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Methodology for Preliminary Design Of Electrical Microgrids

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Abstract

Many critical loads rely on simple backup generation to provide electricity in the event of a power outage. An Energy Surety Microgrid™ can protect against outages caused by single generator failures to improve reliability. An ESM will also provide a host of other benefits, including integration of renewable energy, fuel optimization, and maximizing the value of

energy storage. The ESM concept includes a categorization for microgrid value propositions, and quantifies how the investment can be justified during either grid-connected or utility outage conditions. In contrast with many approaches, the ESM approach explicitly sets requirements based on unlikely extreme conditions, including the need to protect against determined cyber adversaries. During the United States (US) Department of Defense (DOD)/Department of Energy (DOE) Smart Power Infrastructure Demonstration for Energy Reliability and Security (SPIDERS) effort, the ESM methodology was successfully used to develop the preliminary designs, which direct supported the contracting, construction, and testing for three military bases.

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Abbreviations and Acronyms

ATS automatic transfer switch

CONOPS concept of operations

COTS commercial off-the-shelf

CSWG Cyber Security Working Group

DBT design basis threat

DER distributed energy resource

DHS Department of Homeland Security

DOD Department of Defense

DOE Department of Energy

DSM design screening model

EMS energy management system

ENM electrical network model

ESM Energy Surety Microgrid™

EV electric vehicle

FEMA Federal Emergency Management Agency

GIS geographic information system

HILF high impact/low frequency

ICS industrial control system

IEE Institution of Electrical Engineers

IEEE Institute of Electrical and Electronics Engineers

JBPHH Joint Base Pearl Harbor-Hickam

LV low voltage

MC Monte Carlo

MDT Microgrid Design Toolset

MV medium voltage

NCSD National Cyber Security Division

NIST National Institute of Standards and Technology

NISTIR NIST Interagency Report

NPV net present value

O & M operations & maintenance

PES Power Engineering Society

PRM performance reliability model

PV photovoltaic

RE renewable energy

RFP request-for-proposal

ROM rough order of magnitude

SGIP Smart Grid Interoperability Panel

SNL Sandia National Laboratories

SPIDERS Smart Power Infrastructure Demonstration for Energy Reliability and Security

TMO Technology Management Optimization

UFC Unified Facilities Criteria

UPS uninterruptible power supply

US United States

V2G vehicle-to-grid

WWTP waste water treatment plant

Chapter 1

Introduction and Rationale

Over the past century, the use of electricity has become one of the defining features of a modern society. The use of electricity has become so engrained in every facet of our lives that its loss has a tremendous negative effect, as was evident during recent natural disasters such as super storm Sandy [1].

To address the need of secure and reliable electric power, Sandia National Laboratories (SNL) has developed a methodology for designing electric microgrids called the ESM methodology. Thus far, ESM reports have been developed for over 20 Department of Defense (DOD) installations and ten civilian sites [2], several are under contraction or complete. Thus far, the scope of the projects intended for ESM are single customer or campus-scale microgrids, although this could change with the evolution of the ESM approach under the Department of Energy (DOE)-funded Microgrid Design Toolset (MDT) program [3].

An ESM is defined as an integrated energy system consisting of loads and distributed energy resources (DERs) operating as a coherent unit, either in parallel with or islanded from the power grid, whose main purpose is support of critical loads during severe contingencies. Since an ESM can be operated independently of the power grid, they are invaluable in facilities that have high uptime requirements, in either terms of protecting life (such as hospitals), security (military installations), or economic factors (manufacturing facilities with high restart costs or sites with high opportunity cost). An ESM improves resiliency in regions susceptible to natural disaster [4] or unreliable grids, possibly also caused by poor security against malevolent threats.

The six key properties of an ESM are:

- Safety
- Reliability
- Security
- Sustainability
- Cost Effectiveness
- Resiliency

The first attribute, *safety*, ensures that energy is provided in a safe manner. The microgrid must function well during an unplanned power outage but also must be designed with safety as a top concern. As an example, an ESM design must ensure that interconnecting DER does not compromise safety, particularly in light of evolving standards like IEEE 1547.

The second feature, *reliability*, reflects a power system's ability to meet its mission-critical electric demands. Although it is not possible to ever achieve 100% reliability, installing a microgrid system can significantly improve electrical availability. By itself, conventional building-dedicated on-site generation reduces the number of critical load failures associated with long-distance power transmission. However, a microgrid configuration further 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 for all critical load.

Security makes a power system more resilient to various cyber and physical threats, including terrorist attacks. Threats against power systems have escalated in recent years. As a result, cyber security standards and effective design approaches [5] must be considered and included in a microgrid design from the very beginning.

Sustainability is the ability to reliably operate power systems for extended periods of time and in a manner that will not compromise the future. Sustainability can be improved at a microgrid site, for example, by including renewable sources of distributed generation such as solar or wind power, thus reducing – or even eliminating – a facility's dependency on fossil fuel resources. The microgrid itself will allow for generation dispatch that can improve energy conversion efficiency (which can be poor for generators operating at low output capacity) and thus conserve and extend onsite fuel supplies during extended outages. An ESM can enhance maintenance capabilities by allowing for necessary downtime of site backup and microgrid generators during extended outages without interruption of service, as well as enabling full-load testing of machinery while grid-connected. The ESM design may feature analysis to reflect resource availability and promote strategies to minimize or eliminate dependency on depleting resources (and potentially also reduce carbon emissions).

Cost effectiveness reflects the importance of providing power at the reasonable investment cost. The addition of renewable energy (RE), for example, reduces a site's dependence on the utility grid and also on a sites fuel storage when utility power is unavailable, thus leading to cost savings. Thus far, ESM designs have leveraged as much existing on-site equipment as possible – including generators, RE, medium voltage (MV), and low voltage (LV) – to minimize implementation costs. And ESMs can easily reduce energy costs during normal, grid-connected operations by controlling microgrid resources to reduce utility costs or perhaps generate revenue through contractual relationships or markets.

Finally, *resiliency* has recently become a key R&D focus both in the United States (US) and internationally. As defined by [6], resiliency can have a number of different meanings, but the ESM approach specifically aims to manage risk from unusual or severe energy threats (either natural or man-made) by cost-effective strengthening. An ESM at a site improves energy flexibility, as non-critical (but still desirable) loads can be selectively energized during extended outages. An ESM design includes quantitative evaluation of the resiliency benefits.

Chapter 2

Value Propositions for Energy Resilience Improvements

The term design basis threat (DBT) is 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. For an ESM, a DBT defines the most stringent conditions (threats) that must be met by the system design. These threats may be environmental (such as a hurricane) or man-made (such as a cyber or physical attack), and is typically one of the first decisions reached between microgrid analysts and the prospective ESM stakeholders.

For prior ESM work by SNL, DBTs have included:

- Regional electrical blackout lasting 72 hours
- Regional electrical blackout lasting 24 hours at 0.4 probability, 72 hours at 0.3, 1 week at 0.2, and 1 month at 0.1
- Flood level at the Federal Emergency Management Agency (FEMA) 100 year flood plain plus 2.5 feet [4]
- Active cyber security threats with specified characteristics against microgrid industrial control system (ICS) [7]

A key concept for an ESM is that energy surety investments are intended primarily to improve performance for the DBT – the energy resiliency for the site. Obviously, investments in energy surety can also provide improvement during normal periods, or more conventional emergencies (not to the level of the DBT). The three operating conditions for an ESM are defined as:

- **Normal:** No emergency conditions.
- **Typical Emergency:** Abnormal conditions that fall under the purview of good planning or engineering (like utility outages in line with historical reliability figures, etc.).
- **Abnormal Emergency:** High impact/low frequency (HILF) events, which are included in the DBT.

Different types of value propositions can apply to each operating condition. The value propositions can be categorized as:

- **Technical:** Applies to benefits that are not immediately quantifiable using dollars or environmental measures; these measures are quantifiable using engineering or other metrics, like expected outage durations, fuel consumption, etc.
- **Financial:** Benefits that are calculated in dollars (possibly as a net present value).
- **Environmental:** Values for the environment, like reduced emissions or pullutants.

Overall, the value propositions may be sorted as shown in Table 2.1.

Table 2.1. Taxonomy for benefits from grid resiliency investments

			Operating Mode		
			Normal	Typical Emergency	Abnormal Emergency
		Abbreviation	*N*	*TE*	*AE*
Benefit	Technical	*TC*	N-TC	TE-TC	AE-TC
	Financial	*FN*	N-FN	TE-FN	AE-FN
	Environmental	*EN*	N-EN	TE-EN	AE-EN

Although all nine boxes are theoretically relevant, the technical benefits during abnormal emergency events have dominated ESM designs in SNL's experience. However, the other benefits can help with the cost and investment justification and should be calculated when feasible and useful (contributing to cost effectiveness, mentioned previously). This is a key investment issue, particularly since normal conditions dominate as a fraction of operating time, and may allow for financial benefits through revenue generation or cost avoidance (through site energy or demand reduction, peak shaving/shifting, energy contracts with the local utility, participation in local markets, etc.). Conceptually, *the investment in energy surety – performance during DBT and other HILF events – is amortized by the improved performance that the investment provides during normal (grid-connected) and typical emergency conditions.* And that is a fundamental design criterion, since the DBT is frequently without any good quantification of its frequency or likelihood of occurrence, which makes it difficult to compare to conventional investment criteria. Conversely, the normal and typical emergency conditions are well-established, and so the value of the ESM investments in improving those can be easily expressed succinctly, perhaps as a net present value (NPV). The stakeholders for an ESM can compare the difference of the NPV of the ESM costs and the NPV of the benefits during normal and typical emergency conditions to the expected, quantified benefits calculated by the performance reliability model (PRM) for DBT conditions (which are not expressed financially). This represents their investment in energy surety and resiliency for the planned microgrid site. Obviously, if the first quantity (the difference) is negative, then the DBT performance is "free" and the project is very easy to justify (in SNL's experience, this is not the case). This perspective simplifies the ESM investment question for stakeholders.

Some examples for two high priority value areas include:

- Abnormal emergency, technical (AE-TC):
  - Improved energy availability for critical loads during extreme events, including differentiated reliability
  - Reduced loss of energy availability for DBT events
  - More rapid recovery for energy during DBT events
  - Flexibility to easily power non-critical loads during extended outages
  - Better fuel endurance
  - Better maintenance opportunities
- Normal, financial (N-FN):
  - Reducing energy billing costs through energy consumption management
  - Revenue from market/demand response participation
  - Revenue from energy contracts with utilities
  - Possible savings from reduced fuel usage for islanded systems
  - Lower operations & maintenance (O & M) costs from easier maintenance

Other potentially important microgrid benefits are also possible. For "normal, technical" (N-TC) operations, benefits might be improved power quality for equipment [8] or simpler backup generator testing through improved control and flexibility. An ESM that can optimize efficiency and RE could have a big "normal, environmental" (N-EN) impact with lowered emissions by reducing consumption and offsetting utility generation. Finally, for "typical emergency, technical" (TE-TC), an ESM will improve reliability for critical loads, since systems designed for resiliency could be used to support critical load during normal outages if there are failures in normal backup procedures or equipment (basically, starting microgrid operations quickly to support the load).

One other benefit that does not seem the fit the taxonomy is that to the rollout of an advanced energy infrastructure is the improvement in energy awareness, resulting from the communications and sensing infrastructure that is a necessary component for modern control. The data accrued from these systems will enable data-driven decisions on energy management. This is a particular boon for a site with little or no existing monitoring that acquires a microgrid.

Chapter 3

Concept of Operations (CONOPS) for an ESM

For design purposes, ESM loads are sorted into the following types:

- **Tier C** – those loads / buildings that are critical to the mission or function of the facility; these loads usually have dedicated backup generators. Critical loads, further subgrouped as Tier C/U (uninterruptible) and Tier C/I (interruptible, can withstand momentary losses of power without loss of critical function, like while waiting for a backup generator to start)
- **Tier P** – those loads / buildings that are of high priority ("nice to have"), but that can be switched on or off of microgrids at the discretion of the designated emergency authorities.
- **Tier O** – those other loads / buildings that will not be powered during islanded, microgrid operations.

With respect to design, an ESM is always planned to make optimal use of existing onsite resources. This means that existing MV infrastructure between buildings and areas within a site will preferably be configured to support microgrid operations (minimally impacting the normal utility supply). This must be done carefully to ensure that protection requirements are satisfied and ensure ESM safety (one of its six core properties). Likewise, in-place LV equipment will be leveraged. In either case, the final ESM design can certainly augment or replace the onsite equipment, but specific decisions about re-use, upgrade, or replacement are ultimately cost-benefit tradeoffs.

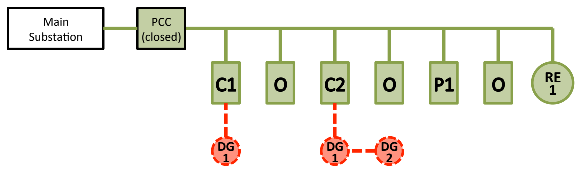
Candidate sites for ESMs already have critical load, and so probably also include backup generation and uninterruptible power supply (UPS). Re-using existing generation for an ESM is not free, as the controls would need to be altered and integrated into the microgrid energy management system (EMS), but this could be less expensive than purchasing new generation (which is obviously an option). To electrically integrate existing generation with automatic transfer switchs (ATSs), a breaker with synchronizing check functionality is installed between the ATS's "normal" (utility-connected) side and the generator side. In microgrid mode, this switch is closed – safely – and the generator can back-feed the site's MV system through the existing transformer.

The recommended connection above allows the ATS to remain in-place, and the obvious question is why that would be a desired characteristic. While the contemporary installation of an ESM does not rely on advanced equipment or control – indeed, commercial off-the-shelf (COTS) products are generally suitable – the idea is novel enough that an ESM should "do no harm." The site should be able to operate as it would have prior to the ESM installation in the event of unexpected microgrid failures, or even breakdowns in training for operations staff. In the future, the need to fallback capability will diminish, but right now it is a key feature.

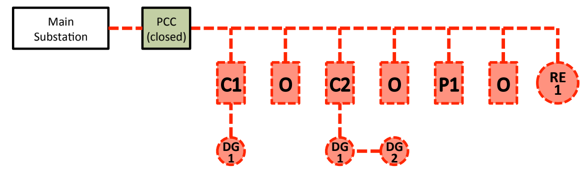
A microgrid can support a seamless transition to microgrid operation, or or it may not. (Here, the word "seamless" refers to the electrical loads not perceiving any interruption in service.) In the case of an unplanned and unexpected utility outage, an intentional lack of requirement to support seamless transition is likely a good cost-benefit proposition. Critical loads that require uninterrupted service (Tier C/U) will almost certainly already have UPSs, and these may be relied upon during the post-outage period before microgrid operations. Otherwise, the site's ESM would need to have constantly running generation or significant energy storage, at increased capital and operating cost. However, the construction and testing of a microgrid should have as low of impact to ongoing site operations as is technically and programmatically feasible. A key element of this is to ensure that various systems can transfer to microgrid or backup modes seamlessly, *when the transfer is planned or foreseeable*. Seamless transition out of islanded microgrid mode is always desirable, provided it is achievable per interconnection requirements.

Diagrams can best illustrate the process used to transition the Smart Power Infrastructure Demonstration for Energy Reliability and Security (SPIDERS) sites into a simple microgrid without seamless transition, respecting the "do no harm" dictum. Figure 3.1(a) illustrates an ESM feeder with a PCC main breaker dividing the upstream non-ESM portion of the feeder from the downstream ESM portion of the feeder. Green signifies that the system has power and red signifies loss of power. The ESM consists of a collection of Tier C / Tier P mission buildings and Tier O buildings, designated by C, P, and O. The Tier C mission buildings may be connected to DERs (likely, at least one diesel backup generator). Note that in this example, an RE source is not attached to a particular building but is connected to the grid as an independent generation asset. As shown in Figure 3.1(b), all buildings lose power immediately after the utility is lost.

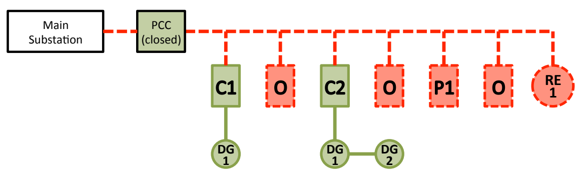
During this period prior to microgrid activation, the Tier C-U load is powered by their distributed UPS; later, Tier C/U and C/I are powered by local generator systems as shown in Figure 3.1(c). The RE source is also shut down due to IEEE standard 1547, which does not allow any inverter based power generation to operate on a de-energized grid. If loss of power is greater than some predetermined interval, then on-site personnel can enable microgrid operation. This step can also be automated with the triggering mechanism being a length of time or specified set of conditions. The first step is that the control system sends signals to disconnect all building feeds, in order to prepare for carefully managing the step-by-step interconnection of the ESM (this also prevents Tier O buildings from being powered during the outage). In Figure 3.1(d), the microgrid is isolated from the utility by opening the PCC



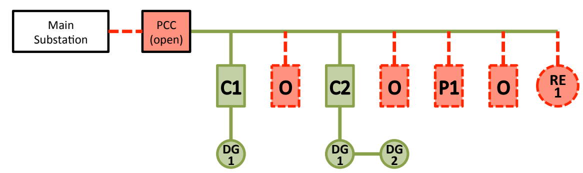
(a) All buildings on the microgrid are powered by the local utility; DGs are off and RE is outputting energy (C, P, and O correspond to load tiers)



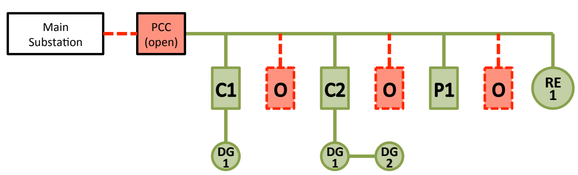
(b) Immediately after the loss of utility power, no loads or generation are active (distributed UPSs support Tier C/U load)



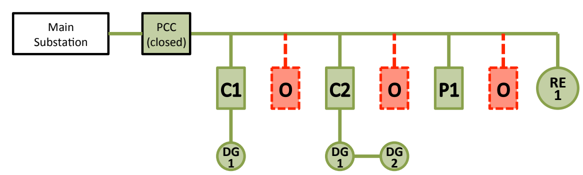
(c) DGs power up and first energize the buildings they are designated to support; this is exactly the same as non-microgrid backup operation



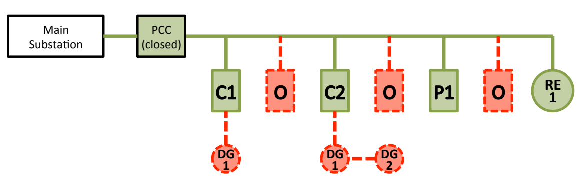
(d) The PCC opens and MV switching disconnects all loads and RE from the microgrid; one-by-one, DERs synchronize to energize the microgrid



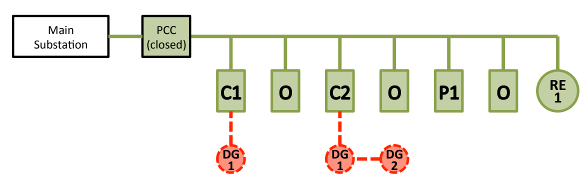
(e) All Tier C loads are powered, and after a delay RE sources and priority loads return to service (this is the stable ESM operational state)



(f) Once utility power returns, the PCC reconnects the microgrid in a careful and coordination fashion



(g) After reconnection, DGs shut down (active loads are not affected as they are being supplied by the utility



(h) The microgrid ESM restores the site MV network to its normal state, which allows Tier O loads to be served

Figure 3.1. Basic ESM CONOPS (solid lines indicated energized equipment, and dashed are de-energized)

breaker and then the generators are synchronized, sequentially, to the ESM portion of the feeder until they are all connected and all Tier C buildings in the ESM are energized. At this point, the generation provided by the diesel generators is automatically adjusted for more efficient use. After some additional delay, then as shown in Figure 3.1(e), the RE source can come back online to start supplying power and site personnel can elect to supply Tier P loads. When utility power is restored for some long enough interval deemed sufficient by site personnel, the ESM is reconnected to the utility as depicted in Figure 3.1(f) (possibly a seamless transfer, but not necessarily). Later, the DER is deactivated as shown in Figure 3.1(g). Lastly, in Figure 3.1(h) the Tier O loads are restored to the MV network and the site resumes its normal, grid-connected operations.

Chapter 4

ESM Design Process

The goal of a preliminary design is to provide a site microgrid framework as a list of requirements and recommendations, with a clear summary for the customer/stakeholder to enable them to understand the limits, tradeoffs, and potential costs and benefits of implementing the microgrid. Thus far, many preliminary design reports for ESMs have been formatted for ready inclusion in requests-for-proposal to streamline the acquisition process for the stakeholders. The approach for a full ESM design assessment is shown in Figure 4.1.

4.1 Data Gathering and Stakeholder Coordination

Developing the ESM includes a number of technical analysis activities, but it is foremost a methodology and approach. The foundation of the process is coordination between a group of expert analysts and the site's stakeholders. The experience of the analysts can support data elicitation and normalizing for stakeholder's knowledge and opinions, but ultimately it is the latter which defines the project space. Stakeholder personnel whose involvement is vital to the successful defining and implementation of the microgrid include the facilities manager, the energy manager, and key points-of-contact for site O & M, such as the site electrical engineer. During this stage of the process, additional consideration must be made for future change, including future probable change in personnel and succession of responsibility for system operations.

4.1.1 Mission/DBT Characterization

The first step is defining and characterizing the mission space of the facility, and the DBT that will be referenced during the design. Knowing the extent of critical power needs bounds the problem. Additionally, it also helps define which buildings are needed to maintain the critical mission of the facility. Next is to determine which buildings and loads fall into the critical/non-interruptible, critical/interruptible, priority, and other ESM load categories. The relative locations (geospatially and electrically) of the loads also need to be determined, as well as any temporal relationship[s between critical facilities and mission space. As for the DBT, different stakeholders face different challenges; for military applications, very advanced

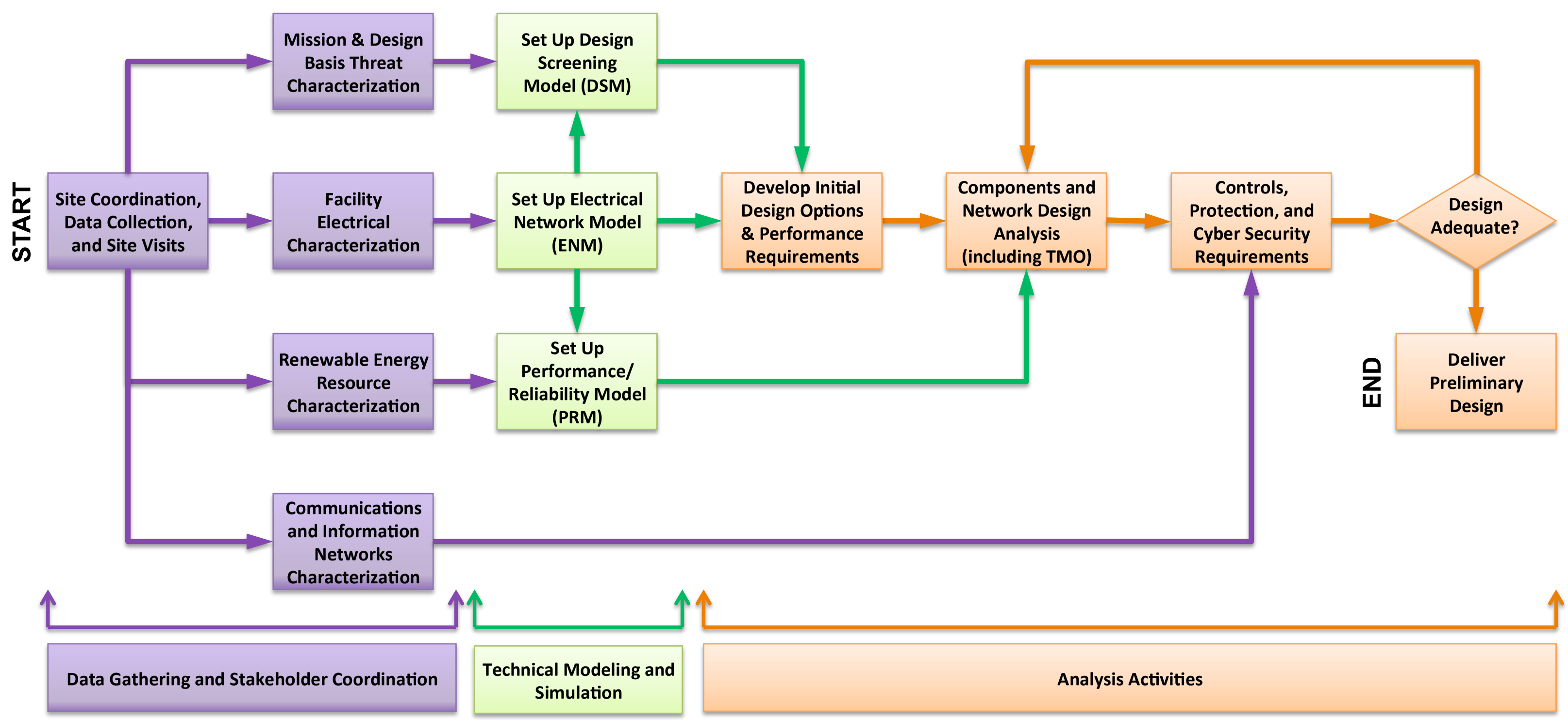


Figure 4.1. Technical analysis approach for ESM preliminary design.

cyber adversaries are reasonable to assume. The geography and history of the facility will inform the disaster elements of the DBT.

4.1.2 Facility Electrical Characterization

In order to adequately characterize the site's electrical distribution system it is necessary to obtain as much information about the site as possible. The information can be grouped into three principal categories: physical equipment, load data, and operations. For the physical equipment, one-line drawings, both LV and MV are invaluable. One-line drawings show how the existing electrical distribution system is laid out and what equipment is currently in the field (including feeders, buses, transformers, switches, normally-open/normally-closed, conductor size, and shunt compensation). One-line drawings for the individual buildings and loads are also beneficial. Drawings such as site layouts that have geographic information system (GIS) information detailing specific locations of buildings, loads, roadways, and other infrastructure are helpful when trying to narrow down feasible options and in determining rough order of magnitude (ROM) cost estimations. Detailed information on existing backup generation including size, location, ratings (voltage and power), fuel used, and fuel storage capacity is also needed. Load data such as peak load and load profiles are necessary, for both the electrical distribution system as a whole as well as for individual buildings and loads, including Tier C, P, and O loads. A designation as to which buildings are critical or if only a portion of a building load is critical is also required. If this data is not available, either metering needs to be deployed, or estimates will be calculated. When metering, the desired suite of data to be captured is kW, true power factor, displacement power factor, kVAR/kVA, voltage/current, and measures of power quality such as THD or harmonic levels. The desired interval is one minute with a maximum interval of five minutes and a minimum duration of one month, though one year is preferable since it can capture the seasonal variation of the load profile.

Another important aspect of site characterization is an understanding of the potential for future growth of the loads and a variance of the loads due to a change in function. Any planned or proposed changes to the site's function and future needs to be accounted for, including near-term modernization/upgrades and proposed installation of RE generation resources. Lastly, detailed information on the normal and emergency operations including procedures enacted during a grid outage (especially continuity of operations planning) are required.

4.1.3 RE Resource Characterization

Any information on existing renewable energy resources photovoltaic (PV), wind, biomass, etc. (make, size, location, and ratings) that may impact the loads on the system must be collected. Additionally, any planned or proposed systems need to be noted and incorporated into the microgrid design plan. If any electrical energy storage systems are existing or planned, then the type, size, power rating, location, and load served need to be known. Information as to how any existing or proposed energy storage is or will be operated is needed.

4.1.4 Site Network Characterization

The purpose of this activity is to gather data about a facility's network and management processes to ensure that the control and cyber security requirements in the preliminary ESM design are suitable. Important data includes the site communication network topology, which includes how the communication is implemented (such as via Ethernet, fiber optics, wireless, etc.) as well as communication protocols and security enhancements deployed. Given the need for control in a microgrid, the network characterization should develop menthols of estimating the feasibility and cost of adding bulk communications capability. Also, the ESM design will be sensitive to the approval and accreditation procedures required for potential ESM cyber components. Finally, the characterization must delineate the current environment and requirements for connections to partner/third-party information systems (if it is even feasible, and in many cases – especially military – it is not).

4.1.5 Missing Data

Often data is missing. If information pertaining to existing infrastructure is needed, then personnel communication with stakeholders and site visits may be required and might be the only available avenue to obtain the information. Many facilities do not have current historical load data, which would suggest metering as described previously. Another method of determining peak loads is to extrapolate and estimate based on the transformer size. Oftentimes facility operators have a first-order estimation of the peak loads of a given facility. This reinforces the need for good communication between the stakeholders and the team performing the microgrid analysis.

4.2 Technical Modeling and Simulation

4.2.1 Design screening model (DSM)

The DSM is used throughout the microgrid design process to narrow microgrid design options by elucidating key relationships between mission load, renewable generation, energy storage, and fossil generation. SNL develops the DSM using standardized systems dynamics modeling approaches, where time series of flows and accumulations of flows are central to the process. For microgrid applications, power and load flows and energy accumulations are simulated based on the critical mission requirements, base load, and ESM design options. The model can track many other aspects of microgrid performance including: building diesel generator duty cycles, ramp rates, building heat consumption, and battery charge-discharge cycles and associated stored energy requirements. The outputs of the DSM are used to develop the options space for the ESM design. Done carefully, the DSM may also be leveraged as a tool for eliciting key information from stakeholders by describing possible microgrid options and functionality.

4.2.2 Electrical network model (ENM)

Ensuring that all sources operate within their power limits and that other equipment (like transmissions lines and transformers) are not overloaded are essential requirements of an ESM. A load flow study, also referred to as a power flow study, is a common tool used for AC analysis of a power system in steady state and to ensure that all requirements discussed above are met during the planning stages of a power system. Similar analysis is used for heat generation, flow, and consumption. The ENM also includes the development of a proposed one-line diagram for the ESM. A one-line diagram consists of a set of schematics representing the full energy system and may include generators, buses, loads, distribution lines, transformers, protective devices, heat sources and sinks, etc.

4.2.3 Performance reliability model (PRM)

An ESM design includes quantitative analysis for the proposed microgrid improvements against some set of the selected value propositions for the DBTs. One well-accepted method for valuing the performance of an engineered system is Monte Carlo (MC) sampling. The process has been used extensively for power system planning, with formulations for both generation adequacy and system adequacy assessment (the latter includes the electrical network, while the former is more about simple generator capacity). The desired analysis will leverage existing system adequacy assessment formulations [9] [10] [11].

Existing software called the PRM is used to calculate performance metrics. It includes a few specific characteristics:

- The DBT is expressed as a probability density function of expected utility outages (in hours)
- Instead of a bulk power system, the analysis is for microgrids, which share similarities with bulk power
- A sequential MC is used, covering the entire outage interval; this allowed modeling for operational characteristics (like generator conditional restart attempts)
- The system includes the ability for multiple energy islands and backup connections between them

- Currently modeled are diesel generators (and fuel consumption), all three tiers of load (including C/U and C/I), energy storage, lines, transformers, UPSs, RE, etc.
- New DER, lines, transformers, storage, or microgrid operation schemes can be analyzed
- Outage rates, recovery rates, variable RE output, variable loads, and start probabilities are included
- The system uses an event-driven simulation approach, which allows for variable time steps (seconds, hours, others) and maximum execution efficiency (calculating new states only when things change)

4.3 Analysis Activities

4.3.1 Develop initial design options and performance requirements

The ESM analysis process depends on an understanding of the option space and range of potential costs/benefits. At any site, the stakeholders have a "wish list" and a concept of their budget (which may be resolutely fixed, or have some wiggle room). Usually, there are some fundamental requirements for any microgrid at a facility that are conducive to the likely budget. This "core" microgrid is important to characterize, as all further options leverage it. At this initial stage, the DSM is used to narrow microgrid design options by elucidating key relationships between mission load, renewable generation, energy storage, fossil generation and other design parameters/decisions. The information from the DSM is checked against the ENM in order to ensure electrical feasibility of the candidate designs. Finally, the initial analysis will quantify the reasonable ranges of benefits for different opportunities in Table 2.1, which ensures that the subsequent analysis is calculating performance of candidate designs in the neighborhoods of reasonable and attainable goals (and acceptable budget).

4.3.2 Components and Network Design Analysis

Design options and requirements determined and developed in the previous section are used to in conjunction with Technology Management Optimization (TMO) to optimally determine several design parameters for the microgrid. TMO is designed to help decision makers optimally manage high-value, long-lived, highly technical equipment over the lifetime of a system. TMO users define choices that affect the performance parameters of the system. It then performs an optimization of the system, using input from the PRM, and analyzes how these user-defined choices affect the relevant performance parameters of the system. The PRM was developed to help understand the impact that loss of power has on critical missions at military bases in terms of probability and expected behavior. The model allows for comparison between different energy system configurations to evaluate key tradeoffs, costs and performance indicators. The model takes inputs such as system configuration, energy assets, etc. and calculates applicable metrics described in the introduction. This model is used as an external evaluator by TMO. TMO is run using a multi-objective optimizer approach, resulting in a set of solutions. The analysis and optimization of the design results from the interaction between TMO and PRM, where statistics of interest based on candidate design parameters are fed from PRM to TMO. Then, based on the input statistics, TMO calculates the fitness of the design. The TMO and PRM compares the performance and reliability of these conceptual design options to a baseline performance and reliability of the existing system without any improvements to meet the DBT in order to make these comparisons. A prerequisite for this analysis is the determination of a starting point upon which this further analysis can be done. The limits and objectives were chosen based on initial PRM runs. It is important to note that TMO will take into account the limits and objectives when finding Pareto Optimal Solutions but if none of the solutions can meet the objective values for the parameters, TMO will consider those that get closest to the objective "more fit" for the particular parameter. The scores of the design are retained in memory by TMO while a new set of design parameters are fed back to PRM. As this design iteration cycles through, a set of Pareto optimal points are developed by TMO. TMO and PRM analysis collectively determines the performance versus the reliability of a set of options as well as costs for the sets required and optimal buildings or loads.

4.3.3 Controls, Protection, and Cyber Security Requirements

A safe, secure, reliable, and sustainable microgrid requires a cyber security architecture commensurate with the criticality of facilities on the microgrid and the level of risk deemed acceptable by the stakeholders. Industry standard best practices for typical power grid ICS, including those found in NERC CIP and NISTIR 7628 [12], should be incorporated where possible; however, it is recommended that most microgrids should be more robust than that of traditional ICSs given that:

- Most microgrids will be used in emergency situations and may be critical to continuity of emergency operations
- Microgrids must function during active attack by a capable adversary

As such, traditional design and implementation of an ICS is likely not sufficient for implementing a robust and secure microgrid. Therefore, in addition to referenced best practices, additional rigor should be applied to strengthen defense-in-depth for the microgrid control systems. Best practices for securing ICSs often leverage network segmentation [13, 14]; however, in most cases, network segmentation is focused on separation of the control system network from other less-trusted networks, such as an enterprise network and the Internet. The concept of network segmentation within the control system itself should be leveraged to further reinforce defense-in-depth practices. Such a scheme is consistent with Sandia's Cyber Security Reference Architecture [5] developed for DOD microgrid implementations and provides a framework for a higher level of security than industry best practices can provide alone.

Chapter 5

Examples from the SPIDERS Program

To demonstrate the value of microgrids on DOD installations, the DOD and the DOE jointly funded a demonstration project called SPIDERS. The SPIDERS project comprises three candidate sites: Joint Base Pearl Harbor-Hickam (JBPHH), located in Honolulu, Hawaii; Ft Carson, located in Colorado Springs, Colorado; and Camp Smith, also located in Honolulu. The SPIDERS project is unique because it included conceptual, preliminary, and detailed (engineering) design, in addition to construction, commissioning, and demonstration of the three microgrids, each of which will be transitioned to the installations as fully operational infrastructure improvements.

The technical progression of the project followed the crawl, walk, run philosophy of starting small and progressing in complexity with each subsequent phase. One of the program's metrics for success was the off-grid endurance of the microgrid during electrical power outages. To optimize system performance in this respect, the ESM design optimized the renewable energy contribution to the system as well as generator fuel efficiency. SNL also considered the energy security and resilience of the system by including "N+1" generator redundancy and available capacity based on the peak critical load.

An overarching philosophy and key to acceptance by the facilities was that the SPIDERS design would "do no harm" in the installation of the microgrid. Functionally, this meant that the facility could deactivate the microgrid *at any time* and revert back to the conventional back-up system that was in place prior to the installation of the SPIDERS microgrid. In each of the following subsections, a brief description of the extent of the installed microgrid and the results of the improvement with the installed microgrid are given.

5.1 Phase I: Joint Base Pearl Harbor-Hickam

5.1.1 Objectives

The goal of SPIDERS JBPHH (Phase 1) was to quantifiably demonstrate that SPIDERS delivered an energy secure and cyber secure microgrid architecture with the ability to maintain operational surety through robust, reliable, and resilient electric power generation and distribution. In keeping with the "crawl" aspect of project progression, this phase had several basic objectives:

- Reliable power to critical loads
- Circuit level MV diesel integration
- Demonstration of CONOPS
- Utilization of RE
- Energy optimization to reduce fuel consumption
- Cyber-secure control system
- Demonstrate "do no harm" principle
- Develop training for onsite operators

5.1.2 Design and Implementation

The waste water treatment plant (WWTP) and part of its associated feeder at JBPHH was selected for implementation of a microgrid. The initial backup power configuration was two diesel generators, 600 kW and 1600 kW. Due to the site's construction, during grid outages both generators were required to run, even though both were significantly oversized for their respective loads. Additionally, a critical/non-interruptible (C/U) water treatment system had no UPS. There was also a 146 kW PV system connected to a separate circuit from the WWTP that would not be able to supply power to the system during an outage, given that there is no MV connectivity then. Overall, during an outage event, the existing system had resources that were poorly matched to the existing load (resulting in extreme under-utilization of generators) and a renewable resource that would sit idle. To remedy this situation, the microgrid design implemented the replacement of the 600 kW generator with a 800 kW generator (rated based on SNL modeling that showed this generator alone would be optimal for most WWTP load conditions), the installation of a UPS, and linked the system together to allow for one of the two generators to power all critical loads in the WWTP as well as connected the existing PV to the system. The preliminary design based on the ESM process was used in the request-for-proposal (RFP) to describe requirements, design options, costs, and the expected quantitative benefits.

5.1.3 Results

There were significant results from on the ESM at JBPHH. Some of the key results are as follows:

- **Renewable Integration:** During a 72-hour demonstration period, the 146 kW PV array achieved a capacity factor of 12.5. Of the approximately 43 MWh of energy produced, 1.3 MWh of that was produced by the PV array, and directly reduced the consumption of diesel fuel. By providing over a megawatt-hour of power, the PV array was successfully integrated into SPIDERS operations.
- **Emissions Reduction:** The demonstration resulted in an estimated 1,138-pound reduction of carbon-dioxide emissions. NOx, SOx, and particulate matter (PM-10) emissions are estimated to have all decreased by a noticeable amount as well. This can be attributed to RE integration and decreased fuel usage (due to operating the diesel generators more efficiently).
- **Operational Endurance:** The facility was supported primarily by the 800kW diesel generator, supplemented with the 146 kW photovoltaic array when available and the 1600 kW diesel generator when necessary. Using these assets the microgrid was able to run 93.9 hours on the same amount of fuel it would traditionally have required to run for 72 hours (a 30.4% increase in operational endurance).
- **Reliability:** The final microgrid configuration increased energy reliability (as either generator could carry the critical load for most conditions).

All of the objectives were met or exceeded.

5.2 Phase II: Ft Carson

5.2.1 Objectives

The goal of SPIDERS Ft Carson (Phase 2) was to advance the microgrid concepts demonstrated at JBPHH as well as to include the following capabilities:

- Greater scale involving multiple feeders
- Prioritized loads/assets (now including Tier P)
- Large-scale renewable integration
- Energy storage incorporating vehicle-to-grid (V2G)
- Robust cyber security

SPIDERS at Ft Carson was also unique in that it was one of the first microgrids to fully leverage V2G technology using bi-directional electric vehicle (EV) aggregation points to allow the microgrid to fully exploit the EVs as both energy storage and back up facility electrical needs.

5.2.2 Design and Implementation

Each critical facility located within the microgrid boundary had a building-dedicated emergency generator. Each of these units typically operated at very low load factors and no renewable resources were part of the contingency power solution before the microgrid was installed. SPIDERS networked each of these generators and interconnected a 2MW PV system to allow the renewable resource to contribute to the microgrid system during electrical power outages. Again, the optimal preliminary design was used as the major technical component of the RFP.

5.2.3 Results

Again, the system was tested over a 72-hour demonstration window. The results from Phase II at Ft. Carson added on the JBPHH experience:

- **Renewable Integration:** An existing third-party-financed PV system was integrated into the microgrid, and the bi-directional V2G integration provided energy storage stabilization/power factor correction for the microgrid using five EVs
- **Energy Security and Demand Response:** The microgrid demonstrated that fast demand response and energy marketplace participation is possible using microgrid controls to manage the solar array and fossil-fuel-based generation.

All of the other objectives were met. The larger scale of the microgrid did not negatively affect the timing for the control systems.

5.3 Phase III: Camp Smith

5.3.1 Objectives

The major goal of SPIDERS Camp Smith (Phase 3) was to deliver a fully mature microgrid design using the lessons learned from JBPHH and Ft Carson. Camp Smith will be DOD's first installation-scale microgrid (the microgrid is sized to backup all installation loads). Camp Smith also includes the following capabilities:

- Tier 4I EPA-certified clean diesel generation for utility support, ancillary services and revenue generation
- Automatic load shedding
- Fully developed cyber security architecture

5.3.2 Design and Implementation

Camp Smith also previously relied on load-dedicated generation during outage events. This contingency solution includes many legacy generation technologies and systems that do not provide comprehensive backup to their facilities. To elevate the energy security and efficiency of the site, the microgrid design includes four Tier 4I generators that will serve as key resources for the microgrid along with a subset of the existing generator fleet. This is combined with 300kW of existing PV and strategic energy storage to deliver a fully resilient and efficient microgrid. The final microgrid configuration at Camp Smith is expected to significantly increase the energy security at the site when compared with the legacy, spot generation currently in place. The initial site development and microgrid operation plans were delineated in the ESM preliminary design report, which also includes estimates that quantify the expected benefits (which will be tested when construction is complete in late 2015).

Chapter 6

Conclusions

6.1 Success of Preliminary Design Methodology

Microgrid demonstrations like SPIDERS have shown that microgrid technology can help the federal and private sectors meet both their energy resilience and renewable energy goals. While integrating microgrid technology into existing infrastructure is often challenging, electrical system modeling and critical load analysis is an important first step to ensuring the final design is sufficient to meet the user's operational and performance requirements. Based on SPIDERS experience, the organization, analysis, and output of the ESM design methodology is extremely conducive to fielding effective military microgrids.

6.2 Microgrid Lessons Learned

Apart from the design methodology, the SPIDERS program has identified several important lessons learned and best practices for planning, construction, and evaluating microgrid systems. As part of the SPIDERS program, DOD is updating its Unified Facilities Criteria (UFC) and construction guidance to include microgrid standards, performance metrics, and best practices. DOD is publishing best practices and lessons learned for utility companies, industry groups, and the private sector.

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