2	4.0
60	1.8	2.9	3.8	4.8
75	2.4	3.4	4.6	6.1
100	2.6	4.1	5.8	7.4
125	3.1	5.0	7.1	9.1
135	3.3	5.4	7.6	9.8
150	3.6	5.9	8.4	10.9
175	4.1	6.8	9.7	12.7
200	4.7	7.7	11.0	14.4
230	5.3	8.8	12.5	16.6
250	5.7	9.5	13.6	18.0
300	6.8	11.3	16.1	21.5
350	7.9	13.1	18.7	25.1
400	8.9	14.9	21.3	28.6
500	11.0	18.5	26.4	35.7
600	13.2	22.0	31.5	42.8
750	16.3	27.4	39.3	53.4
1000	21.6	36.4	52.1	71.1
1250	26.9	45.3	65.0	88.8
1500	32.2	54.3	77.8	106.5
1750	37.5	63.2	90.7	124.2
2000	42.8	72.2	103.5	141.9
2250	48.1	81.1	116.4	159.6

7.6 Module 7 Exercise 3

Calculate the performance risk for a three-day outage based on the following data table.

Asset	Facility	Critical Building Served (CBS)	Critical Load Served (CLS)	Generator Reliability (RG)	Existing Fuel Capacity (Da/Dn)	PR (1-(CBS*CLS*RG*(Da/Dn))
1	Public Works Garage	0/2	0%	N/A	N/A	
2	Fire Department	3/3	100%	60%	2 days	
3	Police Department	3/3	100%	95%	> 3 days	
4	Water Treatment Plant	1/1	100%	80%	> 3 days	
5	Waste Water Treatment Plant	1/1	60%	60%	1 day	
6	Radio Repeaters/Police and Fire	1/2	50%	80%	> 3 days	
7	High School	0/3	0	N/A	N/A	
8	Flood Control	3/4	75%	80%	> 3 days	
	Average					

Performance/risk defined as:

$$\boldsymbol{PR} = \mathbf{1} - \left(\boldsymbol{CBS} \times \boldsymbol{CLS} \times \boldsymbol{RG} \times \frac{\boldsymbol{Da}}{\boldsymbol{Dn}}\right),$$

$\boldsymbol{CBS}$ = % Critical Buildings Served
$\boldsymbol{CLS}$ = % Critical Loads Served
$\boldsymbol{RG}$ = Reliability of generation system
$\boldsymbol{Da}$ = Operational availability based on fuel available at start of outage
$\boldsymbol{Dn}$ = Operational duration needed (outage duration)

8. System Reliability and Availability

This module provides a general discussion of power system reliability and availability, how these differ, and how to calculate system reliability and availability from component reliability and availability.

Reliability of a power system is the ability to provide sufficient power, especially during critical conditions. Although it may not be possible to achieve 100% reliability of a system (due to the prohibitive costs associated with supplying redundant power networks or backup equipment and supplies to all facilities), the reliability of the electrical distribution system on a campus or military base still can often be significantly improved to meet critical mission operational needs using appropriate risk-based evaluations and energy infrastructure modernization.

8.1 Reliability

The definitions for reliability (as well as availability, discussed later) are based on the IEEE Gold Book.[5]

For engineering purposes, reliability is defined as:

> ***Reliability:*** *The probability that a device, or system, will perform its intended function without failure under stated conditions for a stated period of time.*

Mathematically, reliability is a function of time, expressed as $R(t)$. Let T be a random variable representing time to failure of a component or system. Then, $R(t)$ is the probability that T is greater than a specified time, t.

$$R(t) = Pr\{T > t\} = \int_t^{\infty} f(x)dx,$$

Here, $f(x)$ is the failure probability density function describing the probability of occurrence of outcomes of the random variable T, and t is a specified time (which is measured starting from $t = 0$). In other words, $R(t)$ is the probability that the device, or system, will **not** fail on or before t. Therefore, reliability can also be written as:

$$R(t) = 1 - Pr\{T \leq t\},$$

where $\Pr\{T \leq t\}$ is the probability that the device, or system, will fail on or before time t. $\Pr\{T \leq t\}$ is commonly referred to as the device, or system, probability of failure, $F(t)$.

$$R(t) = 1 - F(t)$$

Methods such as fault tree analysis can be used to identify and evaluate components of a systems probability of failure; then, this relationship can be used to compute the reliability of the system.

The most common failure probability density function used in reliability analysis is the exponential density. Empirically, the exponential density has been found to accurately characterize the time to failure of many components and systems that are well maintained and are operating in the usable portion of their lifespans (i.e., not at start up or end of life). The usable portion of a system's life is generally a long period. A common characteristic of a component or system in this stage of its lifecycle is a constant failure rate, λ. During this period, failures occur at random times. The units of λ are failures per time period. The time period could be seconds, minutes, hours, days, etc. and is generally chosen to provide appropriate scaling for λ. The parameter λ completely characterizes the exponential density function.

$$f(t) = \lambda e^{(-\lambda t)}, 0 \leq t \leq \infty$$

The mean value of the exponential density is found by integrating t times $\lambda e^{(-\lambda t)}$ from 0 to infinity. The result is the mean time to failure (MTTF) and is equal to $1/\lambda$. For a repairable system, the mean time to failure is also equal

[5] *Transmission and Distribution Committee of the IEEE Power Engineering Society (2004) IEEE Std 1366™-2003: IEEE Guide for Electric Power Distribution Reliability Indices.*

to the mean time between failures (MTBF). In terms of the exponential failure density function, reliability is easily found to be:

$$R(t) = e^{(-\lambda t)}, \qquad 0 \leq t \leq \infty$$

Since the single parameter λ completely characterizes the exponential failure density function, some engineers like to use the MTBF as a measure of component or system reliability. This can, however, lead to confusion and errors because it leaves out the fact that reliability is also a function of time. $R(t)$ always decreases with increasing time, regardless of the form of the failure probability density function. Two systems with the same MTBF could have different reliabilities if the time period specified by t is different for each system.

When conducting a reliability analysis, it is important to note four key elements of the definition:

- First, reliability is a probability. This means that failure is regarded as a random phenomenon: it is a recurring event, and we do not express any information on individual failures, the causes of failures, or relationships between failures, except that the likelihood for failures to occur varies over time according to the given probability density function describing the occurrence of outcomes of T.
- Second, reliability is predicated on "intended function." Generally, this is taken to mean operation without failure. However, even if no individual part of the system fails, if the system as a whole does not do what was intended, then the system has failed.
- Third, reliability and failure probabilities apply to a specified period of time. In practical terms, reliability means that a system has a specified chance that it will operate without failure on or before time t. Units other than time may sometimes be used. The automotive industry might specify reliability in terms of miles. The military might specify reliability of a gun for a certain number of rounds fired. A piece of mechanical equipment may have a reliability rating value in terms of cycles of use. The specification of the time period used in the reliability analysis is critical. Evaluations of system availability will be made for the standard period of one year. Definitions and methods for calculating availability are made in the relevant sections below.
- Fourth, reliability is restricted to operation under stated (or explicitly defined) conditions. This constraint is necessary because it is impossible to design a system for unlimited conditions. For example, the failure modes of a system under normal operating conditions are likely different from those when the system is being operated under stress, outside of intended operating conditions. For power system reliability analysis, we assume the entire power system is operating under normal, expected conditions, and not subject to adversarial attack.

In reliability analysis, it is also critical to establish the failure rates for the different elements that make up the system. Mistakes at this point would obviously result in incorrect reliability calculations. Failure rates are generally established based on empirical evidence derived from historical observations of measured time between failures of different components.

8.2 Availability

The availability of a component or system refers to the probability at a given point in time that the component or system will be available for service. It can be defined as follows:

> ***Availability:*** *The probability that a device, or system, will perform its intended function at a stated instant of time for a stated period of time.*

The availability of a system or component is distinct from the reliability of a system or component. As we have discussed, reliability considers only the mean time to failure (MTTF) equivalent to the mean time between failures (MTBF) of a component, which are both equal to 1/λ, where λ is the failure rate of the component in failures per year. The availability of a system also takes into the account the mean time to repair and/or replace (MTTR) a piece of equipment after a failure and is termed r:

$$\begin{aligned} r &= \text{average downtime per failure (hours per failure)} \\ &= \text{mean time to repair or replace a piece of equipment (MTTR) after a failure} \end{aligned}$$

The availability of a component is then defined as the mean time between failures divided by the mean time between failures plus the mean time to repair:

$$A_C = \text{availability of a component} = \text{MTBF}/(\text{MTBF} + \text{MTTR})$$

Since $r = \text{MTTR}$ in hours and $\text{MTBF} = 1/\text{failure rate} = 1/\lambda$ in years, the MTBF is equivalent to the standard of 8,760 hours/year or $\text{MTBF} = 8{,}760/\lambda$.

So, the expression can be converted to:

$$A_C = (8{,}760/\lambda)/(8{,}760/\lambda + r)$$

The expression can be further reduced to:

$$A_C = 8{,}760/(8{,}760 + \lambda r)$$

In contrast to reliability, availability takes into account both the failure rates of a component or system and the mean time to repair the components in a system in order to calculate the availability of a component or system.

To demonstrate how reliability and availability are calculated, as well as to show how they can both differ significantly, consider the following three components with associated failure rates λ and repair times r below:

$$\text{Component A: } \lambda = 1 \text{ failure/year; } r = 1 \text{ hour}$$
$$\text{Component B: } \lambda = 0.01 \text{ failure/year; } r = 1 \text{ hour}$$
$$\text{Component C: } \lambda = 0.01 \text{ failure/year; } r = 100 \text{ hours}$$

Component A represents a component that fails approximately once per year and requires a mean time of 1 hour to repair. Components B and C both have equivalent failure rates of once per 100 years, but Component B only requires 1 hour to repair, while Component C requires 100 hours to repair when it fails.

Calculating the reliability of each of the components for a time frame of one year gives the following values:

$$R_{\text{Component A}}(\text{year}) = 0.3679$$
$$R_{\text{Component B}}(\text{year}) = R_{\text{Component C}}(\text{year}) = 0.9900$$

The reliability of Component B and Component C will be the same since they have the same failure rates. Calculating the reliability values for these components for 1 week instead of one year gives the following values:

$$R_{\text{Component A}}(\text{week}) = 0.9810$$

$$R_{\text{Component B}}(\text{week}) = R_{\text{Component C}}(\text{week}) = 0.9998$$

Notice that the reliabilities of the components are significantly higher for shorter time periods for all components. The availability of the components using the failure rates and repair times for 1 year gives the following values:

$$\text{A}_{\text{Component A}}(\text{year}) = 0.999886$$
$$\text{A}_{\text{Component B}}(\text{year}) = 0.999999$$
$$\text{A}_{\text{Component C}}(\text{year}) = 0.999886$$

Notice, in this case, that the availability values for this equipment are much higher than the reliability values. Again, availability measures the likelihood that a component or system will be in service at a given time, while reliability measures the likelihood that a failure will have occurred for a given time frame. Also notice that the availabilities of Component A and Component C are equivalent, even though the failure rates and underlying reliability of Component A is much less than Component C. Similarly, the calculated availability of Component C is much less than Component B because the repair time for Component C is much longer than Component B (100 hours versus 1 hour).

The reliability of a component or system depends only on the failure rates of the component or system and is highly dependent on the time frame used for the analysis. The availability of a component or system depends both on the failure rates and repair times.

In general, the reliability of a system will be disproportionally affected by components with relatively high failure rates, while the availability of a system will be disproportionally affected by components with a combination of high failure rates and/or long repair times.

Both public discourse and the literature frequently mention that a system has so many "9s of reliability" or that, with improvements, a new set of "9s of reliability" have been made to the system. Care must be taken, however, to ascertain whether reliability or availability is really what is being addressed. Oftentimes, what is meant is that the system has increased availability—not necessarily more reliability—with these improvements. This is important because reliability is defined for a specific time frame, while availability is usually defined for a prescribed period of time, typically a year. For a given component or system and underlying assumptions, availability values will be invariant while reliability values will depend on the time frame considered.

Availability and reliability of components, subsystems, and systems are important to analyze because they provide different pieces of information about a system. Reliability analysis in general will show how likely it is *for a designated duration of time* that a component, subsystem, or system will experience a failure of any type to take it out of service. Availability analysis will show how likely a component, subsystem, or system will be available for service *at a given period of time*.

Reliability and availability may have specific implications for microgrid operations. For some critical services which can accept occasional failures if overall uptime is good (e.g., water pumping stations), high availability will be important. However, for systems which require significant effort to restore after a loss of power (e.g., data centers with critical information), high reliability may be the primary concern.

9. Formulating and Evaluating Design Options

This module provides a general discussion of how to formulate and evaluate initial conceptual design options to meet identified performance objectives for critical services and facilities against a set of DBTs. Advanced optimization and performance tools, can be used to map out the relative performance versus the cost of various options to help evaluate the set of candidates microgrid options for those that provide the highest performance at the most reasonable cost.

The main goal is to formulate design options based on performance objectives for the set of critical service assets required to serve during the DBT event. To do this, we utilize methods and tools to come up with a set of resilient design options. Part of this analysis may be to cluster critical assets and to overlay these clusters onto the existing distribution system to determine which areas might be initial microgrid candidates. One can then use performance metrics to further define and select which of the initially identified candidates should be further developed with conceptual microgrid designs for resilience improvements and what additional assets might require hardening for resilience even if a microgrid is not implemented.

9.1 Initial Design Phase

The initial conceptual design phase (10-15% design) is focused on the development of initial project scope, objectives, and requirements. This provides a general description of the major design and construction elements, best locations of microgrid components to enhance energy surety, and suggestions of the elements and operational scenarios to be included. A flow chart of the initial design process is seen in Figure 9.

The process begins with a vulnerability analysis study to determine parts of the system most likely to be impacted by the events described in the design basis threat (DBT) and for which microgrids might be of most value. For example, communities connected by overhead power lines and on the end of a distribution feeder may be especially vulnerable and hence especially good candidates for microgrids, as failures anywhere along the feeder could cut off their connection to the main electric grid. The design options identified for consideration will represent a set of options that may improve the surety of the system for the critical loads, DBTs, and performance metrics that were identified in previous modules.

Once the design options are identified, quantitative evaluation of the system-level impact of the proposed design options is done through simple simulation of system performance.

9.2 Final Design Phase

The final design phase (30% design) considers the several designs evaluated in the initial design phase and selects a final conceptual design. The initial conceptual design renders several options for meeting the same set of surety goals by either using different technologies or deploying similar technologies in different manners. The final conceptual design takes those initial conceptual designs, expands them using more accurate models/descriptions, and performs detailed studies to determine which option should be implemented based on factors including feasibility, cost, and performance.

Technical feasibility is evaluated in detail during the final conceptual design using steady-state and dynamic simulation and optimization tools.

There are two cost aspects considered: capital costs and operating costs. These costs are studied in detail using capital and installation cost estimates for each option, and simulation of daily, weekly, and seasonal operations under different system conditions to account for the variation in inputs such as renewable generation, fuel costs, and loads.

The performance of the system will be measured in terms of the energy surety goals and the project scope. For example, if increased reliability is a focus, then performance can be measured in terms of improvement in reliability metrics such as System Average Interruption Duration Index (SAIDI), System Average Interruption Frequency Index (SAIFI), etc.

Detailed schematics will also be developed during the final design phase and will be shared with the engineering firm that will ultimately be responsible for constructing the microgrid.

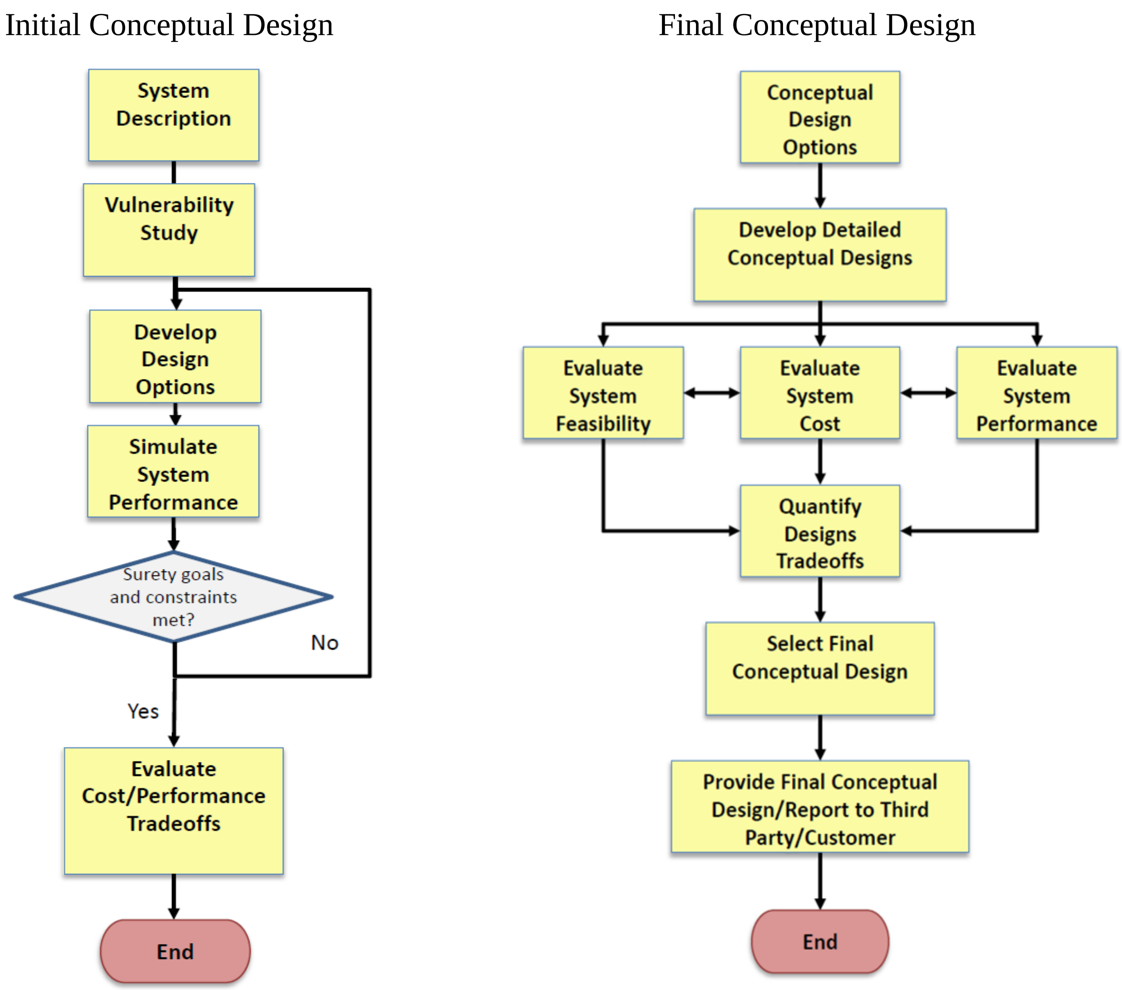


Figure 9: Initial (left) and final (right) conceptual design process.

9.3 Microgrid Design Toolkit

The Microgrid Design Toolkit (MDT) is a decision support software tool for microgrid designers in the early stages of the design process. The software employs powerful search algorithms to identify and characterize the trade space of alternative microgrid design decisions in terms of user defined objectives. Common examples of such objectives are cost, performance, and reliability.

The MDT can not only be used to illuminate the trade space of design alternatives when planning a microgrid, it can also provide a variety of performance, reliability, and cost-related insights for candidate microgrid designs. Without this type of information, designers rely on engineering judgement and a quantitative analysis of relatively few candidate designs. As a result, a full understanding of the trade-offs inherent in the problem is often not achieved.

The MDT performs a multi-objective search to produce a Pareto frontier of efficient microgrid solutions. That frontier is the expression of the efficient trade-offs that can be made amongst the user-defined dimensions (commonly cost, performance, reliability, etc.). The MDT provides a wide range of interactive displays and charts, such as the cost versus performance tradeoff shown in Figure 10, to help a designer understand the results of the search and the implications of different decisions on the resulting quality of the microgrid.

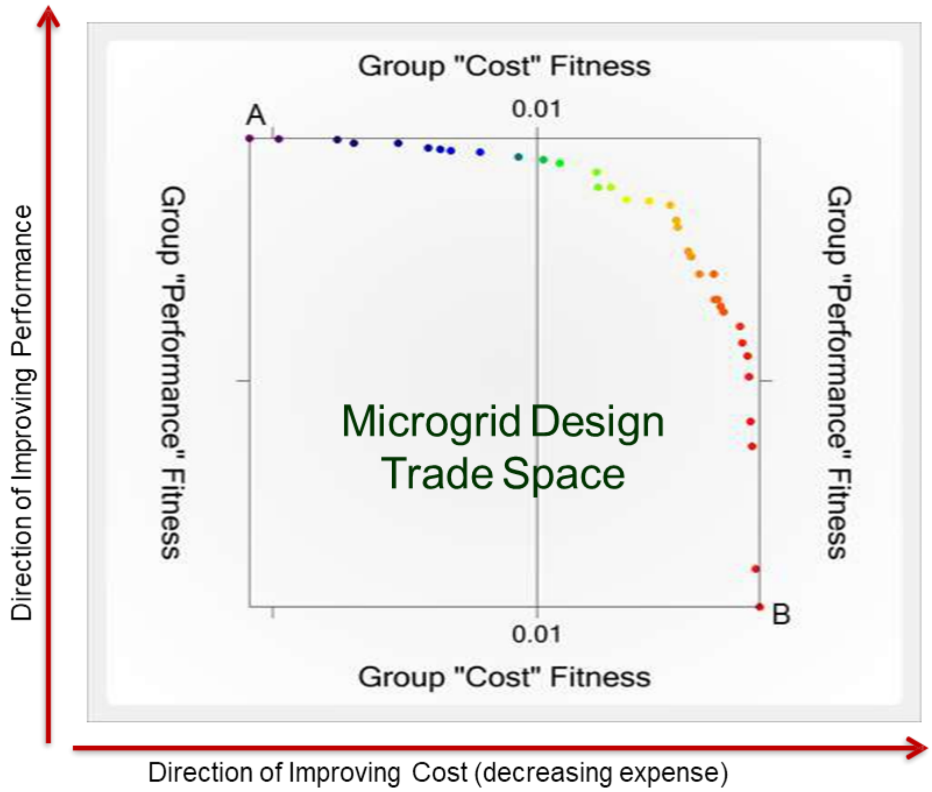


Figure 10: Example output from the Microgrid Design Toolkit showing the tradeoff between cost (x-axis) and performance (y-axis).

The microgrid design toolkit is available for download at: https://energy.sandia.gov/download-sandias-microgrid-design-toolkit-mdt/.

9.4 Load Estimation Techniques

In most cases, electric equipment is primarily powered by an electric utility and the main metering concern of the utility is to gather sufficient information for billing. For many residential and commercial customers, this will entail gathering monthly energy use data, and for larger industrial customers, both monthly energy use and peak demand data. Though there has been a trend towards the increased use of advanced metering infrastructure (AMI) to provide 15-minute or 1-hour energy use and demand data, widespread implementation of these meters is still limited, and missing data is common. For microgrid conceptual designs, it is necessary to have a solid understanding of the expected peak loads and range of loads. Since the microgrid can be, and in many cases is, operated islanded from the utility, the power available to serve loads depends on the capacity of distributed generation resources on the islanded microgrid. Knowledge of the expected range of loads, as well as the peak, informs the amount of generation required to operate the microgrid efficiently.

Unfortunately, in many cases, given the lack of adequate metering, individual building energy use (kWh) and demand (kW) data are unknown. This module presents a simple estimation method for critical building loads to estimate the size of generation needed. It may be necessary to install meters on critical facilities to supplement these estimates at some point during the microgrid design process to supply enough generation to meet the design loads for the critical buildings included within a microgrid. Otherwise, generators may be oversized to ensure that they can meet expected loads and will operate less efficiently than if they were properly sized.

Rough estimates of peak demand can be performed as follows:

- Feeder and building peak demand (kW) can be estimated from monthly and yearly energy usage (kWh) by calculating an average demand and multiplying it by a demand factor
    - For example, a building with 50,000kWh monthly energy use
        - Average demand is 69.4kW, assuming a 30-day month
        - A demand factor of 1.5, this gives a peak demand estimate of 104.1kW
- Peak demand for buildings can also be estimated from feeder demand or energy use data (if available) and building transformer ratings
    - Divide the feeder peak demand by the kVA rating of all transformers on the feeder
    - For example, for a feeder demand of 10MW with a total of 40MVA of connected transformers
        - Average connected load is 0.25W/VA
        - If building A is 500kVA, then it has a peak load estimate of 125kW

Additional resources for load estimation include the DOE Open Data Catalog entry on "Commercial and Residential Hourly Load Profiles for all TMY3 Locations in the United States" (https://openei.org/datasets/dataset/commercial-and-residential-hourly-load-profiles-for-all-tmy3-locations-in-the-united-states), and the EPRI Load Shape Library (loadshape.epri.com).

9.5 Cost Estimation

Cost estimates should include initial equipment purchase costs, future maintenance requirements and costs, design costs (for a design firm to survey the electrical system, do supporting analysis, and create design drawings to outline the changes in the existing grid necessary to implement the design), engineering costs (including all of the additional support to review and oversee the design and construction phases), and construction costs (including the labor to install and test the equipment, as well as any overhead costs associated with a general contractor assigned to oversee the construction).

Cost tools can be used to simplify this approach by using equipment costs to help identify estimates of the other cost categories based on construction and engineering cost estimating procedures, such as RS Means. Once the base equipment costs are estimated, the labor cost estimates are added to determine the overall base costs to install the equipment. The construction management oversight costs are often estimated to be ~20% of the overall equipment costs. The engineering and design costs are estimated to be ~12.5% of each of the construction equipment costs. A 25% contingency is usually included to account for the lack of complete information at the conceptual design level. Therefore, a cost estimate approach is:

- Calculate equipment, installation and labor costs – construction baseline costs (C)
- Calculate additional construction management costs (0.2*C)
- Calculate design cost (0.125*C) and engineering cost (0.125*C)
- Sum the overall design, construction, and engineering costs and multiply by 0.25 to get ranges of costs
- Additionally, add any overall facility overhead costs to these estimates (e.g., 10%).

For example, if it is determined that the overall costs for procuring and installing equipment, including labor, for a small project is $1,000,000, then the construction management costs can be estimated to be $200,000. The design and engineering costs are estimated to be $125,000 each. Therefore, the overall minimal costs for this microgrid will be $1,450,000, and the range of costs, including a contingency, will be ~$1,450,000 - $1,810,000. Additional facility overhead costs, if known or estimated, can be added to these cost ranges.

This approach shows that ~45% – 80% of additional costs (not including facility overhead), on top of construction equipment procurement and implementation costs, should be expected to install system upgrades to build a microgrid. Cost estimates for electrical equipment and labor can be determined using the following:

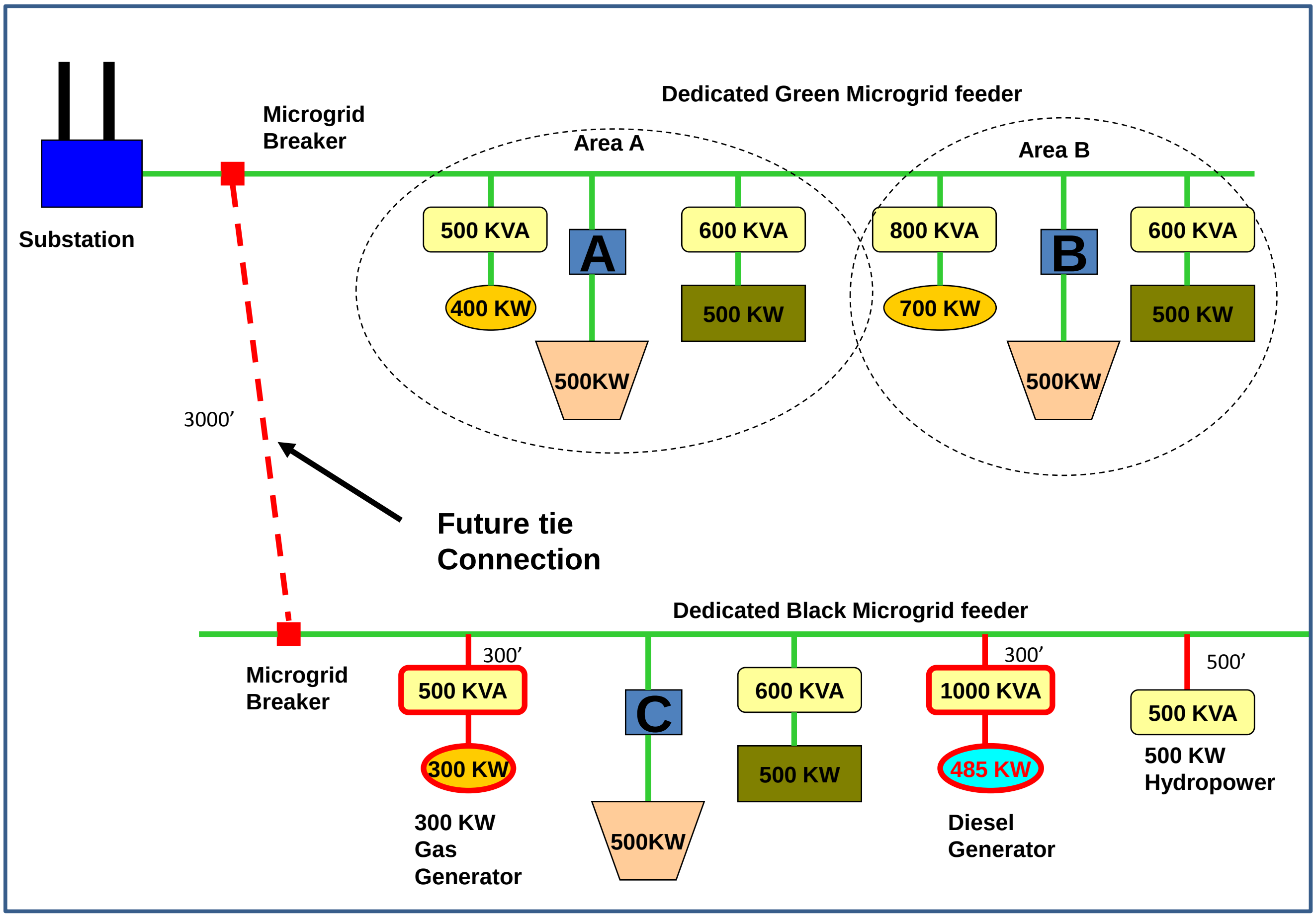
- Electrical equipment and installation cost data can be obtained with estimate resources such as RS Means
- For equipment not included in these estimates, published reports or equipment manufacturers can be consulted for additional cost information

- Regional Davis-Bacon labor wage rates can be used to modify the basic installation costs for the equipment
- An additional labor productivity adjustment of 15% for construction costs is included to account for any additional costs associated with safety and security requirements and training needed to work on city utilities
- Labor overtime is not included in the estimates.

In the case of a conceptual design, since many of the details of a final design and construction need to be more fully scoped, this approach provides a rough order of magnitude (-30% to +30%) estimate of the likely range of costs associated with the project energy system upgrades identified.

9.6 Module 9 Exercise

Below is a proposed microgrid conceptual design. In red are new equipment elements, which will work with existing elements to form the microgrid. All lines are underground, and lengths are shown in feet. Calculate costs for this microgrid conceptual design using the cost table and worksheet below.



Equipment Cost Table

Equipment	Cost
OH Cable	$150/ft
UG Cable	$300/ft
Transformers	$40/KVA
HV Breakers	$100k/unit
Reclosers	$30k/unit
HV Switches	$20k/unit
LV Breaker	$50K/unit
Manhole	$15k/unit
Pin & Sleeve	$100k/unit
Controls	$100k/generator
Diesel Generator	$500/kW
Natural Gas Generator	$1000/kW
PV	$3500/kW
Wind	$1000/kW
CHP (Control Heat & Power)	$2500/kW
Batteries	$3000/kW
Fuel Tank	$1/gallon
Retro fit Buildings	$750/kW
Natural Gas Fuel	$10/MMBtu

Conceptual Design Cost Evaluation

	Quantity	Cost ($K/unit)	Total ($K)
Cable			
Transformers			
Switches			
Misc. Cost			
Generators			
Renewables			
Energy Storage			
Controls			
Cost Savings			
		Subtotal	
		25% Design & Eng. Cost	
		25% Contingency Cost	
		Total Cost ($k)	

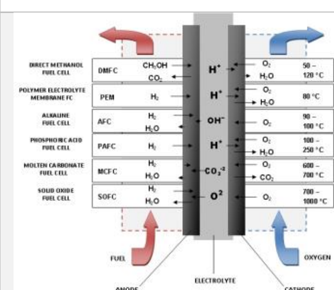
Appendix A – Distributed Energy Generation and Storage

Some types of distributed energy generation and storage devices are listed in the table below.

Generation	
Diesel Generators ▪ **Most common DER used for backup power** ▪ **Power ratings from kW to MW** ▪ **Standby, prime, or continuous** ▪ **26-33% energy efficient, efficiency varies based on loading** ▪ **Costs $0.25-$1.00/W**	
Gas Generators ▪ **Power ratings from kW to MW** ▪ **24-30% energy efficient, efficiency varies based on loading** ▪ **Typically, more expensive per Watt than diesel generators** ▪ **Lower emissions than diesel generators** ▪ **Costs $0.60-$1.20/W** o **20% to 100% more expensive than diesel generators**	

Solar Photovoltaics
▪ **Power ratings from W to MW**
▪ **10-30% energy efficient,**
▪ **Costs have decreased rapidly:**
  o **Commercial PV (~200kW): $1.83/W in 2018**[6]
  o **Less for larger installations**
  o **Fuel (sunlight) is free**
	

Wind
▪ **Power ratings from kW to MW**
▪ **75% energy efficient**
▪ **Costs are decreasing:**
  o **Median cost of $1.60/W in 2017**[7]
  o **Fuel (wind) is free**
	

Other Generation Sources ▪ **Fuel cells** ▪ **Microturbines** ▪ **Hydroelectric** ▪ **Biomass** ▪ **Geothermal** ▪ **…**	

[6] National Renewable Energy Laboratory, "Costs Continue to Decline for Residential and Commercial Photovoltaics in 2018," https://www.nrel.gov/news/program/2018/costs-continue-to-decline-for-residential-and-commercial-photovoltaics-in-2018.html
[7] U.S. Department of Energy, "2017 Wind Technologies Market Report," https://www.energy.gov/sites/prod/files/2018/08/f54/2017_wind_technologies_market_report_8.15.18.v2.pdf.

Storage	
Uninterruptible Power Supply (UPS) ▪ **Typically put in series with a critical load** ▪ **Voltage and power disturbance ride through of 5-20 minutes** ▪ **Increases reliability and power quality served to the critical load**	

Batteries
▪ **Various technologies, effective for different operations**
    ○ **Fast discharge**
    ○ **Long-term storage**
    ○ **High performance over many cycles**
▪ **Sizes range from Wh to MWh**
	

Other Storage ▪ **Pumped hydro** ▪ **Compressed air energy storage** ▪ **Flywheel** ▪ **Capacitor** ▪ **…**	

Appendix B – Examples of Advanced Engineering Analysis

This appendix provides a general discussion of two more advanced sets of analysis that can be done on conceptual designs. Depending on the options proposed, these and other advanced analysis will help determine the most feasible sets of options in terms of performance and cost.

Power Flow Analysis

Several requirements are essential for the successful operation of a power system. One requirement is that the generating sources be sufficient to compensate for all loads, plus losses, within the system. Generation-to-load balance is required to maintain system frequency because there is little energy storage in the system. Another requirement is that voltage magnitudes should remain as close to rated values as possible at all buses. This will not only avoid any equipment damage but will also decrease the likelihood of voltage collapse. Successful operation of a power system also involves ensuring that all generators operate within their power limits and that lines and transformers are not overloaded. A power flow study, also referred to as a load flow study, is a common tool used for AC analysis of a power system in steady state and helps to ensure that all requirements discussed above are met during the planning stages of a power system. A power flow study is also used to both study system behavior with increasing load and aid in real-time applications, such as network optimization, state estimation, and VAr planning. There are commercial software power flow analysis tools available for finding a power flow solution.

A power flow model considers different levels of system generation and load, as well as effects of equipment disruptions on the system and the resulting changes. After each change in generation, load, or disruption event, the model of the system is solved and compared to the initial system. The model records:

- Changes in power flow between regions due to the differences in generation, load, or disruption
- Changes in the overall voltage profile of the system as a result of the differences or disruption
- Changes in the overall system generation as a result of the differences or disruption.

The power flow model ensures that the system is designed so that generation meets load requirements, both when the system is grid-tied and when it is islanded in a microgrid configuration. The microgrid generation should be designed with redundancy, meaning that the loss of any single generator in the system will not result in the loss of load. The power flow model also ensures that the system voltages and power flow conditions do not exceed equipment limits (such as cable carrying capacities) and system parameters (such as voltages between 0.95-1.05 per unit) to ensure the system will perform as designed. If conditions that exceed these limits do occur, the conceptual design must be modified so to meet the necessary performance requirements.

Consequence Modeling Analysis

Consequence analysis modeling can be used to further optimize the utilization of building energy resources and evaluate ideas that have the potential to increase energy security. Consequence analysis involves:

- Defining problems using a system dynamics approach and characterizing the significant dynamics of a system related to power system applications.
- Defining a system as a continuous quantity interconnected in loops of information feedback and circular causality.
- Deriving understanding and applicable policy insights from the resulting model.
- Implementing changes resulting from model-based understandings and insights.

Systems dynamics modeling uses pivotal time series of flows and accumulations of flows. For energy reliability analysis applications, power and energy accumulations are tracked to evaluate the power and energy characteristics of the generators and loads in critical buildings.

For example, in one application of consequence modeling, we can model how to efficiently implement PV, energy storage, and gas or diesel generators within a microgrid. The model inputs a time series of building load data and dispatches a predefined suite of generators required to meet that load. The model tracks numerous aspects of generator performance, including generator ramp rates, fuel consumption, fuel tank refills, and generator efficiency. The model can then input expected PV characteristics, such as outputs, based on solar inputs for a particular area, and include energy storage dynamics for particular battery technologies. The combined model can then be used to size an appropriate amount of energy storage to PV use to operate generators efficiently with a high level of utilization (>70%). When available, energy storage can be used to balance out the expected fluctuation in PV outputs to optimize the use of PV, energy storage, and backup generators in a system. Consequence modeling can be used in many other applications, such as implementing peak shaving and power wheeling in a microgrid; using cogeneration by balancing heating, cooling and electrical loads in a system; integrating with other renewables, such as geothermal or wind; and other examples where system dynamics approaches are useful.

Glossary of Terms

Advanced Microgrid [Module 3]: A microgrid is designed through the systematic ESDM process to enhance system safety, security, reliability, sustainability, cost-effectiveness, and resilience. Advanced microgrids use controls to efficiently manage multiple generation resources to match the needs of the microgrid loads, including prioritizing critical loads.

Automatic Transfer Switch (ATS) [Module 2]: An automated switch that is typically used to attach a portion of a building's load onto a backup generator, isolating this load-generator pair from the rest of the grid and allowing for operation of the backup generator. In microgrid operations, an ATS may be opened to isolate a generator during startup, then may be closed once the generator's operation is established to energize the microgrid.

Baseline Design [Module 8]: This is a reference point against which potential improvements suggested by the design methodology are assessed. For a site with existing backup generation, this amounts to the observed historical performance before energy surety improvements such as microgrids are installed.

Community [Module 4]: The group of people considering a microgrid. A community may be a few neighbors or an entire city. Community stakeholders will help define critical loads, design basis threats, and performance goals.

Conceptual Design [Module 8]: The ESDM process results in an initial design which describes microgrid functional requirements as well as quantifiably justified recommendations that will meet the stakeholder concerns. Requirements and recommendations are specified for generation, utility connections, controls, and cyber security.

Critical Load [Module 5]: Critical loads are electrical loads that are critical to the community. These loads often already have dedicated backup generators. Some critical loads are non-interruptible and will include uninterruptible power supplies (UPSs), while other critical loads can endure short losses of electrical power.

Design Basis Threat (DBT) [Module 6]: The ESDM uses DBTs to define the conditions (threats) affecting the critical loads and under which the microgrid must continue to operate. These threats may be environmental (such as a hurricane) or man-made (such as a cyber or physical attack).

Energy Surety Design Methodology (ESDM) [Module 3]: An analysis process developed by Sandia National Laboratories that quantifies and optimizes six key attributes for energy systems (safety, reliability, resilience, security, sustainability, and cost effectiveness) as a systematic preliminary design process.

Main Electric Grid [Module 1]: The large electric system which serves customers before microgrid installation, and which may continue to be partially utilized after microgrid installation. Main electric grids may span entire continents or may cover only a small island.

Microgrid [Module 2]: A set of loads with local generation that can be isolated from the main electric grid. Microgrids may range from small single-customer solutions to large solutions covering much of a feeder.

Non-critical Load [Module 5]: Electrical loads that will not be prioritized and may not be powered during islanded microgrid operations.

Performance Goals [Module 7]: Objectives for the microgrid. Performance goals may include reducing costs, limiting fuel usage, or using renewable energy. Microgrid performance is evaluated against these goals.

Point of Common Coupling (PCC) [Module 2]: The location of the switch that isolates a microgrid from the main electric grid.