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SYSTEMS ENGINEERING CAPSTONE REPORT

TRADEOFF ANALYSIS OF BACKUP POWER GENERATION SOLUTIONS FOR MILITARY BASES

by

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December 2021

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Energy security is becoming increasingly important as the DOD relies on energy to build and project combat power from military installations. Installation energy managers currently ensure uninterrupted power to mission-critical facilities through emergency stand-alone diesel generators. Research has recently indicated that networks of smaller diesel generators offer greater energy security benefits than a network of a few large diesel generators. However, existing research has not compared or analyzed the cost and resilience between the two strategies. This capstone examines the cost and resilience of centralized and decentralized power architectures by developing a general methodology to capture comprehensive life-cycle costs and metrics. It examines resilience for various configurations of networked diesel generators. Installation power managers can apply this method to quantitatively compare life-cycle cost and resilience of emergency diesel generator solutions to improve energy security within the unique constraints of an installation. The capstone then applied this methodology to the aging diesel generator power plant at Naval Station, Rota, Spain, which demonstrated that decentralized architecture was the most cost-effective strategy for resilience. Finally, the capstone presents these findings and general methodology for future application.

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ABSTRACT

Energy security is becoming increasingly important as the DOD relies on energy to build and project combat power from military installations. Installation energy managers currently ensure uninterrupted power to mission-critical facilities through emergency stand-alone diesel generators. Research has recently indicated that networks of smaller diesel generators offer greater energy security benefits than a network of a few large diesel generators. However, existing research has not compared or analyzed the cost and resilience between the two strategies. This capstone examines the cost and resilience of centralized and decentralized power architectures by developing a general methodology to capture comprehensive life-cycle costs and metrics. It examines resilience for various configurations of networked diesel generators. Installation power managers can apply this method to quantitatively compare life-cycle cost and resilience of emergency diesel generator solutions to improve energy security within the unique constraints of an installation. The capstone then applied this methodology to the aging diesel generator power plant at Naval Station, Rota, Spain, which demonstrated that decentralized architecture was the most cost-effective strategy for resilience. Finally, the capstone presents these findings and general methodology for future application.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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LIST OF ACRONYMS AND ABBREVIATIONS

AEMRR	Annual Energy Management and Resilience Report
BESS	battery energy storage systems
BOE	Basis of Estimate
CER	cost estimating relationship
CNO	Chief of Naval Operations
COTS	commercial off the shelf
DOD	Department of Defense
DODI	Department of Defense Instruction
DON	Department of the Navy
EDG	emergency diesel generators
EPSS	emergency power supply system
IEEE	Institute of Electrical and Electronics Engineers
IEP	installation energy plans
INCOSE	International Council on Systems Engineering
ISO	International Standardization Organization
kV	kilovolt
kW	kilowatt
LCC	life cycle cost
MODM	multi-objective decision making
MTBF	mean time between failure
MW	megawatt
NASA	National Aeronautics and Space Administration
NAVFAC	Naval Facilities
NAVSTA	Naval Station
NFPA	National Fire Protection Association
NPS	Naval Postgraduate School
NREL	National Renewable Energy Laboratory
ROI	return on investment
RTCL	resistance to capacity loss
TCO	total cost of ownership

UEM	Utilities and Energy Manager
UFC	Unified Facilities Criteria
USACE	U.S. Army Corps of Engineers
VOLL	value of lost load

EXECUTIVE SUMMARY

Aligning to National Defense Strategy, the Department of Defense (DOD) now identifies energy as a key resource in future conflicts. Primarily, the DOD is concerned with energy in two forms: operational and installation. Operational energy is concerned with maneuverability and freedom of action and typically takes the form of fuel in vehicles or battery cells which enable systems to move and operate in a battle space. Installation energy manifests itself in numerous forms but is chiefly exemplified as power generated to support military installations. The DOD argues that the current energy infrastructure for most installations is vulnerable to natural and man-made disruptions. As such, considerable effort has been focused on increasing the energy security across DOD installations. This effort necessitates increased reliability and resilience of power generation. This capstone responds to National Defense Strategy and the DOD by developing and proposing a general methodology through which power managers may increase installation resilience using diesel-powered backup power architectures.

Our methodology enables the procedural examination of centralized and decentralized architectures as they relate to life-cycle costs (LCC) and resilience. Installation energy managers tasked with developing strategies to improve energy security may apply this methodology to support their efforts. Decomposed, the general methodology follows seven steps:

1. Identify possible diesel power generation architectures
2. Estimate system reliability
3. Analyze system resilience
4. Analyze alternative architecture LCCs, reliability, and resilience
5. Generate trade-off analyses depicting the interaction between LCCs and resilience
6. Analyze results for sensitivities
7. Develop backup power generation architecture design recommendations.

Successful application of this method generates architectural alternatives that allow decision-makers to choose resilient and cost-effective solutions unique to their circumstances.

We applied this methodology to two case studies: The Naval Postgraduate School and Naval Station Rota, Spain. In practical application, this method revealed the following:

- Decentralized architectures offer the most cost-effective strategy when prioritizing resilience over LCC;
- Centralized architectures offer the least expensive LCC but suffer from lower overall resilience;
- Solutions utilizing fewer but larger diesel generators typically have a lower 25-year LCC than smaller more numerous solutions;
- Solutions using smaller, more numerous generators yield higher resilience and fuel efficiency;
- Using diesel generators as dispatchable power sources in conjunction with microgrid distributed energy resources, requires a minimum sizing of 1500 kW to integrate into the 12.47kV medium voltage distributions system;
- The 1500 kW sizing limitation will drive which architecture and solutions are most appropriate for each installation.

In addition to these findings, our study enabled the outlining of six steps, distinct from the general methodology, that installation energy managers can use to guide their efforts. These six steps are: gather information, analyze centralized and decentralized architectures, determine best location for generators, assess demand and emergency diesel generator (EDG) requirements, analyze the costs and resiliencies of alternatives, and reassess the proposed solution.

Lastly, our research revealed several gaps and future recommendations regarding diesel backup power generation systems. First, integration of smart systems into diesel backup power systems may prove valuable in the future of energy security and resilience. Second, while connecting all of the existing generators into a single installation-wide network was considered unrealistic by engineers due to the differences in age, size, and manufacturer, the team was not able to explore the concept of utilizing existing gensets rearranged into power nodes in the decentralized model. This concept would take oversized building-tied EDGs and rearrange them into decentralized power nodes as explored in this capstone. Lastly, would the requirement to have backup power generation supporting critical facilities be satisfied by a centralized power resource or would these buildings still require an additional backup power source tied directly to the building? The capstone was unable to answer this question and this aspect of the Unified Facilities Criteria 3-540-01 should be re-examined and clearly articulated as the utilization of microgrids and distributed energy resources increases in frequency across military installations.

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I. INTRODUCTION

Aligning to National Defense Strategy, the Department of Defense (DOD) now identifies energy as a key resource in future conflicts. Primarily, the DOD is concerned with energy in two forms; operational and installation. Operational energy is concerned with maneuverability and freedom of action and typically takes the form of fuel in vehicles or battery cells which enable systems to move and operate in a battle space. Installation energy manifests itself in numerous forms but is chiefly exemplified as power generated to support military installations. The DOD argues that the current energy infrastructure for most installations is vulnerable to natural and man-made disruptions. As such, considerable effort has been focused on increasing the energy security across DOD installations. This effort necessitates increased reliability and resilience of power generation. The U.S. Department of Energy and DOD collectively define energy resilience in a memorandum of understanding dated 28 September 2020:

> Energy resilience means the ability to avoid, prepare for, minimize, adapt to, and recover from anticipated and unanticipated energy disruptions in order to ensure energy availability and reliability sufficient to provide for mission assurance and readiness, including mission essential operations related to readiness, and to execute or rapidly reestablish mission essential requirements. (Bose & Castillo, 2020)

Since energy disruptions pose a serious threat to national security, resilience has become a top priority. As an initial step, each of the armed services have taken up efforts to identify aging infrastructure that poses a risk to energy resiliency. An example of such initiatives is evident in the Navy's Installation Energy Plans (IEPs) (Department of the Navy 2020). This plan not only addresses current vulnerabilities and power requirements but also forces the Department of the Navy (DON) to consider power demands of new weapons systems. Moreover, the Navy's IEP guidance necessitates thorough analysis of current and future energy requirements and examination of solutions to meet the Navy's goals of energy resiliency, reliability, and efficiency to supply quality power to critical defense assets. As a response to, and in support of the initiatives described above, the U.S.

Naval Station (NAVSTA) Rota, Spain is examining opportunities to increase their installation energy resiliency through the installation of a microgrid.

A. PURPOSE

The purpose of this capstone is to support National Defense Strategy and the DOD by investigating whether centralized or decentralized generator architectures are better for providing backup power generation capabilities. This capstone accomplishes this purpose by developing an approach to compare centralized versus decentralized generator architectures based on cost and resilience. Investigating centralized versus decentralized diesel generator architectures offers the DOD a valuable method for future applications such as backup power generation replacement strategies, increasing installation resilience, and reducing the DOD's vulnerability to power disruptions. We also demonstrate the method by assessing the current diesel power generation infrastructure at NAVSTA Rota, Spain and proposing new diesel power generation configurations. The capstone applies a trade-off analysis to identify replacement strategies based on life cycle costs (LCC) and resilience. Results from the trade-off analysis provide the DOD with a viable replacement strategy that can be applied across all DOD installations.

B. DEFINING RESILIENCE

Though many definitions of resilience exist, the International Council on Systems Engineering (INCOSE) offers a starting point from which the concept of resilience can be narrowed. According to the *INCOSE Systems Engineering Handbook* (2015), resilience is, "The ability to prepare and plan for, absorb, or mitigate, recover from, or more successfully adapt to actual or potential adverse events" (p. 229). In much the same line of thinking, the DOD defines resilience in DOD Directive 4715.21 (2016) as, "the ability to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from disruptions" (p. 11). This capstone's focus, in terms of resilience, seeks to plan for and to mitigate actual or potential adverse events affecting power supply on a base in accordance with definitions in both the DOD's directive and the INCOSE Systems Engineering Handbook.

Measuring resilience is not simple. Context is critical in ascertaining which data is relevant to resilience as defined by the project. In the case of backup diesel power generation, this capstone considers two distinct components of resilience: resistance to capacity loss (RTCL) and fuel efficiency as a measure of how long the backup can operate during a disruptive event. These determinations collectively provide quantitative measurements against which each system design can be assessed against resilience.

C. STAKEHOLDERS

In keeping with the structure provided through a systems engineering approach, identification of stakeholders is the logical next procedural step. INCOSE (2015) defines a stakeholder as, "A party having a right, share, or claim in a system or in its possession of characteristics that meet that party's needs and expectations" (p. 265). The primary stakeholders for this project are the Navy Facilities (NAVFAC) Utilities and Energy Manager (UEM) Branch Head for NAVSTA Rota, Spain. Primary stakeholders for this project are concerned with feasibility and cost. Moreover, they require an architecture capable of meeting their critical load requirements. Feasibility and cost are closely related as stakeholder concerns because feasibility of a design may primarily be driven by cost across the architecture's life cycle. Budgetary constraints may also influence feasibility of design. Meeting critical load is a need for the primary stakeholders as the design will function as a backup power source for the installation. The secondary stakeholders are NAVSTA Rota, Spain Tenant Units; the Utilities and Energy Engineer for NAVFAC Engineering and Expeditionary Warfare Center; the DON; and the DOD. From the perspective of secondary stakeholders, such as the DON and DOD, the project's conclusions and recommendations provide insight and strategies for enhancing resilience and reducing vulnerability of installations.

D. ARCHITECTURE BEING EVALUATED

The purpose of the architecture definition process is to generate and evaluate architectures that suits stakeholder needs and requirements (INCOSE 2015). An installation seeking backup power generation must assess the current system architecture while considering the needs and requirements of all stakeholders. For example, at

NAVSTA Rota, Spain, the system architecture in question comprises numerous paralleled backup diesel generators arranged into a centralized configuration. Alternative system architectures are distinctly developed according to two architecture patterns: centralized and decentralized. Under a centralized architecture, all backup diesel power generation is arrayed into a single generator 'farm' and power is dispensed into the grid from a single location. A centralized architecture for a single installation is illustrated in Figure 1. A centralized architecture offers stakeholders the convenience of co-located power generation. This yields the benefit of reducing travel time between scheduled and unscheduled maintenance actions on individual generators. Centralization also reduces the total number of control units for the overall system. Moreover, it offers reduced refueling times by again reducing travel time between generators. However, a centralized architecture does not come without drawbacks. Centralized systems are inherently more vulnerable to threats because the power sources are co-located rendering the system vulnerable to a single attack. This type of architecture also is more vulnerable to disruption on account of the single or reduced number of control units.

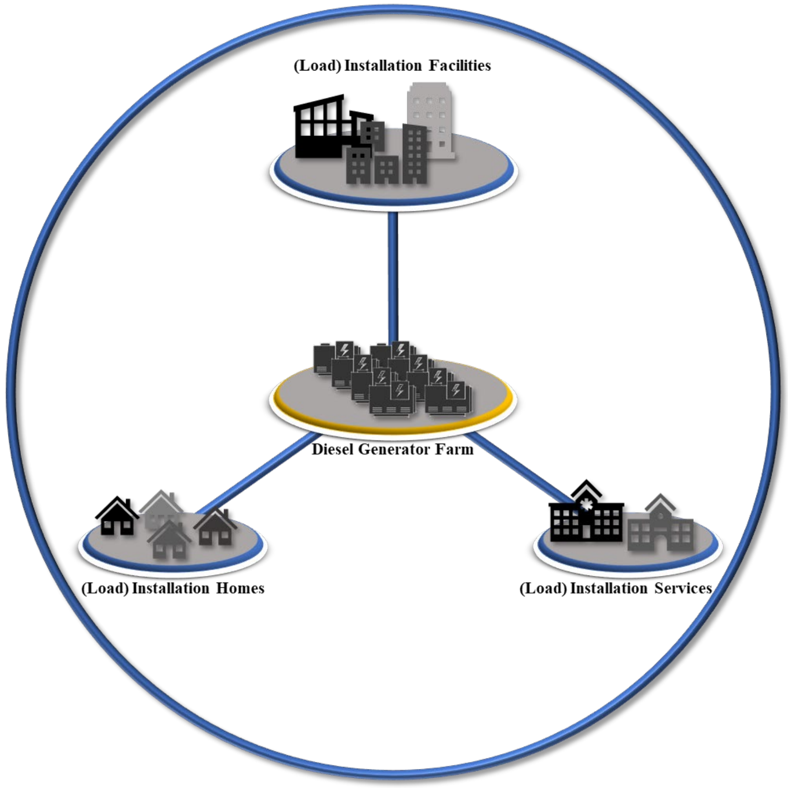


Figure 1. Generic Centralized Architecture. Adapted from Wood (2020).

A decentralized architecture disperses backup diesel power generation into several generator 'farms' from which power is dispensed. Figure 2 depicts a decentralized architecture for a single installation. A decentralized architecture offers stakeholders reduced system vulnerability through dispersion of power distribution from all stakeholder perspectives. Simply put, the system is subdivided and dispersed into many systems which is inherently harder to disrupt or destroy. The decentralized architecture also offers a reduced system susceptibility to disruption as it can sustain a greater rate of failures and still provide a reduced amount of power. Decentralized systems do not come without drawbacks, however, as their dispersion lengthens sustainment efforts and maintenance actions. Moreover, a decentralized system is islanded, meaning, islands are not mutually supportive of each other.

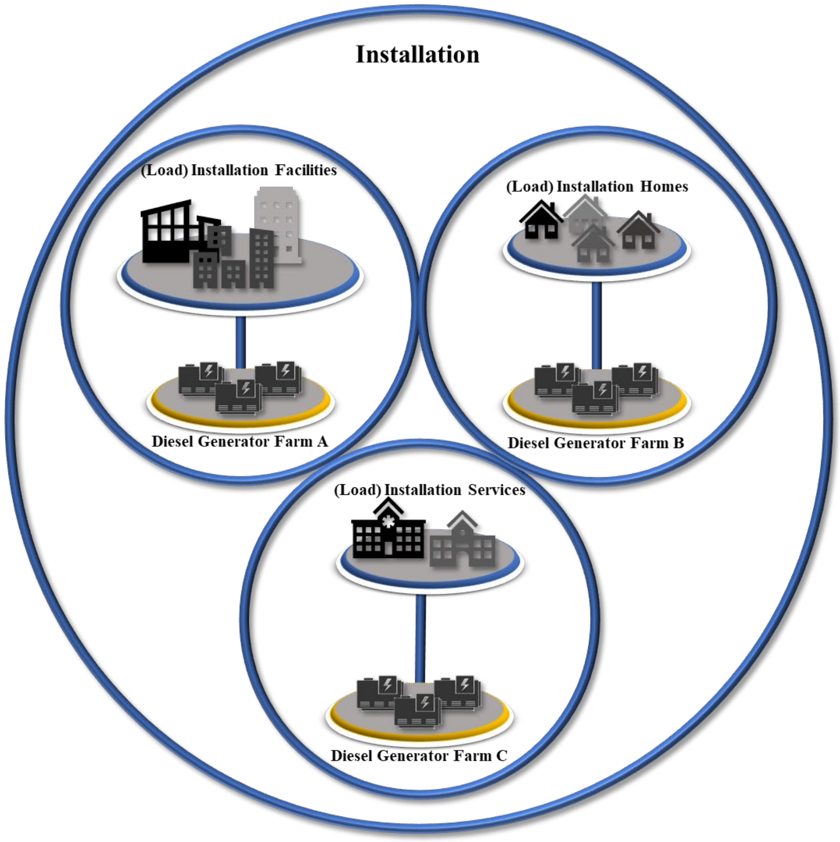


Figure 2. Generic Decentralized Architecture. Adapted from Wood (2020).

E. CAPSTONE OVERVIEW

Chapter I discussed the purpose of this research and provided a brief background on the driving factors that prompted the research. This chapter also provided general descriptions of resilience, stakeholders, and the architecture being evaluated. Chapter II serves as a literature review, identifying previous and relatable research. Chapter III describes the approach and general methodology for analyzing diesel generator architectures. Chapter IV applies the approach and general methodology for analyzing diesel generator architectures to the case study of NAVSTA, Rota, Spain. Chapter V discusses research conclusions, recommendations for future study, and acknowledgements.

II. LITERATURE REVIEW

Chapter II serves as a literature review of research conducted for this capstone. The literature review covers topics relevant to the capstone such as installation energy security, DOD power generation requirements, resilience, LCC estimation, and cost drivers external to LCC. The literature review also identifies knowledge gaps. The topics attempt to lend context to the capstone and provide the framework upon which definitions and approaches are developed. Collectively, the literature review provides a snapshot of the current body of work relevant to this capstone, enabling it to provide sound and informed conclusions and recommendations.

A. INSTALLATION ENERGY SECURITY

The DOD provides the framework for establishing new energy management systems or upgrading existing infrastructure. It starts with Department of Defense Instruction (DODI) 4170.11, *Installation Energy Management* (2018), which states that emergency generators, "shall be properly designed to have the ability to prepare for and recover from energy disruptions that impact mission assurance. Their design shall include automatic transfer switching, inverters, and black-start capabilities to minimize energy resilience risks" (p. 16). The DODI 4170.11 (2018) adds that, "at a minimum, DOD Components shall maintain primary power and emergency generation systems according to their technical specifications and ensure that there is a trained operator assigned to maintain the energy generation system, infrastructure, equipment and fuel" (p. 16). DODI 4170.11 (2018) states that installations are obliged to determine their critical load requirements which shall be reviewed and amended annually. DOD Components must, "consider both host and tenant critical energy requirements" (p. 15) throughout their emergency plan and that emergency energy generation systems must be implemented to support critical requirements. Furthermore, selecting systems must be accomplished utilizing the most recent Unified Facilities Criteria (UFC) 3–540-01, which outlines engine-driven generator criteria to ensure designs are effective and minimize risks.

While the DOD has implemented an Installation Energy Management effort through DODI 4170.11, the DOD has decentralized its facilities energy program and tasked DOD Component headquarters with providing guidance and funding to their respective installations. In this approach, each service is allowed to solve energy security based on the service needs at their installations, but this has also led to multiple, different standards across the services. The DON currently plans for 14-day outages (DON 2020).

The DON's 2020 *Installation Energy Resilience Strategy* identifies that while the Navy projects its power onto the water, the shore is where naval power is developed, built, and maintained. Echoing this point, the Chief of Naval Operations (CNO) elevated energy security to a major objective and selected NAVFAC as the lead organization responsible for spearheading the Navy's energy security effort. As such, the DON is working to improve installation energy structured around the three pillars of energy security: reliability, resiliency, and efficiency as depicted in Figure 3. The 2020 *Installation Energy Resilience Strategy* examines the ability to resist and respond to a utility disruption.

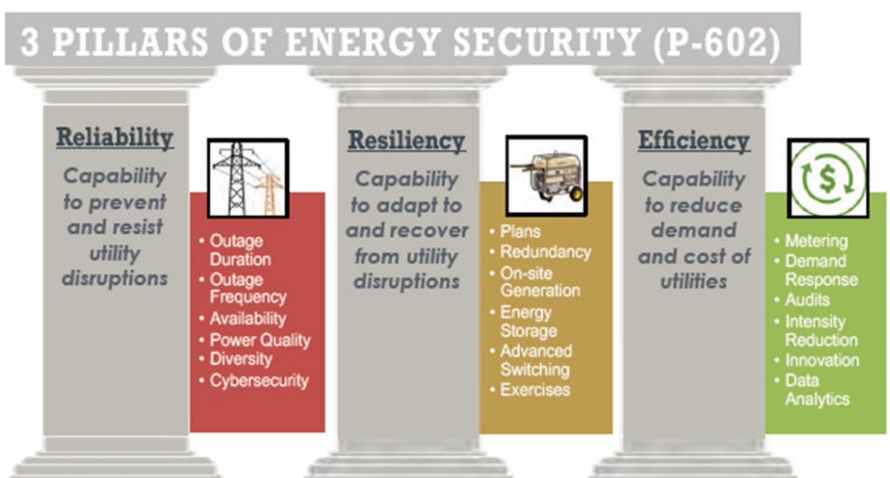


Figure 3. Three Pillars of Energy Security. Source: DON (2020).

B. DOD POWER GENERATION REQUIREMENT

Energy is what moves the military today, whether as operational energy in the form of petroleum in our ships and tanks or facility energy that powers the dining facilities and command centers. Without energy, the DOD cannot accomplish its mission. Energy security is not a new concern but has grown increasingly important as more systems, processes, and controls are dependent on reliable energy than ever before (DON 2020). Consumption of and demand for quality power is expected to increase. While the power grid has improved efficiency over the last two decades, power outages have also increased (Marqusee et al. 2017; Ericson and Olis 2019). Power disruptions have a variety of sources including extreme weather events, hardware failure, and accidental or purposeful destruction of infrastructure (Office of the Assistant Secretary of Defense for Sustainment 2020). Military installations are dependent on the commercial energy grid and the aging transmission systems, which presents an energy security vulnerability. The DOD described this vulnerability in its 2020 Annual Energy Management and Resilience Report (AEMRR) to Congress for Fiscal Year 2019. The report revealed that out of 2,572 unplanned utility outages, over 542 lasted eight hours or longer, and 90% were electricity related as shown in Figure 4. Critically, 2019 saw an increase of 32.8 percent in outages lasting 8 hours or longer from 2018. Because military installations are the primary source from which combat power is developed, supported, and deployed, it is critical to reduce their energy security vulnerabilities. The AEMRR also points out that outages on the commercial grid are expected to grow. A viable solution to this issue is emergency diesel generators (EDG), which offer the most cost effective and proven solutions in the near future.

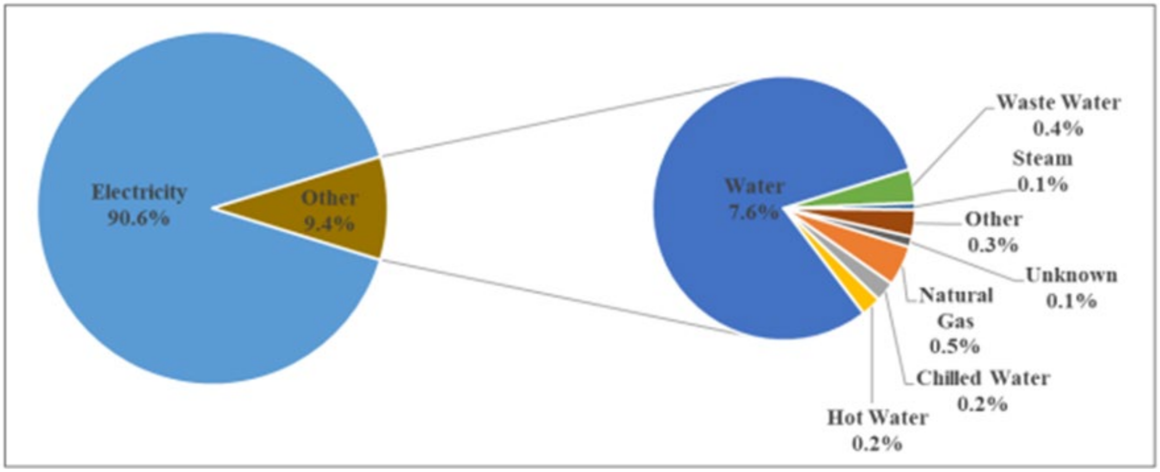


Figure 4. DOD Utility Outage by System. Source: Office of the Assistant Secretary of Defense for Sustainment (2020).

1. Emergency Diesel Generators

EDGs are utilized when facilities need to ensure a constant supply of backup energy during a power disruption. This is certainly the case for nuclear power plants and hospitals that must provide power without interruption to equipment and facilities critical to life and safety. Diesel generators are widely utilized for their ability to quickly take on the energy demand in the event of disruption, their proven reliability, and their cost to power ratio (United States Nuclear Regulatory Commission 2011). While alternate systems like photovoltaic systems, battery energy storage systems (BESS) and hydrogen fuel cells are making advances, their costs, reliability, and power capability have not overtaken diesel as the most prominent and widely utilized emergency energy resource (Kurtz, Saur, Sprik and Ainscough 2014). This is in large part due to technological immaturities, LCCs, and reliability. Photovoltaics, battery energy storage, and hydrogen fuel cell systems simply cannot deliver the same reliability and technological maturity benefits compared to the cost of diesel power generation.

Traditionally, both in the civilian and DOD sectors, EDGs are stand-alone and tied to a single building and the specifications are outlined in the UFC 3–540-01. The UFC provides criteria and ensures compliance when designing engine driven systems for prime power and standby functions on DOD installations. Modernization of current systems should implement design considerations from the UFC, but entire facilities are not required to be upgraded for the sole purpose of meeting those requirements. The UFC specifies that any permanently installed generator for the purpose of emergency power supply must comply with all National Fire Protection Association (NFPA) 110 requirements. Generators operating in an emergency power supply system (EPSS) are required to be Class X and Type 10 for medical requirements and Type 60 for everything else. They must also comply with the associated Level I or Level II criteria as laid out in the NFPA 110 and the NFPA 70 Article 700 Emergency Systems, Article 708, Critical Operations Power Systems or Article 701, Legally Required Standby Systems. Additionally, International Standardization Organization (ISO) 8528 rating classifications standards must be followed as they have been adopted by Europe (DOD 2019).

The criteria also outline additional requirements for EDGs utilized at federal facilities including identifying the fuel types that are authorized. The authorized fuel types are diesel, jet fuel, or natural gas (unauthorized for onsite storage) and unauthorized are biodiesel and liquefied petroleum gas. A system is required to have at least seven days of fuel storage on site or a reliable delivery source and a 24-hour tank capacity. Environmental requirements state that all systems must meet federal, state, and local requirements domestically or "Host Nation-specific Final Governing Standards" or the DOD Overseas Environmental Baseline Guidance Document internationally. New or modified power generators also must comply with EPA New Source Performance Standards. Appendix F of the UFC lays out emergency power requirements that are authorized for different facilities throughout the installation. Tables F1 and F2 annotate specific equipment and requirements that must be met per facility type (DOD 2019).

2. Current EDG Acquisition Strategy

Despite regulations that require EDGs for critical loads as outlined in the UFC and guidance to units that direct them to ensure energy resilience, the current strategy is uncoordinated and highly decentralized. The study by Marqusee et al. (2017) on military installation energy found that there is little to no coordination when it comes to selecting, purchasing, and maintaining EDGs. The study found that one installation had 42 EDGs from 11 different companies and unit ages spanned 49 years. Additionally, the tenant units, those that are based at the installation but are not under the control of the property, often bought and maintained their own EDGs without coordinating with the installation. Speaking with the power manager at the Naval Postgraduate School (NPS), it was found that while tenant units can purchase EDGs without coordination with the installation, the installation power manager becomes responsible for the EDG once it needs to be connected to the building in a permanent method (Clint Gorman, personal communication, September 9, 2021).

3. Issues in Oversizing EDGs within the DOD

Diesel generators sizing must be based upon the peak load that it will be required to support. Caterpillar states that EDGs are designed to operate between 50 and 85 percent of their maximum capable power output, while continuous-rated diesel generators are optimized between 70 and 100 percent of maximum capable power output (Jabeck 2013). An experiment by students at the Moscow Automobile and Road Construction State Technical University found that generators operating within 80 to 100 percent of their operational capacity are the most fuel efficient and operate the most effectively (Golubchik et al. 2019, 1–3). Industry standards recommend sizing generators 10–25% greater than the peak load to account for variation in load and the higher demand placed upon the engine upon assumption of the load (Norwall Power Systems n.d.; Generac 2011). The study by Marqusee et al. (2017) found that 13 of 15 EDGs at a military installation were on average 427 percent larger than the peak load leading to inefficiencies. The same study states that DOD guidance directed units to size EDGs twice as large as the peak capacity to allow for an increase in future load, while this could not be verified, this trend was observed in the limited building load data from NAVSTA Rota the team was able to obtain (Ronald Giachetti, unpublished data, May 3, 2021; Marqusee, Ericson, and Jenket 2020). In the case of diesel generators, bigger is not always better. A diesel generator operating below 30 percent of the rated capacity begins to wet-stack. Wet-stacking is the term industry uses to describe when a diesel generator is operating below the threshold needed to burn off residue that will, over time, lead to reduced power capacity, deficient performance, and accelerated component wear (Jabeck 2013). The result is increased maintenance and increased likelihood of failure. Current guidance from UFC 3-540-01 states that "The Designer of Record must use commercially available generator sizing software provided by the generator manufacturer to determine the required rating" (p. 5).

Oversizing has a direct impact on efficiency and operational life, as such, appropriately sizing EDGs to the required load is the most effective cost savings measure. Green, Mueller-Stoffels and Whitney (2017) support this finding through their research and states that "the size of the installed system directly affects capital costs" (p. 8). Additionally, their research revealed that bigger diesel-powered electrical systems are "more cost-effective per kilowatt" (p. 8). Lastly, their study concluded that determining appropriate size for a system is more cost-effective than using an oversized system. While a large EDG might be cheaper per kilowatt (kW) of capacity, the customer will be paying for kWs of power that are never utilized.

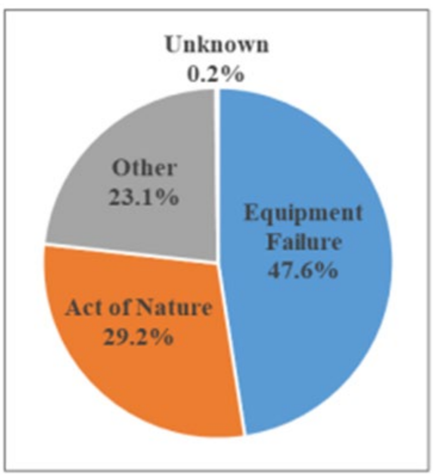
4. Stand Alone vs. Paralleled Diesel Generators

Diesel generators operating in parallel have a much higher probability of successfully sustaining the needed power generation during an extended disruption than standalone EDGs. According to a study by the National Renewable Energy Laboratory (NREL), a single well maintained EDG has a 92–96% likelihood of providing power for 96 hours and a 75–87% probability of providing power for 336 hours (Marqusee, Ericson, and Jenket 2020). The likelihood of EDG failure increases significantly when maintenance is irregular. According to data collected from the U.S. Army Corps of Engineers (USACE) database for diesel generator reliability, the NREL study found that EDGs without routinely scheduled maintenance and testing have only an 80% chance of successfully providing power for 12 hours. Utilizing a unique combination of reliability calculations to analyze paralleled EDG reliability, researchers at NREL were able to estimate the probability of paralleled EDGs sustaining power throughout a disruption as depicted in Table 1. Their study revealed that by paralleling diesel generators, the base could significantly increase the probability of supporting all critical loads for the duration of a disruption.

Table 1. 90% Confidence Ranges Probability of Meeting Duration Requirement. Source: Marqusee, Ericson, and Jenket (2020).

Base	Very Large		Large		Medium		Small	
Architecture	Microgrid (%)	Stand-Alone (%)	Microgrid (%)	Stand-Alone (%)	Microgrid (%)	Stand-Alone (%)	Microgrid (%)	Stand-Alone (%)
1 day	100	3 - 17	100	17-41	100	41 - 64	100	84 - 91
3 days	100	0 - 1	100	1-9	99 - 100	8 - 29	99 -100	60 - 78
7 days	98 - 100	0	98 - 100	0	95 - 99	0 - 6	97 - 99	32 - 57
14 days	91 - 98	0	90 - 98	0	85 - 97	0	87 - 97	10 - 32

Paralleled diesel generators have empirically demonstrated that they offer reliable back up power during outages. While paralleled EDGs have a much higher reliability to power critical loads, they bring inherent risks as well when considering how the paralleled EDGs are utilized. The risks stem from electrical and equipment failures, as evidenced in a 2020 AEMRR study revealing that 90 percent of utility outages in 2019 were electrical and just under half were related to equipment failure as depicted in Figure 5. Most disruptions were linked to issues on the installation vs issues outside the gate (Office of the Assistant Secretary of Defense for Sustainment 2020).



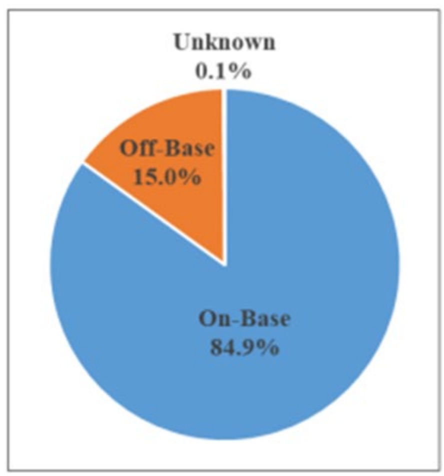


Figure 5. DOD Utility Outage by Cause and DOD Utility Outage by Cause Location. Source: Office of the Assistant Secretary of Defense for Sustainment (2020).

The report demonstrates that while a centralized paralleled power model might have certain advantages, those benefits are rendered moot if the distribution system is damaged, broken, or suffers from neglect. Many reports highlight the aging civilian infrastructure across the United States as a risk to energy security, however, the 2019 AEMRR report differs in that it shows that more than half of the disruptions occur within the installation fence line and occur due to the categories of events.

These disruptions have resulted in costly redundancy practices across the DOD. For example, tenant units can and do purchase standalone EDGs independently as a means of ensuring they can generate power in the event of disruptions. Current regulation mandates a responsibility transfer of these EDGs to the installation power manager. As consequence, the DOD has a vast array of EDGs across many installations, that vary widely in age, size, and manufacturer. From a maintainability and supportability perspective, this creates challenges as tenant unit funding also varies wildly across the DOD. This unintended consequence likely means that most, if not all, tenant unit standalone EDGs receive infrequent maintenance.

C. RESILIENCE

DOD energy resilience is defined in the DODI 4170.11 (2018) as “the ability to prepare for and recover from energy disruptions that impact mission assurance on military installations” (p. 24). For organizations as large as the DOD, this definition best serves as a conceptual blanket definition, however, the focus of this capstone necessitates further decomposition of the concept of resilience. Madni, Erwin, and Sievers (2020) decompose resilience by breaking it into four distinct characteristics as shown in Figure 6.

- Resilience = restoration of pre-disruption state (“capacity to rebound”).
- Resilience = withstand disruption within performance envelope (“capacity to resist”).
- Resilience = extend resources to fit a surge-type disruption (“capacity to adapt”).
- Resilience = continue to meet performance requirements in the face of ongoing changes (“capacity to continually adapt”).

Figure 6. System Resilience Characterizations. Source: Madni, Erwin, and Sievers (2020, 3).

These characteristics provide a framework from which resilience can be further evaluated. Decomposing resilience into characteristics also offers the benefit of tailoring resilience evaluations to specific circumstances by selecting relevant characteristics to assess.

The flexible nature of this approach is particularly beneficial when determining how to develop metrics for meeting or exceeding resilience objectives. This is because the measurement of resilience for each project does not necessarily encompass every characteristic, and as such, their selection must be evaluated against what they provide. In practical application, this capstone views EDG resilience as decomposed into three distinct categories, survivability, RTCL, and fuel consumption.

1. Survivability

Because diesel generators can readily and reliably dispatch power whenever needed, they are the most commonly used method of backup power generation. All nuclear power plants in the United States utilize EDGs for backup power regardless of the fact that no regulation requires the specific use of diesel (USNRC 2011). Most commercial entities requiring backup power generation use diesel generators, although, recently, some have begun to adopt alternate greener solutions (Roach 2020). DOD has relied on diesel power generation not only for backup power but prime power in austere operating environments ranging from the Middle East to Antarctica. An in-depth analysis of EDG reliability conducted by NREL found that proper maintenance and testing has the greatest impact upon the probability of EDG survival during an outage as depicted in Figure 7.

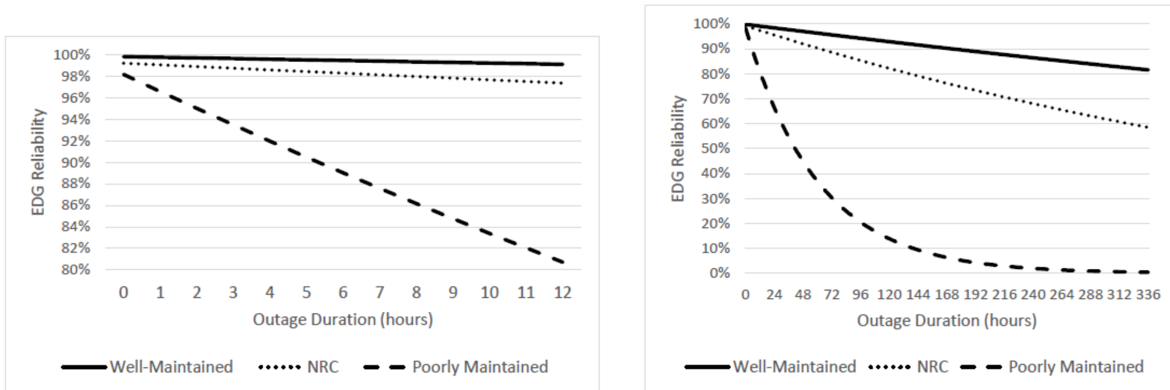


Figure 7. EDG reliability for 12- and 336-hour Outages. Source: Marqusee, Ericson, and Jenket (2020).

2. Resistance to Capacity Lost

Systems that require a high level of reliability can utilize components in parallel or standby redundancy to improve overall system reliability. Incorporating multiple components in parallel increases the reliability of the system by ensuring operation of the system despite the failure of one or more of the components.

Current installation energy postures integrate redundancy and resilience for main grid power loss but do not account for standby system resilience. EDGs on military installations are typically stand-alone systems without redundancy of any kind. If the generator fails during operation, the load cannot be supported resulting in a total power loss to the critical building. Studies by NREL have shown that the likelihood of a single EDG to survive a two-week outage is limited unless the system has been perfectly maintained. Critical facilities can increase the reliability of their standby systems by adding an additional generator in standby. This is known as an *N*+1 configuration with *N* representing the required number of EDGs and the *+1* representing an additional EDG in the configuration. This comes at significant cost to the customer to gain this resilience.

To increase the resilience and reliability of an installations standby power systems, paralleled generators are recommended by NREL in their study (Marqusee and Jenket 2020, 2–7). Paralleled diesel generators offer a method to mitigate the loss of a standby system by spreading the load to multiple generators simultaneously. Statistically, the probability of every EDG in a group of paralleled generators surviving decreases as the total number of generators increases, however, each generator added increases the ability to provide sufficient power to the facility despite the generator failures. The more EDGs paralleled together to support the load, the smaller the portion of lost capacity each EDG represents. For example, the loss of a single EDG in a paralleled system of 20 will have little effect upon the ability to support the total load, as the demand supported by the failed EDG can be spread to the remaining 19. While the loss of a single EDG can be supported by some configurations, the inability of the configuration to support the peak load does not mean that no benefit was derived from the system. Paralleled EDGs can still produce enough power to support half, or three quarters of the load, providing significant benefit to the mission when the main grid is inoperable. This concept of providing a degree of capacity, despite component failures in the system, is referred to as RTCL.

a. *Fuel Consumption*

Fuel efficient diesel generators are desirable to the consumer market, as well as to industry and the DOD. A more efficient use of fuel reduces operating costs and total LCCs. Fuel efficiency is a significant factor for EDGs as their efficiency has a direct impact on their ability to provide backup power for the duration of the outage. The UFC requires that DOD installations "provide a minimum of seven days of fuel storage either in a dedicated on-site main fuel tank or from a confirmed delivery source.…when the seven-day requirement is accomplished by a delivery source, provide each generator set with a minimum local 24-hour capacity tank based on the full-load fuel consumption rate of the engine" (p. 6). A study by Golubchik, Yutt, and Taratutin (2019) of the Moscow Automobile and Road Construction State Technical University revealed that fuel savings can be achieved by utilizing fewer diesel generators while operating at high levels of rated capacity. A study by Kelly, Oriti, and Julian (2013) of NPS revealed that when utilizing an energy management system paired with smaller paralleled diesel generators, significant fuel savings could be realized when the energy management system could activate or shut down diesel generators based upon the varying load demand. While their study focused on fuel conservation for forward operating bases in austere combat zones, the same fuel saving techniques can be utilized during extended power disruptions to military installations. A representative from Cummins explained that new diesel generators from their inventory utilize digital control modules on the generator that allows the user to establish parameters for systems operating in parallel, allowing for the most fuel-efficient use of the systems (Brian Pumphrey, Zoom call, September 3, 2021). The paralleled generators can share or hand off the load based upon the demand at any time to ensure that the EDGs are utilized in their most efficient capacity. Analysis of the literature revealed that groups of smaller diesel generators can be utilized more efficiently with an energy management system by ensuring that the generators are loaded enough to operate within the most designed operating range.

D. LIFE-CYCLE COST ESTIMATION

1. Cost Estimation Techniques

Because the purpose of this capstone is to support National Defense Strategy and the DOD through investigation of centralized and decentralized diesel power generation based on cost and resilience, it is necessary to explore various cost estimation techniques. One primary source of cost estimating techniques manifests as the *NASA* (National Aeronautics and Space Administration) *Cost Estimating Handbook*. The handbook prescribes three methods for conducting cost estimation. The three methods are: analogy, parametric, and engineering. The following sections define and expand on each method.

b. *Parametric Cost Estimation*

On parametric cost estimation, the *NASA Cost Estimating Handbook* Appendix C (2015) states the following, "Estimates created using a parametric approach are based on historical data and mathematical expressions relating cost as the dependent variable to selected, independent, cost-driving variables" (p. 6). In most scenarios, estimators typically select parametric cost estimation when data is limited (NASA 2015, 6). The handbook adds that,

> To develop a parametric CER [cost estimating relationship], the cost estimator must determine the drivers that most influence cost. After studying the technical baseline and analyzing the data through scatter charts

> and other methods, the cost estimator should verify the selected cost drivers by discussing them with engineers, scientists, and/or other technical experts. The CER can then be developed with a mathematical expression, which can range from a simple rule of thumb (e.g., dollars per kilogram) to an equation having several parameters (e.g., cost as a function of kWs, source lines-of-code [SLOC], and kilograms) that drive cost. (p. 6)

c. *Analogy Cost Estimation*

Analogy cost estimation uses cost data from purchases of similar or like items recently purchased (Defense Acquisition University n.d.-a). The *NASA Cost Estimating Handbook* Appendix C provides "Cost data from an existing system that is technically representative of the new system to be estimated serve as the Basis of Estimate (BOE). Cost data are then subjectively adjusted upward or downward, depending upon whether the subject system is felt to be more or less complex than the analogous system" (p. 4). It is important to note that when utilizing this cost estimation method that the historical cost data is both recent and accurate. Utilizing historical cost data that is not recent may yield inaccurate estimations.

d. *Engineering Build-up Cost Estimation*

Engineering Build-up Cost Estimation, also known as a "grassroots-level or detailed "bottom-up" estimate, is described by NASA in their Cost Estimating Handbook as having been, "developed from the bottom up by estimating the cost of every activity in a project's WBS, summing these estimates, and adding appropriate overheads" (NASA 2015, appendix c). This method of cost estimation is used most frequently when a project is sufficiently mature to provide scope of work definitions, determine required resources, and schedule discrete activities (NASA 2015, appendix c).

2. EDG Life-Cycle Cost Estimation

Traditional LCC compositions for DOD systems consist of three main areas: development cost, procurement cost, and operating and support cost which includes disposal. Despite being integrated into support costs, disposal is depicted in Figure 8 as a fourth category for illustrative purposes (DAU n.d.-b). The cost of each area is reflected in the chart in Figure 8 with Operating and Support consisting of most of a system's LCC. Even commercial off the shelf (COTS) systems utilized by the DOD follow a similar trend while research and development costs are reduced or eliminated.

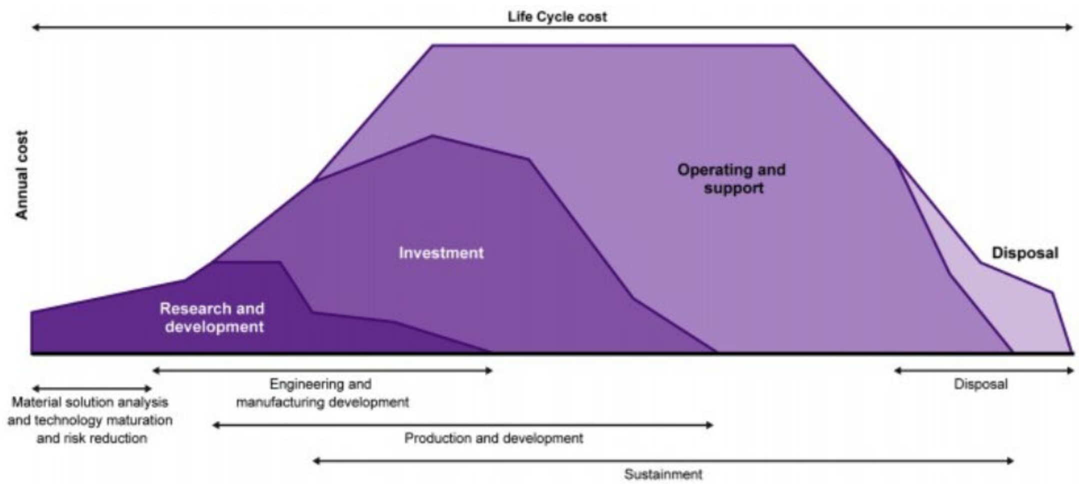


Figure 8. DOD LCC Model. Source: Government Accountability Office (2020).

When examining the LCC for standby diesel generators, the cost model depicted in Figure 8 fails to appropriately capture the true LCC and thus requires the creation of a new model. This is because the LCC for EDGs typically incurs a higher initial investment cost and a lower operating and support cost for the product life cycle. Figure 9 reflects this by graphing the LCC for an EDG. Figure 9 shows that the initial investment and military construction is the bulk of the LCC while operations and management and disposal over the life of the system are a fraction of the overall cost.

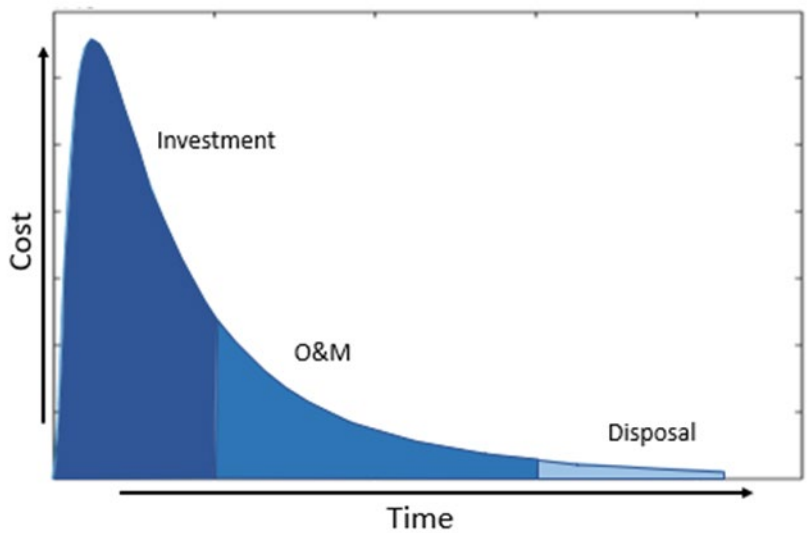


Figure 9. Cost over Time.

Generator manufactures state that they typically utilize a cost estimation method based upon a dollar per kW metric as a rough estimate for equipment cost and one manufacturer stated that installation cost is typically estimated at twice the cost of equipment until a more thorough estimate can be made based upon site specific requirements (D. Lewis, email to author, September 3, 2021).

The significant cost of investment is difficult for many organizations to budget for or afford. For manufacturing or information technology hubs like data centers, it is easy to quantify the value of lost load (VOLL). These sites can calculate how much value is created each hour and compare that to the cost of a redundant power system and determine where the breakeven point is located. This is much more difficult for DOD. Since the DOD provides a service that does not produce a profit, there is not a quantifiable breakeven point for resilient energy. The inability to calculate VOLL for DOD facilities in combination with the initial investment hurdle is one reason this capstone's authors believe the DOD energy strategy has remained standalone building-tied redundancy (NREL 2019).

The selection is binary and inflexible. A facility either requires backup generation, or it does not. Additionally, determining the VOLL proves difficult and prompts several questions. What does it cost if a DOD mission is delayed an hour? A day? A week? If the headquarters is deemed critical and maintains power during an outage but none of the subordinate units have power to execute the mission, does ensuring power to the headquarters ensure the mission will continue and is worth the investment (NREL 2019)?

Lastly, EDGs do not provide a projectable quantitative return on investment (ROI) that many emerging energy resources provide. Renewable energy resources like solar and battery energy storage systems can reduce energy costs and provide a discount on their initial investment cost. ROI for EDGs is qualitative in nature. As the DOD continues to collect data about utility disruptions across the breadth of its installations, this calculation will become easier to quantify because a larger bank of historical data will be gathered (NREL 2019).

E. COST DRIVERS EXTERNAL TO LIFE-CYCLE COSTS

LCC estimates attempt to capture most, or all costs associated with a product or system as Figure 8 suggests. However, the LCC estimate may fail to capture all costs associated with a system or product. Leastwise, when attempting to determine a system's LCC, it is important to ask what the LCC does not include. This section presents cost drivers external to those captured in the LCCs.

1. Cost Associated with Medium vs. Low Voltage Distribution Lines

The use of medium voltage lines instead of low voltage lines depends heavily upon the distance between load and power source. While a low voltage EDG can cost as little as 50% of the cost of medium voltage EDG, the cost of cabling and installation can negate these savings. This is because medium voltage is transmitted over smaller cabling due to lower amperage, thus requiring lower copper content and lower overall cable cost (Bartos 2010). A study by Siemens revealed that the cost to utilize low voltage cabling for 1000 horsepower drives is 24 times higher than medium voltage systems at 100 feet (Siemens 2018). SPOC Automation found significant savings could be achieved when utilizing a 480V low voltage system and cabling (SPOC Automation n.d.). Not only were purchasing and installation costs lower, but the 480V low voltage system also realized economic savings by being more energy efficient. The major difference between the two studies, however, was that the SPOC Automation study was examining attached prime power diesel generators that were the main power source instead of an emergency backup. SPOC capitalized on the efficient operating costs year over year using a 480V low voltage system when compared to a 4160V medium voltage system. This cost savings would not be captured by standby EDGs. Demonstrating when medium voltage is cost effective, Caterpillar supplied EDGs for The Village at the University of Southern California. The intent was to supply nine buildings with a central power plant that needed to supply 1500 kW of power. Due to the distance, the cost savings on the cabling and installation justified the added cost of the transformers to utilize the 4160V medium voltage (D. Lewis, email to author, September 3, 2021).

2. Infrastructural Costs and Considerations

An additional cost consideration when examining an installations energy security posture is the cost to implement a new strategy that would modify existing or require new infrastructure. These costs can span from purchasing software and hardware, to centralize control for power managers, to construction costs to lay new wire and install transformers. These costs vary from site to site and are unique to that specific instance. This makes infrastructural costs difficult to standardize across every site. New construction sites can incorporate the EDG installation into the construction plan while retrofitting can require disruption of operations.

F. CHAPTER SUMMARY

This chapter summarized a review of previous work done on the various aspects of diesel generators as emergency power systems. This chapter covered the need for diesel generators, why diesel generators are the primary choice for emergency backup power, the metrics involved in analyzing generators in the standby power role, and the methods to estimate LCCs. The literature indicates that paralleled systems of smaller diesel generators are beneficial for reliability, appropriate capacity use and fuel efficiency. These works will be utilized in the subsequent chapters to drive our research and analysis of the data to answer the question if paralleled systems of smaller diesel generators are more cost effective when considering both total ownership cost and installation resilience.

III. APPROACH TO EVALUATE BACKUP DIESEL ENERGY SYSTEM ARCHITECTURES

A. CHAPTER INTRODUCTION

This chapter describes the method for analyzing backup diesel generator architectures. To accomplish this end, section B identifies the individual steps and expands upon each one. Generally speaking, the analysis of system architecture is based on examinations of resilience and LCCs of diesel generators both individually and in arrangements consisting of multiple diesel generators. Finally, the general method is applied to a case study for context.

B. ANALYSIS OF SYSTEM ARCHITECTURE

Conducting an analysis of system architecture requires a structured approach to ensure all stakeholders' needs and requirements are comprehensively satisfied. To accomplish this, the capstone decomposed the system architecture analysis into the following steps:

1. Identify possible diesel power generation architectures
2. Estimate system reliability
3. Analyze system resilience
4. Analyze alternative architecture LCCs, reliability, and resilience
5. Generate a trade-off analysis that depicts the interaction between LCCs and resilience for the various identified solutions
6. Analyze results for sensitivities
7. Develop backup power generation architecture design recommendations.

1. Step 1: Design of System Architecture

Diesel generator system architectures are composed of diesel generators organized into a system to satisfy a given load requirement. The design of a diesel generator system architecture will vary based on stakeholder needs and requirements. This capstone examines diesel generator system architectures designed for the purposes of fulfilling backup power generation for DOD installations and enhancing installation resilience. The architectures are designed as either centralized or decentralized with considerations given to both resilience and LCCs. Each design serves as an alternative architecture for comparison in a trade-off analysis and provides decision-makers with multiple options for replacement or installment. When analyzing diesel generator architectures, one must consider the conditions under which the system will operate, for how long the system will operate, and many of the 'ililties' typically associated with system suitability, such as maintainability and supportability. For example, a backup power generation system may need to operate for an extended period of time without the possibility of receiving any spare parts. This may be the product of an environmental disaster, such as a hurricane or tornado, and ultimately means that repairs are not possible during the duration of the event. These considerations provide context to the system design and are captured as assumptions.

a. *Critical and Peak Load Requirements*

A load profile depicts power usage over time. Using a load profile, a facility manager may derive the minimal power required to maintain a facility's critical functions; known as a critical load requirement. In another example of how load profiles are used to determine requirements, a facility manager may determine the maximum power usage of a facility also known as the peak load. As a general method for designing diesel generator architectures, one must work closely with stakeholders, such as facility managers, to determine the critical and peak load requirements. Although all powered buildings have load profiles, it is necessary to note that this capstone only applies critical load requirements to buildings that *must* remain operational in the event of a power disruption.

b. *System Composition*

A system architecture's composition is defined as the assortment of generators that add up to a total kW load requirement. This capstone incrementally increases EDGs in system compositions for each architecture, beginning with the critical and peak load requirement for a single building. Determining the composition for a single building is necessary as it provides the smallest possible system architecture and establishes a baseline from which other compositions may be enlarged. The next approach to system composition is to apply critical and peak load requirements for three buildings. A three building approach was chosen due to the fact that three buildings produced enough demand to require multiple generators beyond the 200 kW capacity while not exceeding the ability to support the load with a single EDG. This allows the team to examine cost, resiliency and fuel for various configurations while maintaining the same load profile. Finally, system compositions are developed using critical and peak load requirements derived from practical application in a case study.

c. *Centralized and Decentralized System Arrangement*

This section discusses diesel generator architectures relative to their compositional orientation. Specifically, the section expands on centralized and decentralized diesel generator arrangements as alternative system architectures. To reiterate, a centralized architecture disperses power from a singular location, while decentralized architectures disperse power from multiple locations. Each architecture offers benefits and drawbacks as discussed in Section B, Chapter I but stakeholder needs, or requirements may constrain the architecture such that centralization or decentralization is necessary. When circumstances do not constrain the architecture, selection of a centralized or decentralized architecture requires much consideration.

The centralization or decentralization determination may be influenced by the conditions under which the system is intended to operate. An example of this are installations considered high value targets by adversaries, such as the Pentagon. Under these conditions, the centralization or decentralization decision may be driven or influenced by the architecture's vulnerability to attack. Centralization or decentralization may also be influenced by the type of installation the system will support. As an example, for remote installations or installations subject to extreme cold weather, a design must consider survivability and RTCL thus enabling the installation to retain backup power generation capability for a longer period without external support. Decisions to centralize or decentralize the architecture are influenced by many external and internal factors, whether considering the examples above, or factors such as budget constraints or infrastructure, the systems architect must carefully and deliberately consider the unique circumstances their system design will operate under.

2. Step 2: Analyze System Reliability

Step 2 of the general method assesses system reliability for system architectures. Reliability is defined as "the probability of a system or system element performing its intended function under stated conditions without failure for a given period of time" (American Society for Quality 2021). The capstone further contextualizes reliability as the probability that a system architecture can support a critical load requirement under a two-week outage condition. NREL's diesel generator reliability metrics, developed from the Institute of Electrical and Electronics Engineers and USACE, are used to establish reliability metrics for this capstone. The analysis calculates the reliability of each system architecture and examines the probability of all diesel generators in a given system surviving the outage and the probability of enough generators surviving to meet the critical load requirement as determined by the stakeholders.

Incorporating emerging reliability analysis methodology developed by Jeffery Marqusee, a Senior Research Advisor for NREL, enables the calculation of a diesel generator's probability that it will provide power during the entirety of a disruption (Marqusee and Jenket 2020, 2–7). The assumptions and variables that guided reliability calculations are:

- All generators have the same reliability based on discussions with industry leaders from Caterpillar and Generac and Jeffrey Marqusee, a leader in the diesel generator research field (Jeffrey Marqusee, Zoom call, October 1, 2021).
- All diesel generators have a constant mean time between failure (MTBF) of 1,662 hours, which equates to a reliability of 0.999398, derived from Jeffrey Marqusee's reliability analysis using, $R(t) = e^{(-\lambda t)}(-\lambda t)$, where

$\lambda = 1/MTBF$ (Blanchard and Fabrycky 2011, 348; Marqusee and Jenket 2020, 2–7).

- Survivability calculations of each diesel generator composition is based on a 336-hour outage, which equates to a 14-day outage derived from the Navy's off-grid operational requirement (DON 2020).

The probability of survival of a diesel generator configuration with no back up is given by:

$$P\ (t \geq 336)\ = e^{(-\lambda nt)}(\lambda nt)^{\frac{x}{x!}} \text{ (Klamo 2021),}$$

where *t* denotes time, *n* denotes the number of generators to supply power to peak load, and *x* denotes the number of failures that may occur and still be able to meet load requirements.

The probability of survival for a composition of diesel generators that can tolerate one failure at the end of 336 hours is given by:

$$P\ (t \geq 336)\ = e^{(-\lambda nt)}(\lambda nt)^{\frac{0}{0!}} + e^{(-\lambda nt)}(\lambda nt)^{\frac{1}{1!}}\ .$$

For each additional redundant generator, the configuration can tolerate one more failure. Calculating additional redundancy is done by adding the probability that exactly *x* number of events occur given the reliability and configuration. The calculations when considering multiple redundant generators in the configuration are:

Two Redundant Generators:

$$P\ (t \geq 336)\ = e^{(-\lambda nt)}(\lambda nt)^{\frac{0}{0!}} + e^{(-\lambda nt)}(\lambda nt)^{\frac{1}{1!}} + e^{(-\lambda nt)}(\lambda nt)^{\frac{2}{2!}}$$

Three Redundant Generators:

$$P\ (t \geq 336)\ =\ e^{(-\lambda nt)}(\lambda nt)^{\frac{0}{0!}} + e^{(-\lambda nt)}(\lambda nt)^{\frac{1}{1!}} +\ e^{(-\lambda nt)}(\lambda nt)^{\frac{2}{2!}} + e^{(-\lambda nt)}(\lambda nt)^{\frac{3}{3!}}$$

Four Redundant Generators:

$$P\ (t \geq 336)\ = e^{(-\lambda nt)}(\lambda nt)^{\frac{0}{0!}} + e^{(-\lambda nt)}(\lambda nt)^{\frac{1}{1!}} + e^{(-\lambda nt)}\ (\lambda nt)^{\frac{2}{2!}} + e^{(-\lambda nt)}(\lambda nt)^{\frac{3}{3!}} + e^{(-\lambda nt)}(\lambda nt)^{\frac{4}{4!}}\quad .$$

3. Step 3: Analyze Design Resilience

Resistance to Capacity Lost (RTCL) seeks to assess how many diesel generators can fail before the architecture's overall capability drops below the critical load while still assigning value to a composition that can provide partial power given generator failure. For example, out of a system of ten generators supporting a critical load, suppose two generators can experience failure before the system loses the capability to sustain the critical load. Assessment for RTCL uses a calculation that includes the total number of generators in the system, the amount of power each generator can provide, the peak load, and determines an RTCL score for a composition of generators by valuing ability to meet peak load but also giving value to partially meeting peak load. The steps for calculation are:

$$RTCL = \sum_{i=1}^{N} PS_i(t \geq 336)\left(\frac{GenCapacity_i}{PeakLoad}\right)$$

$$N = Number\ of\ EDGs\ in\ Composition$$

$$P = Probability\ that\ an\ exact\ number\ of\ EDGs\ survive\ at\ t = 336$$

The last resilience metric, operational fuel consumption, is a measurement of operational duration. Operational duration is a measurement of the EDG's fuel consumption based on gallons per hour and represents the total gallons of diesel the generators will consume in a given period. Fuel consumption is based upon generator load and is sourced from generator manufacturers Caterpillar and Generac. The assessment performs calculations based on a max load of 85%. Any load requirements beyond 85% trigger the next generator in the configuration to turn on. Additionally, if any generator in the configuration decreases to below 40% of max-power output, one generator will shut down triggering the other generator(s) to pick up the load. Given these conditions and load data, one may calculate the amount of fuel each generator architecture will consume in a given period. Fuel consumption is an additional metric the stakeholder must consider when analyzing the different system architectures.

Lastly, each architecture is assessed for wet-stacking susceptibility. Wet-stacking occurs when the load on a generator falls below the 35% threshold of total rated generator capacity. When a generator is underloaded and wet-stacking occurs, "fuel is not burned entirely, which causes exploitative problems in the drive diesel engines of the EDG sets…Not all injected fuel will be burned, and this can condense, creating carbon deposits on the surface of the engine's elements" (German-Galkin, Tarnapowicz, Matuszak, and Jaskiewicz 2020, 2). Wet-stacking can lead to reduced reliability and a shorter total life cycle; thus, it is necessary to develop architectures that mitigate wet-stacking to the maximum extent possible.

The resilience score is calculated by normalizing the survivability, RTCL, and fuel consumption attribute data. After normalization, weights are assigned to each of the attributes. The weighted attributes are then summed up and multiplied by attribute scores. Normalizing attribute scores is done using linear scaling to create the same ranges of values, between 0 and 1, for each attribute, so the resilience attributes can be objectively compared with the resilience equation. Attribute weights are assigned based upon customer inputs, which will adjust the resilience scores. The formulas are shown in Figure 10.

If a high number is good:

$$S_{ij} = \frac{X_{ij}}{X_{i\,\max}}$$

where S_{ij} = the *scaled* value for benefit *i* and alternative *j*
X_{ij} = the raw value for benefit *i* and alternative *j*
$X_{i\,max}$ = the highest (best) raw value for benefit *j*

If a low number is good:

$$S_{ij} = \frac{X_{i\,\min}}{X_{ij}}$$

where S_{ij} = the scaled value for benefit *i* and alternative *j*
X_{ij} = the raw value for benefit *i* and alternative *j*
$X_{i\,min}$ = the lowest (best) raw value for benefit *j*

Figure 10. Linear Scaling Calculation. Source: Boensel (2021).

4. Step 4: Analyze System Architecture's LCC

LCCs are only derived after each alternate diesel generator architecture has been designed and assessed for resilience. This is because architecture designs are likely to be modified to achieve designs that attain the highest resilience scores. Otherwise, one may waste time and effort calculating LCCs only for the design to change, prompting another LCC analysis. Market research serves as the method of choice for finding diesel generator cost data. One tool that is particularly helpful for gathering diesel generator cost data is the Generac Total Cost of Ownership (TCO) Calculator. This tool is especially helpful because its TCO categories closely aligns DODI 5000.02 (2020) LCC categories. The total LCC categories include the following:

1. Capital cost
2. Installation cost
3. Preventative maintenance
4. Initial tank fill
5. Annual fuel replacement

6. Fuel maintenance (fuel polishing)

   1. Routine load bank testing
   2. Purchase of transmission line
   3. Construction costs.

Each of the LCC categories are factored into total LCC for each architecture and serve as a comparative tool for assessment in a trade-off analysis.

5. Step 5: Plot Data

Upon collection of the required data for LCC and resilience metrics, several methods of multiple criteria decision analysis are used to plot and visualize the data. Multi-objective decision making (MODM) methodology is used to find the best balance of LCC and resilience.

6. Step 6: Analyze Results

The final step in this process is to assess the results and conduct trade-off analysis between different architectures of EDGs through data standardization and the application of qualitative weights to achieve a resilience score for each architecture. The results here inform stakeholders and decision-makers regarding the most cost-efficient solutions while maximizing resilience for the installation's backup power system.

C. CASE STUDY: NAVAL STATION ROTA, SPAIN

As the backup diesel generators located at NAVSTA Rota Spain draw closer to their end of service life, the Rota power manager and commander are seeking recommendations regarding cost and purchasing strategies for their eventual replacement. The installation is seeking solutions that span 30–40 years in support of a new military construction project submission with the goals of energy efficiency, reliability, and resilience.

Chiefly, the installation is interested in two options: a centralized solution using a single diesel generator farm and a decentralized solution using multiple, smaller diesel generator farms amounting to the same total power capacity. The Rota commander and power manager are seeking an analysis backed recommendation that addresses LCCs and resilience strategies for both options.

1. General Information

The installation's primary source of backup power generation is an architecture consisting of five centralized diesel generators sized at 2.5megawatt (MW). The generators are connected in parallel at the installation power plant. Rota has an additional 46 building-tied, stand-alone diesel generators attached to key facilities, which include the hospital and the air traffic control tower. For the purposes of this capstone, the 46 building-tied, stand-alone diesel generators attached to key facilities are not considered due to feasibility and accountability issues. The power manager reports that the peak load for the installation is slightly above 16MW, and we assume the critical load is 10MW. Although the stakeholder did not provide this data point, load data pulled from the NPS in Monterey, CA provided sufficient evidence to suggest this is the critical load requirement for NAVSTA Rota, Spain. Figure 11 provides an illustration of the current backup power generation architecture at NAVSTA Rota, Spain.

Figure 11. System Architecture for Naval Station Rota, Spain. Source: Juan Enriquez, Zoom call (April 29, 2021).

2. Assumptions

The following are assumptions applicable to the case study at NAVSTA Rota, Spain:

a. *Assumption 1*

We assume the critical load is 10MW. The fifth 2.5MW generator at the Rota power station is unnecessary to meet the critical load requirement. Rota's power station houses four organic 2.5MW diesel generators and one temporary 2.5MW generator. The fifth temporary generator is considered an unnecessary backup, which is both costly and unused.

b. *Assumption 2*

We assume a fixed price per kW for installation cost based off the TCO Calculator created by Generac. This calculator provides a high, low, and median price for installation because installation costs vary due to the installation location and state of the global supply chain.

c. *Assumption 3*

We assume fuel polishing occurs during the annual maintenance of the generators. To avoid stagnant fuel contamination, a process known as "fuel polishing" is conducted annually and the cost is accounted for in the annual maintenance cost of the generators. During the annual maintenance of the generators, fuel in all tanks is run through a filtration system to eliminate any contaminants found in static fuel at the bottom of a fuel tank due to infrequent use.

d. *Assumption 4*

We assume the base has fuel capacity for 14 days of operation and at no point during the 14-day outage will refueling occur. This assumption is made because each architecture must support the Navy's 14-day outage strategy (DOD 2020).

D. CHAPTER SUMMARY

This chapter describes the general method for analyzing diesel generator architectures by decomposing the general method into traceable steps. Subsections of this chapter describe the steps for analysis with the results serving to inform stakeholders and decision-makers on well-balanced designs to ensure resilient backup power for military installations while balancing total LCCs. Finally, the chapter presents and details a case study to which the steps will be applied.

IV. DATA ANALYSIS

This chapter explains the process and results of diesel generator cost and resilience analysis. The chapter also explores the process for capturing LCC and the combination of metrics that are being utilized to determine the resilience of the diesel generator architectures that are explored. The end of the chapter examines the NAVSTA Rota backup power requirement and utilizes it as a test case to examine the balance of cost and resilience.

A. ESTIMATING LIFE CYCLE COST

To estimate EDG LCC, a complete list of expenses related to buying, maintaining, operating, and disposing of the system must be established. A generator's LCC can be divided into three distinct areas based upon Figure 8: DOD LCC Model from Chapter II. The three LCC areas are Initial Acquisition, Operation and Maintenance, and Disposal. For this capstone, the LCC formula was calculated as follows:

$$LCC = (\text{EC} + \text{SC} + \text{IC} + \text{SGC} + \text{EFC}) + \text{Lifespan}(A_{PM} + A_{FRC} + A_{FP} + A_{LBT}) + \text{RC} - \text{RV}$$

$LCC = Life\ Cycle\ Cost$

EC = *Equipment Cost*

SC = *Shipping Cost*

IC =*Installation Cost*

SGC = *Switchgear Cost*

EFC = *Enclosure & Footpad Cost*

$A_{PM} = Annaul\ Preventative\ Maintenance$

$A_{FRC} = Annual\ Fuel\ Replacement\ Cost$

$A_{FP} = Annual\ Fuel\ Polishing$

$A_{LBT} = Annual\ Load\ Bank\ Testing$

RC = *Removal Cost*

RV = *Resale Value*

Utilizing the LCC formula, the capstone estimated the cost associated with the architecture models and various compositions of EDGs. To establish informed cost estimation techniques, this capstone examined industry practices amongst EDG manufacturers. The examination revealed that manufacturers such as Cummins and Caterpillar utilize a dollar per kilowatt estimation method for generator equipment costs (Brian Pumphrey, Zoom call, September 3, 2021; D. Lewis, email to author, September 3, 2021). Further investigation also revealed that in some cases, subcontractors double the equipment cost to estimate the installation cost for indoor installation, while outdoor installation costs are estimated at one and one-half times the cost of equipment (D. Lewis, email to author, September 3, 2021). Interestingly, none of the estimates received from manufacturers included shipping cost, maintenance costs, or disposal cost. Lastly, research, also revealed one tool known as the Generac TCO Calculator. The Generac Total Cost of Ownership tool is designed to compare the LCCs between diesel generators and natural gas generators, but it can also estimate cost for diesel generators (Generac n.d.). As far as research revealed, this was the only tool of its kind available for public use. Representatives from both Cummins and Caterpillar both noted that neither company had any such tool to their knowledge when the team asked (Brian Pumphrey, Zoom call, September 3, 2021; D. Lewis, email to author, September 3, 2021).

The tool allows the user to customize the factors and configurations impacting LCC. Users can select the number and size of generators desired in either single or paralleled configuration. Other customizable factors offered are the cost per gallon, maintenance schedule and cost, and the estimated cost of installation. These features are presented in an easy to utilize menu as seen in Figure 12. Once the initial information was entered, the calculator provides an initial cost estimate for only the EDG.

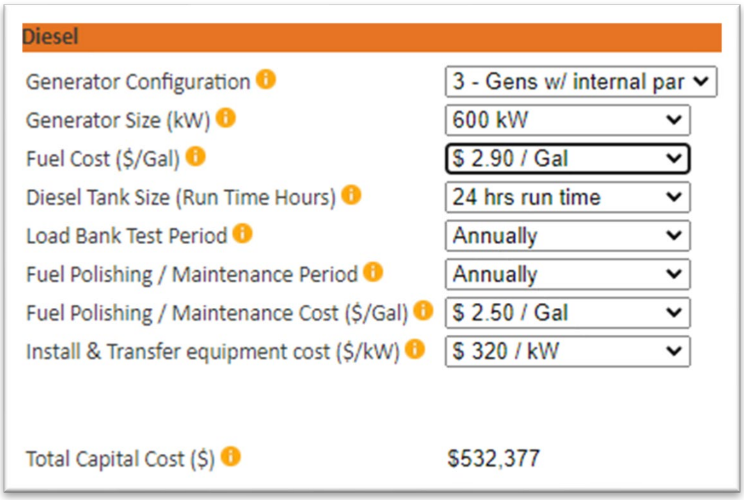


Figure 12. Customizable Capital Cost Estimation Menu. Source: Generac (n.d.).

The Generac calculator utilizes an estimation technique based upon price per kW, similar to those used throughout the industry. Costs generated by the calculator could subsequently be used to extrapolate costs to larger-sized diesel generators. Installation cost, as a feature within the calculator, is set upon a fixed dollar per kW metric as is done with the estimation for equipment cost. Installation cost is the most variable depending on the location, difficulty of delivery, preparation needed to install, and size of crane to lift the generator into place. While representatives from Caterpillar mentioned that their cost estimation department typically uses 1.5-2x capital cost for the cost of installation, the Generac TCO tool advises that "installation costs vary significantly based on application configuration, cabling distance, regional labor rates, etc." (Generac n.d.). Examination of the TCO tool revealed that the tool generally kept installation cost around 1.05-1.4x equipment cost.

The user then fills out the operation section of the tool, depicted in Figure 13. In this section, the user provides their desired load operation estimation. These inputs are estimations formatted into hours of operation per year and represent the total number of hours a user anticipates a generator to operate. The calculator states that for "standby duty only, 30 hrs/year is a fair initial estimate" (Generac n.d.). Thirty hours with load operations was the lowest the calculator allowed and was held constant for all analysis. This section also allows the selection of EDGs that will be utilized for demand response. Demand response is the reduction of electrical demand by the consumer during peak periods to help balance supply and demand (Office of Electricity n.d.). Demand response was not selected in our cost comparison as the costs for achieving diesel emission compliance often exceeds any potential cost savings (Generac 2019).

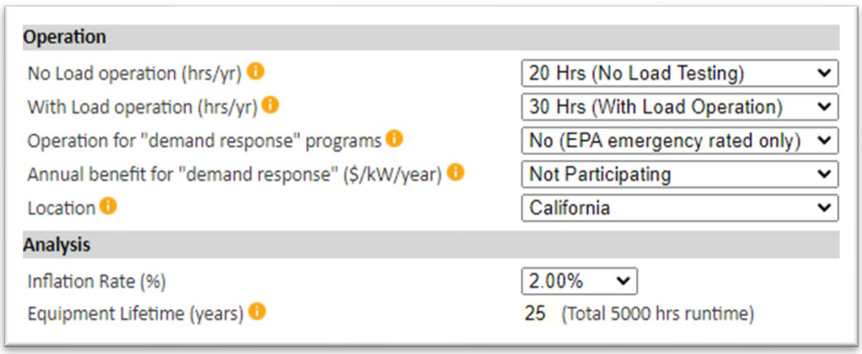


Figure 13. Operation Cost and Inflation Rate Selection. Source: Generac (n.d.).

After all information is selected by the user, the TCO calculator provides a 25-year cost estimation adjusted for a constant inflation rate, which can be modified by the user. For the capstone, inflation was set at 2% for analysis. The analysis breaks down the cost by section and allows the user to examine each aspect for the estimated EDG LCC, as depicted in Figure 14.

Cost Items

	Diesel
Generator - Capital	$532,377
Generator - Installation	$688,368
Generator - PM (annual)	$12,164
Fuel - Initial Tank Fill	$9,911
Fuel - Cost (annual)	$10,221
Fuel - Maintenance (annualized)	$8,544
Load Bank - (annualized)	$9,738
Demand Response - (annual)	$0

Note: Unit with load operation is assumed 75% of capacity for this analysis.

Fuel Consumption

	Diesel
Annual Fuel Consumption	3,524 gal
Annual Source Energy Consumption	582 MMBtu

Figure 14. Breakdown of Life-Cycle Costs for the Selected EDG Configuration. Source: Generac (n.d.).

The fuel consumption estimation and cost for the Generac calculator only includes the amount of fuel consumed by annual maintenance. Consequently, this means the tool does not account for fuel consumption during outages. To account for this shortfall, various configurations were assessed for fuel consumption over a simulated two-week outage in Section B.

While useful, the TCO calculator does have its limitations. One limitation of the tool stems from sizing options. Users may only select generators from 200 kW to 2000 kW. Because of this limitation, reconstruction and adaptation of the TCO calculator became necessary to better suit the purpose of this capstone. To examine the configuration larger than 2000 kW, the team utilized the cost estimates from Caterpillar (D. Lewis, email to author, September 3, 2021). This allowed the team to compare configurations across the full breadth of EDGs, up to 3900 kW.

Another limitation to the TCO calculator is that it does not account for cost factors such as shipping and disposal cost for the systems. These two factors are highly dependent upon location, shipping distance and method, as well as economic conditions. Without the integration of these two factors, cost estimates fail to accurately reflect LCC. Research of industry practices related to these two factors failed to reveal any standardized practice, however, Caterpillar stated that diesel generators "above [the] 1000 kW…size will present shipping challenges as they are larger than freight containers and due to weight and height limitations, often must be disassembled, freighted in pieces and reassembled on site at considerable extra expense" (D. Lewis, email to author, September 3, 2021). Large diesel generators are made more challenging and costly because they require specialized training for disassembly, reassembly, and maintenance. Conversely, smaller generators are more likely to have personnel trained in their repair and maintenance, can be transported as assembled by the manufacturer, and are more likely to fit in standard shipping containers (SPOC Automation n.d.). As a result, smaller generators are typically more economical and cost competitive when accounting for shipping costs. To make a rough estimate for shipping costs, $0.11 per pound was utilized for 1000 kW and below and $0.22 per pound was utilized for all gensets greater than 1000 kW. This was based on a cost estimate from a generator sale website (Generator Source n.d.).

For decommissioning and disposal costs, diesel generators are either sold second-hand or for scrap metal. Investigation into disposal options revealed that many companies offer disposal services. These services typically involve the sale of the generator to a disposal service. Some companies even offer removal services including disconnection and disassembly of the diesel generator(s). Disposal costs are varied based on location and removal service availability. To simplify the accounting of this cost, the capstone assumes that selling the generators for recoupment will negate disposal costs.

1. Comparing Configurations Based Upon Cost

Previous work by NREL indicated that an installation could increase energy resilience and improve energy security by paralleling diesel generators. This approach differs from current practices, which use stand-alone building-tied EDGs (Marqusee, Ericson, and Jenket 2020). In keeping with NREL's findings, this capstone utilized the Generac TCO calculator to determine the estimated 25-year cost data for various paralleled system configurations.

The EDGs were broken into five distinct size categories for cost analysis. The five categories were <400 kW, 401–600 kW, 601–1000 kW, 1001–2000 kW, and >2000 kW. The team observed that below the 600 kW threshold, it is not cost effective to parallel EDGs in comparison to a single EDG as depicted in Figure 15; however, once the peak demand exceeds 600 kW, it becomes more economical to parallel multiple systems.

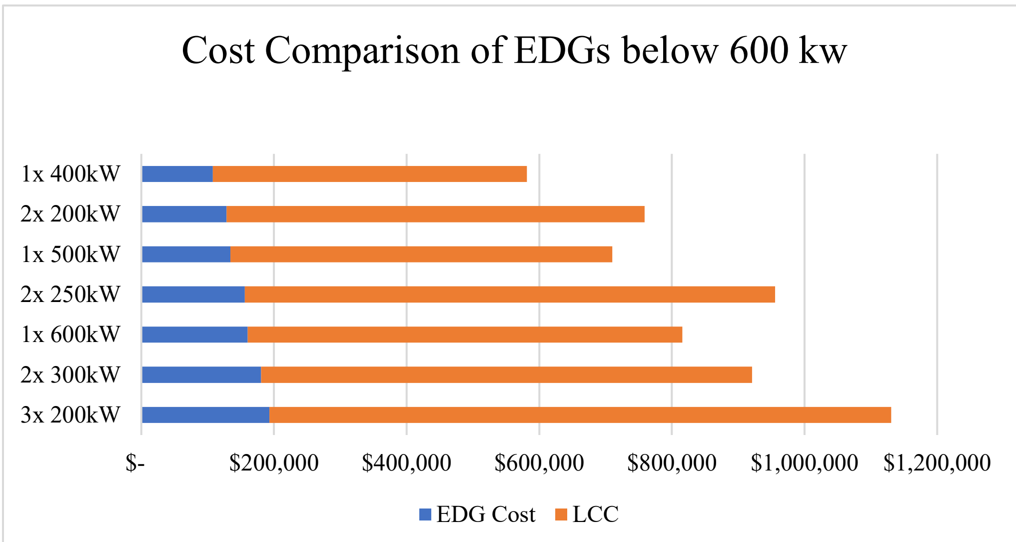


Figure 15. EDG below 600 kW Cost Comparison.

The website, Clifford Power, reveals why it not cost effective to parallel EDGs beflow 600 kW is likely. According to Clifford Power, "The diesel engine cost per kW increases significantly above 600 kW because mass-produced truck engines are typically used in generators that produce less than 600 kW. For example, a 1,000 kW generator typically costs more than two 500 kW generators in parallel" (2020) as depicted in Figure 16.

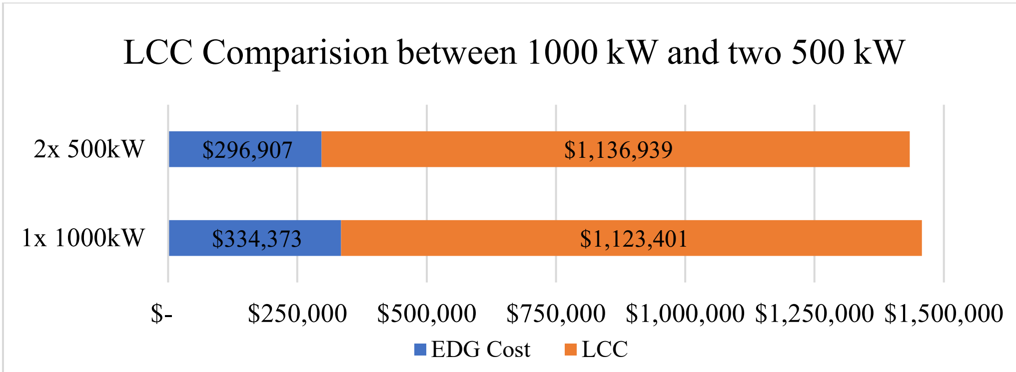


Figure 16. LCC Comparison: 1000 kW vs. 2x 500 kW.

While the estimated purchase cost is approximately 11% cheaper for the paralleled 500 kW generators, the cost savings over 25 years is much narrower. Over 25 years, there is an estimated 1.5% cost savings when purchasing the two 500 kW generators over the single 1000 kW generator. This reveals that preventative maintenance costs on multiple generators will nearly eliminate the savings achieved in equipment cost.

For the loads above 1000 kW, the analysis revealed that, generally, larger EDGs are cheaper than paralleling smaller EDGs. However, paralleling 600 kW EDGs stood out as an exception and was the most economical solution. When compared to a single 2000 kW EDG, three paralleled 600 kW generators realized a cost savings of over $280,000 or 11% over 25 years as seen in Table 2.

Table 2. LCC Breakdown of 1x 2000 kW vs. 3x 600 kW. Adapted from Generac (n.d.).

	1x 2000kW	3x 600kW
Generator - Capital	$688,145	$532,377
Generator - Installation	$717,050	$688,368
Generator - PM(annual)	$8,920	$12,164
Fuel - Initial Tank Fill	$10,858	$9,911
Fuel - Cost (annual)	$11,197	$10,221
Fuel - Maintenance (annualized)	$13,104	$8,544
Load Bank - (annualized)	$10,760	$9,738
Demand Response - (annual)	$0	$0
25 year cost at 2% inflation	$2,754,034	$2,467,815

When comparing three paralleled 2MW generators versus ten paralleled 600 kW generators, cost savings over 25 years was achieved when utilizing the smaller EDGs although the savings narrowed to approximately 3%, which is not very significant given the rough estimation methods. The initial analysis of cost revealed that large EDGs are generally more economical than smaller parallel generators when examining LCCs over 25 years shown in Figure 17.

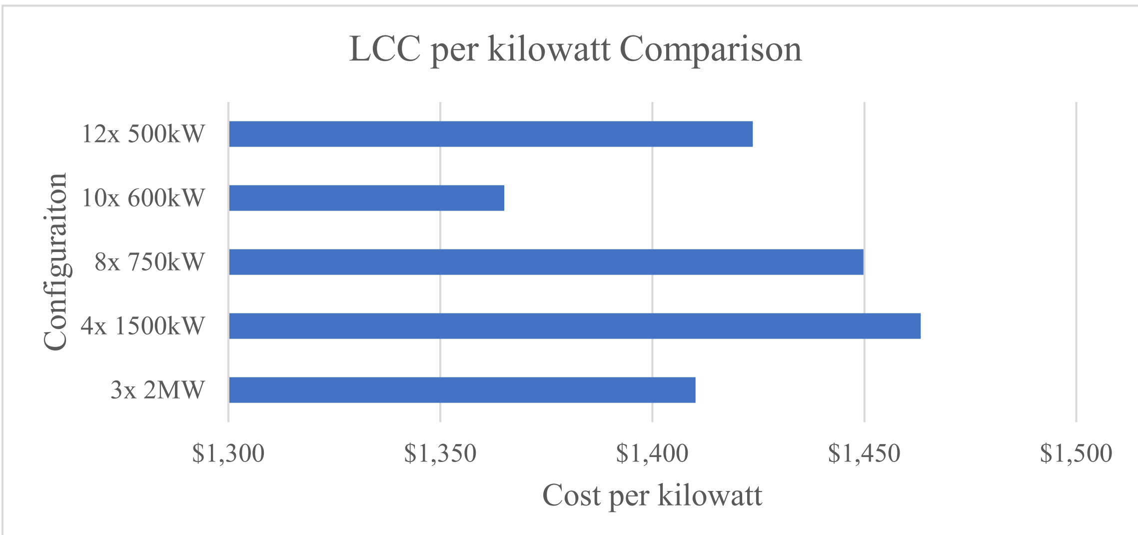


Figure 17. LCC per kW Comparison.

2. Capacity Usage and Issues with Underloading

The team next examined the utilization of the generator rated capacity during a simulated outage. A simulated two week outage was used to examine how much of the EDGs' capacity would be utilized based upon a load profile taken from buildings on the NPS campus. The results showed that an EDG sized to support a facility's peak load plus an additional 25% buffer was frequently underloaded, with demand falling below the 30% rated capacity threshold as shown in Figure 18.

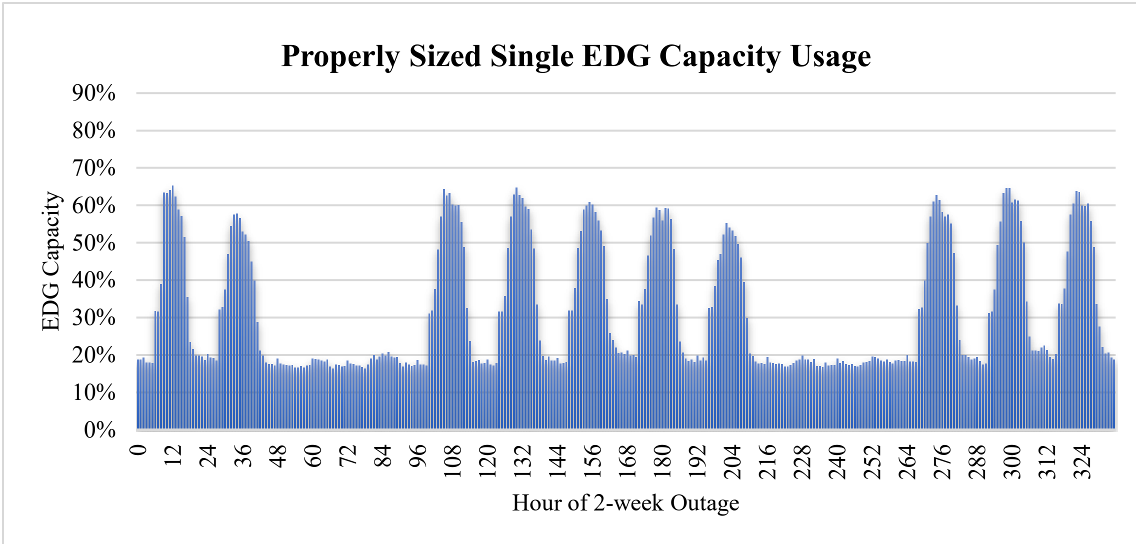


Figure 18. Properly Sized EDG Capacity Usage by Hour.

Utilizing an emergency generator sized to the peak load plus a buffer as recommended by industry, Figure 18 shows that the EDG will drop below the 30% threshold during low-demand times. Generac recommends selecting an EDG rated for approximately 20–25% higher than the peak load (Generac 2011) and for this study, a 25% buffer was utilized for all sizing. An analysis of the two-week outage revealed the EDG would operate under 30% load for over half of the operating hours, a full 200 hours out of 336.

Oversized EDGs push the amount of underloading time significantly higher. NREL's study found that EDGs on military installations are oversized by an average of 400% (Marqusee, Ericson, and Jenket 2020). For this analysis, the team utilized a simulated EDG that was oversized by 100% for our analysis. 100% was selected because the information from our case study indicated that EDGs on the base in Rota were oversized by this amount (Ronald Giachetti, unpublished data, May 3, 2021).

Figure 19 depicts the utilization of an 800 kW EDG oversized by 100% during a simulated two week outage. Based on the EDG's performance over the two week outage, one can see that the EDG is operating below 30% capacity for 91% of the outage, or for 308 hours out of the 336-hour outage. Moreover, the figure reveals that although an oversized EDG LCC might have been more economical, 70% of the rated capacity goes unused for the duration of the EDG's lifespan. Based on a 25-year lifespan, this equates to the user significantly overpaying for capacity that is never used. We do not recommend oversizing single EDGs due to in-efficiencies realized in fuel economy, wet-stacking, and cost.

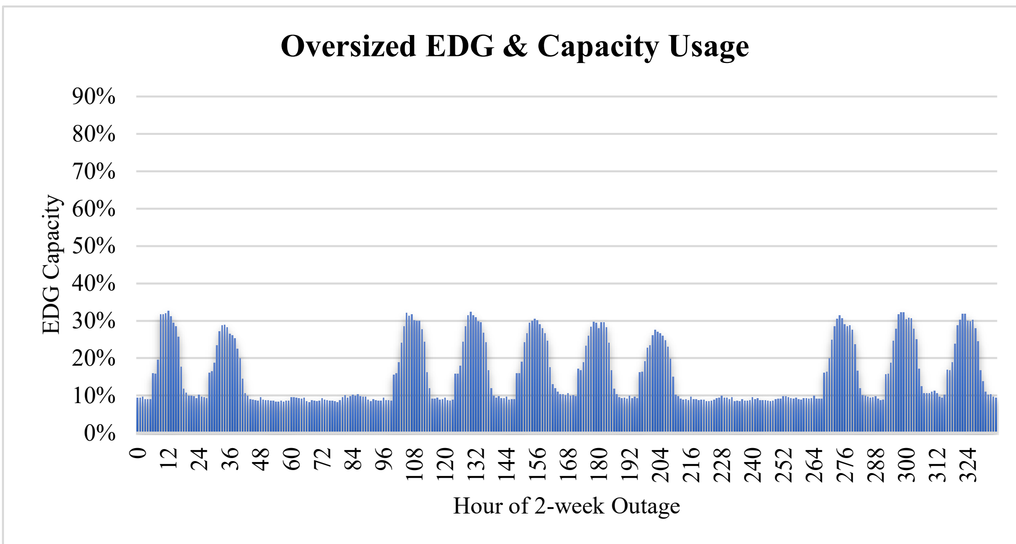


Figure 19. Hourly Capacity Usage for 1x EDG Oversized by 100%.

The amount of time underloaded was mitigated by increasing the number of EDGs in a configuration that could share the load based upon pre-programmed levels. By sharing the load between two or more EDGs, the paralleled systems can ensure that they operate within the most effective range for EDGs of 50–85% of rated capacity (Jabeck 2013). For the analysis, we utilized 85% as the point at which the EDG would share the load with a paralleled EDG in the configuration.

Examination of the paralleled EDG configuration showed that utilizing multiple smaller EDGs mitigated the problem of underloading as seen in Figure 20. The EDGs were better able to accommodate the lower demand hours during the outage without underloading by shutting down any EDG that fell below 35% capacity and passing the load to another EDG. Multiple EDGs also had the added benefit of conserving fuel by running fewer diesel generators during low-demand hours capitalizing on better fuel efficiency by running at a higher rated capacity. An oversized EDG and a pair of load sharing EDGs is depicted in Figure 20 as a performance comparison. This is explored further in our analysis of fuel consumption.

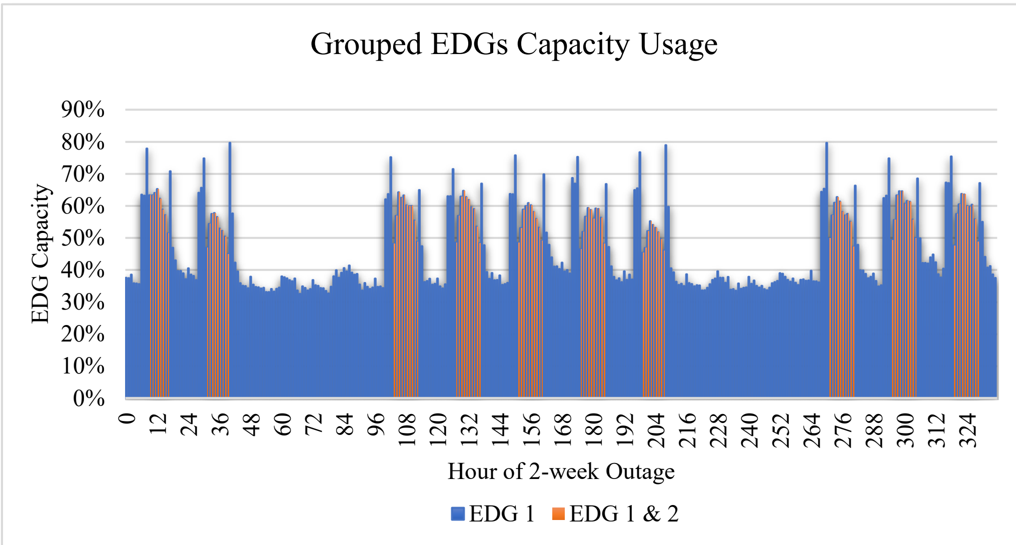


Figure 20. Comparison of Oversized EDG and 2x Load Sharing EDGs.

The team then examined the use of a centralized node of diesel generators to power a group of local buildings. Utilizing the centralized architecture model for a three-building cluster revealed that the underloading observed in the single building scenario continued to occur even with an appropriately sized EDG for a multi-building load, as seen in Figure 21. A simulation showed that a single 2000 kW EDG servicing a 1500 kW peak demand is estimated to be operate below 30% rated capacity during 40% of the two-week outage depicted in Figure 21. A simulation utilizing paralleled EDGs revealed that any combination of paralleled systems eliminated the underloading issue by effectively sharing loads between the paralleled generators as seen in Figure 22. Additionally, Figure 22 shows how many generators are running and the load on each for the duration of the simulated 14-day outage. Having enough generators appropriately sized to share and pass the load demand enables the composition to run efficiently and above the wet-stacking threshold.

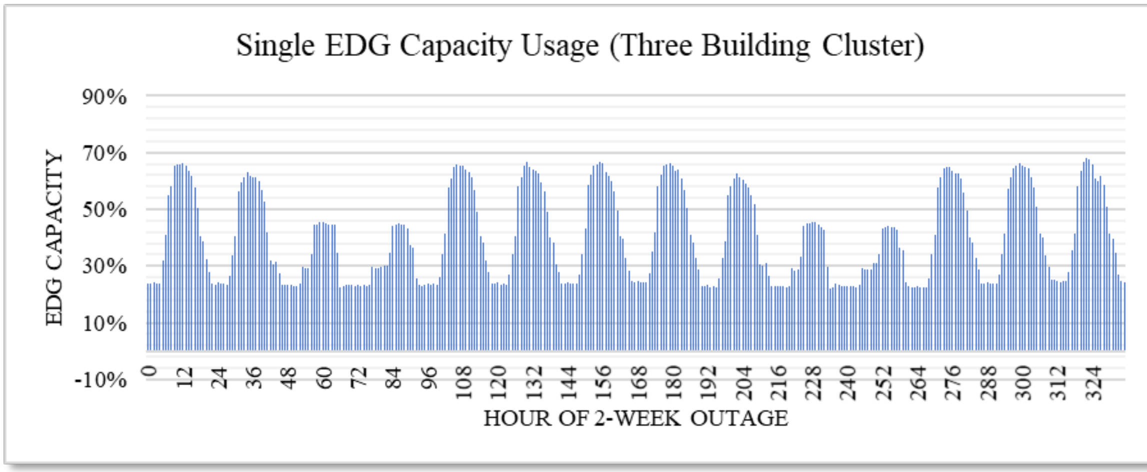


Figure 21. Single EDG Hourly Capacity Usage for three Buildings.

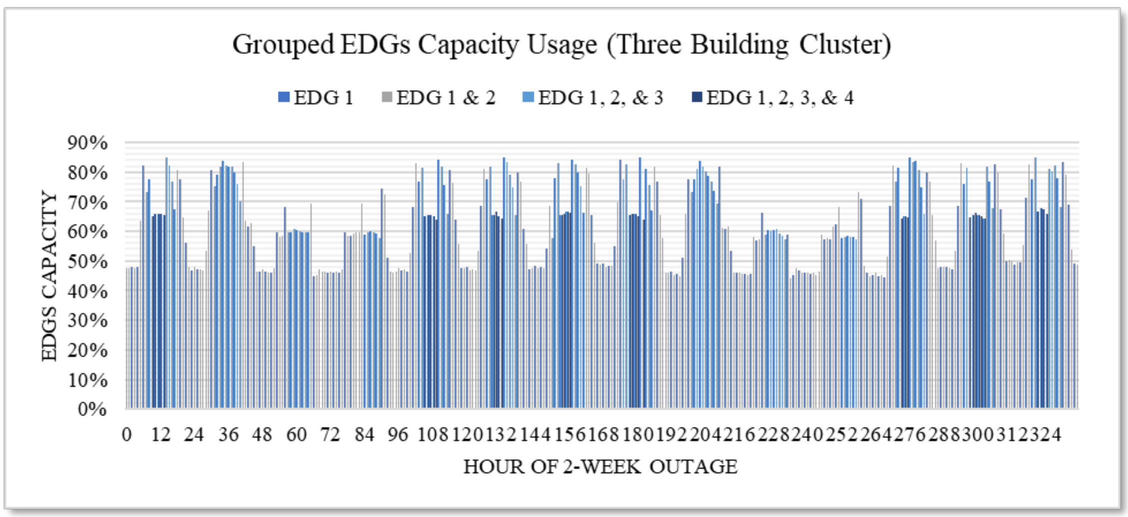


Figure 22. Hourly Capacity Usage of 4x EDGs Capacity Supporting Three Buildings.

Underloading a diesel generator is known to create a condition called wet-stacking. Wet-stacking can lead to power loss, poor performance and accelerated wear of components (Jabeck 2013). Speaking with representatives of Caterpillar, Cummins, and researchers at NREL revealed that there is no known calculation to estimate the loss of power or shortening of lifespan of underloaded diesel generators due to wet-stacking (Brian Pumphrey, Zoom call, September 3, 2021; D. Lewis, email to author, September 3, 2021; Jeffrey Marqusee, Zoom call, October 1, 2021). No known method exists to estimate the degradation of performance caused by underloading; it is widely accepted that underloading EDGs negatively affects the operating life span and efficiency. Utilizing multiple EDGs in an architecture ensures that the EDG power capacity is appropriately utilized, underloading is avoided, and that the EDGs have the ability to meet any sudden increase in demand.

B. FUEL CONSUMPTION

An EDG system designed with fuel efficiency in mind offers two benefits to users. First, an efficient system will use less fuel over time and thus offers cost savings benefits. Second, an efficient system can be made to operate for longer periods of time because of its efficiency. This is particularly beneficial during prolonged outages and therefore is a critical factor that cannot be ignored in the execution of this capstone. This capstone assesses fuel efficiency by comparing fuel consumption rates for various EDG architectures.

One EDG configuration examined for fuel efficiency was comprised of small diesel generators. This EDG configuration was sized in accordance with estimated energy demands for three buildings. Energy estimates for three buildings were sourced from the resident power manager at the NPS and represent energy demands for a two-week period from 2019. The examination then assessed the fuel efficiency of the EDG configuration based on energy demand for an outage scenario lasting for the duration of the same two-week period. The examination utilized the fuel consumption estimates from respective EDG manufacturers' specification sheets for each diesel generator size. Fuel consumption was calculated by using the hourly energy demand paired with the appropriate gallon per hour burn rate. Using this approach, we calculated the total gallons of fuel each EDG would burn over the 336 hours of a two-week outage.

Fuel consumption for the study was calculated using the calendar year 2019 NPS load data from the three buildings, peak load requirements outlined in Section C, and the approach outlined in Chapter III. An additional EDG in a composition powers on when the current EDGs running reach 85% capacity. An EDG in the composition powers down and passes its load to the other EDGs in the composition when the EDGs operate below 40%

capacity. Using that previous criterion for running EDGs in a composition we are able to calculate total gallons of fuel burned over a 14-day outage, which can be seen in Figure 23.

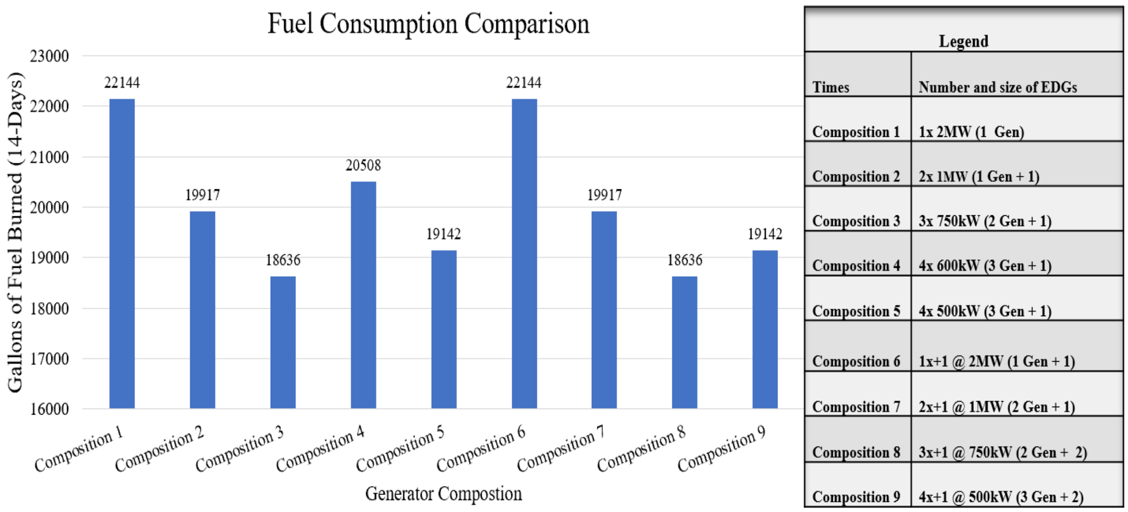


Figure 23. Fuel Consumption by Configuration for Two-Week Variable Load.

The most fuel efficient EDG compositions for the case study are composition 3 and 8. That composition burns 18,636 gallons of fuel over the 14-day outage, which is approximately 1,331 gallons per day. This composition is 18.8% more efficient than compositions 1 and 6 and would last an additional 2.5 days given the same amount of fuel it would take the least efficient composition to last 14 days. The results demonstrated that variable loads with high peak energy demands during the day and low average demands during the nights and weekends favored multiple EDGs to account for the wide variation in demand.

When comparing centralized and decentralized architectures in later sections we will calculate fuel consumption using the worst-case scenario, which assumes the composition must meet peak capacity for the duration of the 14-day outage. This approach is one way to ensure we are evenly analyzing the various compositions of the different architectures.

C. SYSTEM SURVIVABILITY ESTIMATE

The ability of an EDG architecture to provide sustained power during an outage is critical to maintaining an installation's critical mission functions. Any EDG architecture must therefore be designed to meet or exceed critical load requirements for the duration of a stakeholder specified outage threshold. To determine the ability of an architecture to meet this threshold, each EDG configuration was assessed for system survivability. System survivability was calculated for each composition using the survivability equations found in Chapter III. This calculation provides the probability that an EDG configuration will survive an outage. The capstone specifically assessed system survivability for 14 days or 336 continuous hours, simulating a worst-case outage scenario. Using the survivability equation from chapter 3, P $(t \geq 336) = e^{(-\lambda n t)}(\lambda n t)^{\frac{x}{x!}}$, Table 3 shows the system survivability determinations for EDG configurations using time (t) = 336 hours. The table also depicts system survivability results when additional EDGs are added to a configuration for redundancy. For example, a composition of three EDGs has a probability of survival of approximately 54%. When we add one redundant generator to the previous composition the survivability at $t = 336$ increases to approximately 87%. From the example, one can see that a greater number of redundant EDGs in a system results in a higher system survivability probability. Moreover, adding EDG redundancy reduces the impact of EDG failures to a system, resulting in a greater retention of system capacity for any given EDG loss. This approach can be applied to any size generator because the individual reliability of any given DG is constant.

Table 3. Probability of Survival of EDG Compositions.

Time (t)	1 EDG that equals required load	1 EDG that equals required load + 1 redundant EDG of the same size	2 EDGs of the same size that equal required load together	2 EDGs of the same size that equal required load together + 1 redundant EDG of the same size	2 EDGs of the same size that equal required load together + 2 redundant EDG of the same size	3 EDGs of the same size that equal required load together
1	0.9994	1.0000	0.9988	1.0000	1.0000	0.9982
2	0.9988	1.0000	0.9976	1.0000	1.0000	0.9964
3	0.9982	1.0000	0.9964	1.0000	1.0000	0.9946
4	0.9976	1.0000	0.9952	1.0000	1.0000	0.9928
5	0.9970	1.0000	0.9940	1.0000	1.0000	0.9910
6	0.9964	1.0000	0.9928	1.0000	1.0000	0.9892
7	0.9958	1.0000	0.9916	1.0000	1.0000	0.9874
329	0.8204	0.9828	0.6730	0.9395	0.9923	0.5521
330	0.8199	0.9827	0.6722	0.9392	0.9922	0.5511
331	0.8194	0.9826	0.6714	0.9389	0.9922	0.5501
332	0.8189	0.9825	0.6706	0.9385	0.9921	0.5491
333	0.8184	0.9824	0.6697	0.9382	0.9920	0.5481
334	0.8179	0.9823	0.6689	0.9379	0.9920	0.5471
335	0.8174	0.9822	0.6681	0.9376	0.9919	0.5461
336	0.8169	0.9821	0.6673	0.9372	0.9918	0.5451
Time (t)	3 EDGs of the same size that equal required load together + 1 redundant EDG of the same size	3 EDGs of the same size that equal required load together + 2 redundant EDG of the same size	3 EDGs of the same size that equal required load together + 3 redundant EDG of the same size	4EDGs of the same size that equal required load together	4 EDGs of the same size that equal required load together + 1 redundant EDG of the same size	4 EDGs of the same size that equal required load together + 2 redundant EDG of the same size
1	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
2	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
3	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
4	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
5	1.0000	1.0000	1.0000	0.9999	1.0000	1.0000
6	0.9999	1.0000	1.0000	0.9999	1.0000	1.0000
7	0.9999	1.0000	1.0000	0.9999	1.0000	1.0000
329	0.8801	0.9775	0.9968	0.8116	0.9537	0.9537
330	0.8795	0.9773	0.9967	0.8108	0.9534	0.9534
331	0.8789	0.9771	0.9967	0.8099	0.9530	0.9530
332	0.8783	0.9769	0.9967	0.8090	0.9527	0.9527
333	0.8777	0.9768	0.9966	0.8082	0.9523	0.9523
334	0.8771	0.9766	0.9966	0.8073	0.9520	0.9520
335	0.8765	0.9764	0.9965	0.8064	0.9516	0.9516
336	0.8759	0.9762	0.9965	0.8056	0.9513	0.9513

Having calculated probability of survival values at t = 336, we can now apply a peak load requirement to each EDG configuration. We use a load profile for three buildings at NPS with a recorded peak load requirement of 1600 kW. To accommodate any power demands beyond the peak load, an additional 25% capacity was added to 1600 kW requirement. This provides us with a peak load requirement of 2MW (recorded peak load +25% additional capacity) of power to three buildings. EDG configurations were then sized based on the peak load requirement and system survivability values determined from Table 3. Figure 24 shows the outputs from the survivability equations for the different compositions of EDGs at t = 336. These survivability numbers will be utilized as a factor in resilience scores determined in a later section.

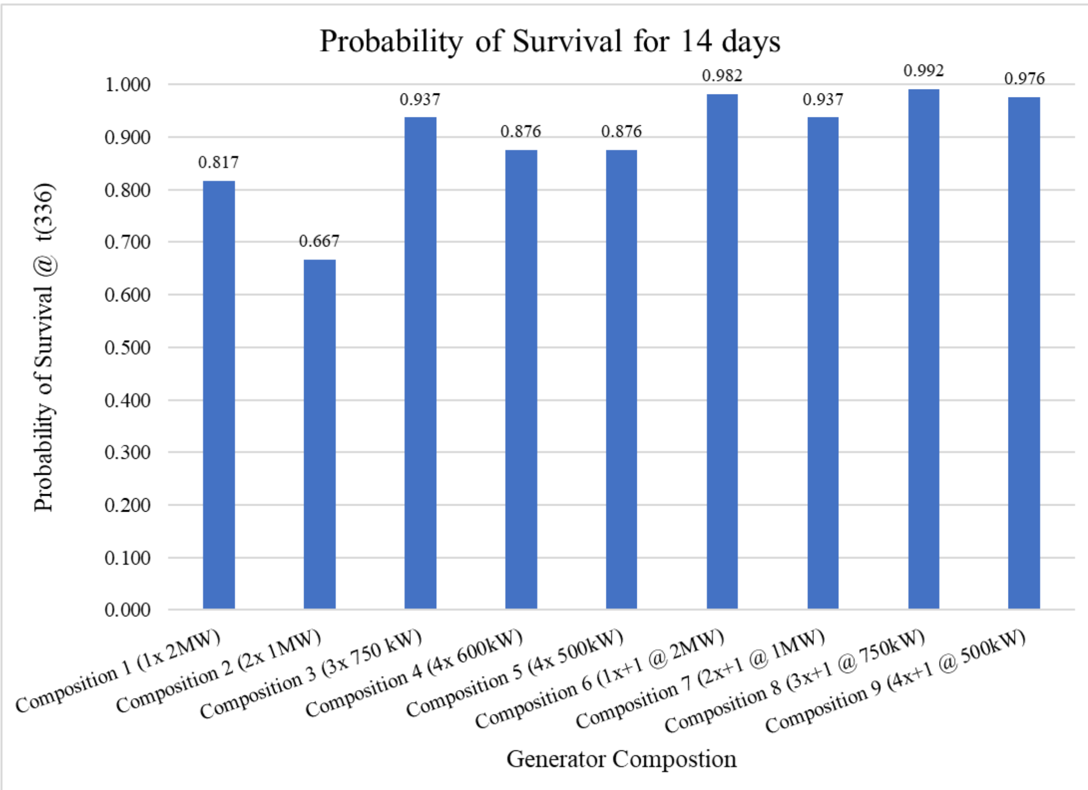


Figure 24. Probability of Survival of EDGs – NPS Case Study.

Of the different compositions in Figure 24, composition 3 and 8 provide the greatest chance of survival over 14 days when compared against the other compositions. If survivability were the only metric factored into the resilience equation or the customer were trying to optimize for the highest survivability number we would recommend this configuration. Survivability is an important metric but is not the only metric factored into our resilience score.

D. RTCL ESTIMATE

RTCL represents a system's ability to retain a capacity at or above its critical load requirement. We calculated RTCL using the probabilities of EDGs failing before t = 336.

RTCL calculations are derived from NPS' calendar year 2019 load data and from each EDG configuration. Figure 25 illustrates the comparative results of nine alternative configurations assessed for their individual RTCL values, using the RTCL equation from Chapter III.

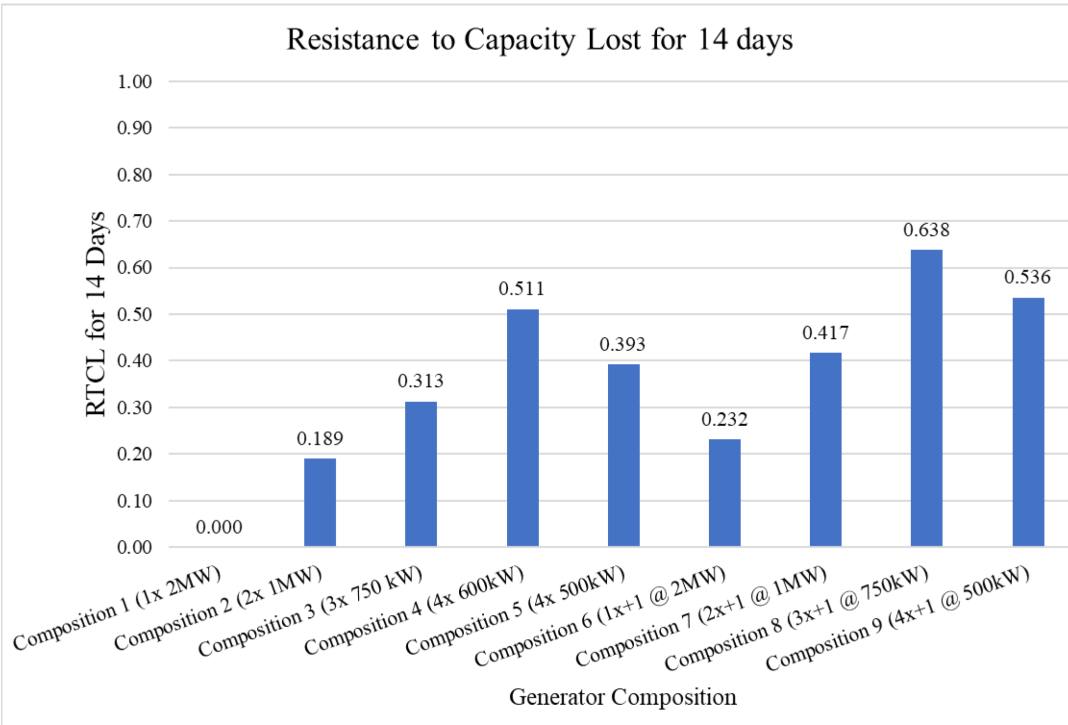


Figure 25. Results of RTCL Calculations.

The RTCL calculations shows that the composition 8 yields the highest value. The RTCL equation favors EDG compositions that have redundancy and that are comprised of smaller generators to meet the peak load. When EDG compositions are made up of smaller EDGs and have redundant standby power, the loss of power is not as drastic when a large EDG fails in a system comprised of a fewer number of largely sized generators. Additionally, EDG configurations made up of many smaller generators enjoy a higher probability that the composition can still meet peak capacity. EDG compositions with fewer and larger EDGs have a higher percentage of lost capacity when an EDG fails in its respective composition.

E. RESILIENCY DESIGN ANALYSIS

Table 4 shows the results of each composition's resiliency score after normalizing the raw data from the three attributes: survivability, RTCL, and fuel consumption, and applying a weighting criteria to each attribute.

Table 4. Weighted Resiliency Matrix.

Attribute	Weight	Composition 1	Composition 2	Composition 3	Composition 4	Composition 5	Composition 6	Composition 7	Composition 8	Composition 9
Probability of Survivability @ 2 weeks	60%	0.824	0.673	0.945	0.883	0.883	0.990	0.945	1.000	0.984
RTCL	30%	0.000	0.297	0.490	0.800	0.615	0.363	0.653	1.000	0.839
Fuel Consumption	10%	0.842	0.936	1.000	0.909	0.974	0.842	0.936	1.000	0.974
Weighted Score (Resilience Score)	100%	**0.578**	**0.586**	**0.814**	**0.861**	**0.812**	**0.787**	**0.857**	**1.000**	**0.940**

Attribute	Weight	Composition 1 (1x 2MW)	Composition 2 (2x 1MW)	Composition 3 (3x 750 kW)	Composition 4 (4x 600kW)	Composition 5 (4x 500kW)	Composition 6 (1x+1 @ 2MW)	Composition 7 (2x+1 @ 1MW)	Composition 8 (3x+1 @ 750kW)	Composition 9 (4x+1 @ 500kW)
Probability of Survivability @ 2 weeks	60%	0.824	0.673	0.945	0.883	0.883	0.990	0.945	1.000	0.984
RTCL	30%	0.000	0.297	0.490	0.800	0.615	0.363	0.653	1.000	0.839
Fuel Consumption	10%	0.842	0.936	1.000	0.909	0.974	0.842	0.936	1.000	0.974
Weighted Score (Resilience Score)	100%	**0.578**	**0.586**	**0.814**	**0.861**	**0.812**	**0.787**	**0.857**	**1.000**	**0.940**

Table 5 shows the resilience scores and LCCs of each composition of generators to show which composition is the most cost-effective way to achieve resilience. LCC compared to resilience score is depicted in the graph below. The compositions highlighted in Figure 26 and Table 5 are solutions on the efficient frontier. These compositions deliver the most cost-effective solutions for resilience. Table 5 compares cost effectiveness for resilience by depicting the cost for each percentage point of resilience. Based on the selected weights of the resilience factors, composition 5 provides the highest value solution, even though this composition does not provide the best resilience score.

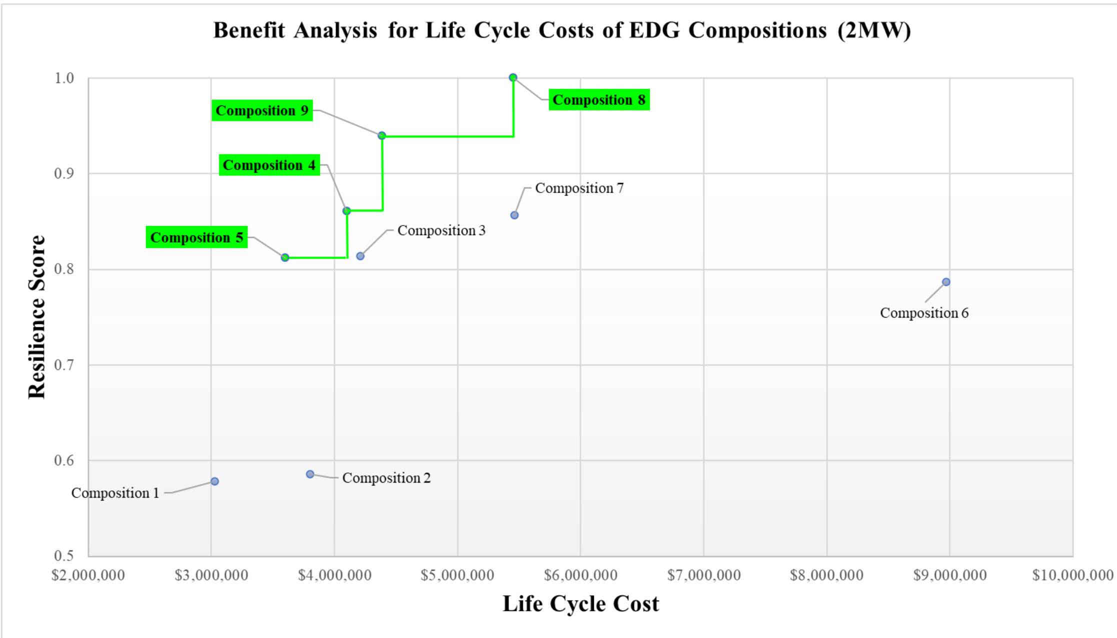


Figure 26. Benefit Analysis for Life-Cycle Costs of EDG Compositions.

Table 5. Breakdown of Resilience Scores and LCC.

Alternative	Resilience Score	Life Cycle Cost	Cost per % of resilience
Composition 1	0.578	$3,024,056	$52,289
Composition 2	0.586	$3,799,871	$64,815
Composition 3	0.814	$4,206,658	$51,681
Composition 4	**0.861**	**$4,099,519**	**$47,628**
Composition 5	**0.812**	**$3,600,576**	**$44,350**
Composition 6	0.787	$8,968,515	$113,927
Composition 7	0.857	$5,459,638	$63,741
Composition 8	**1.000**	**$5,453,944**	**$54,539**
Composition 9	**0.940**	**$4,384,794**	**$46,660**

F. SENSITIVITY ANALYSIS

To determine each variables' sensitivity, an analysis was conducted. The sensitivity analysis isolated survivability, RTCL, and fuel consumption to understand how changes in user's preferences, expressed as weights, change the overall resilience score. Figures 27, 28, and 29 show how the overall resiliency score changes when adjusting each of the three attribute weights from 0%-100%.

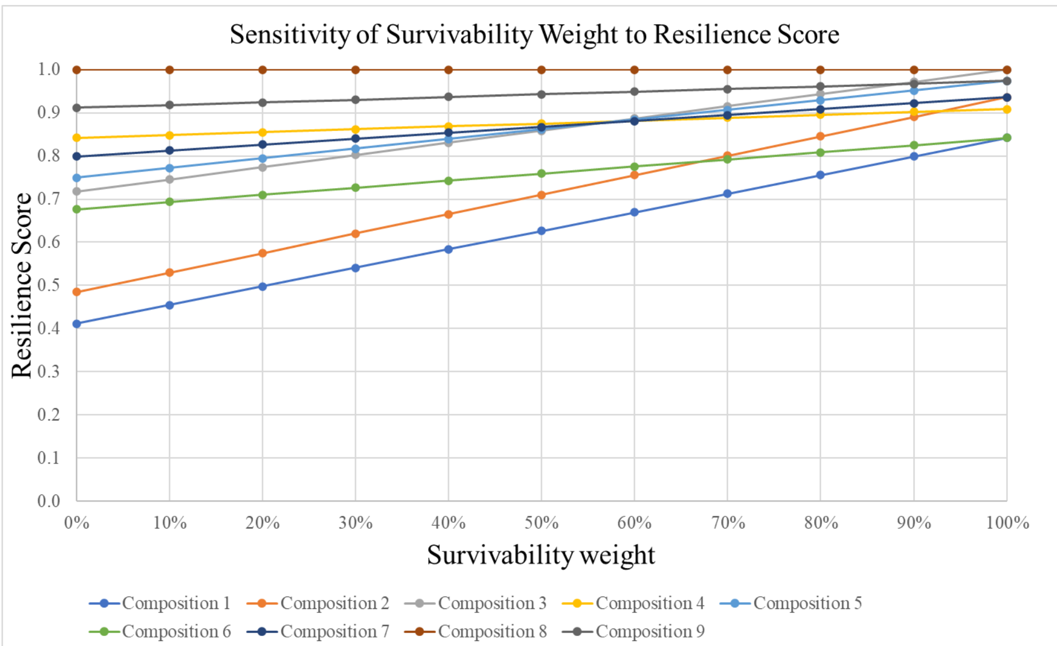


Figure 27. Sensitivity Analysis for Survivability.

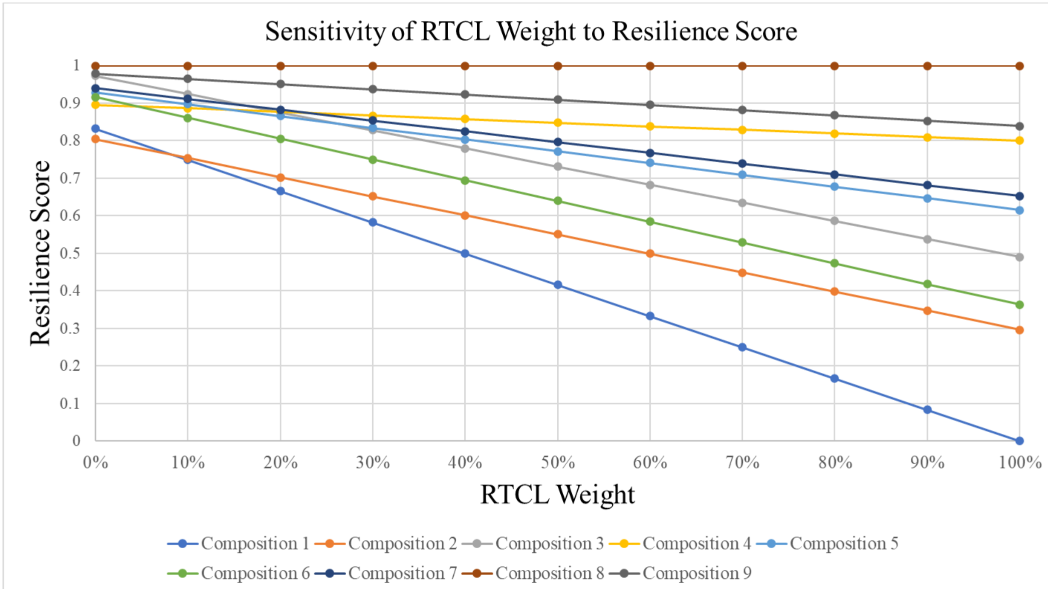


Figure 28. Sensitivity Analysis for RTCL.

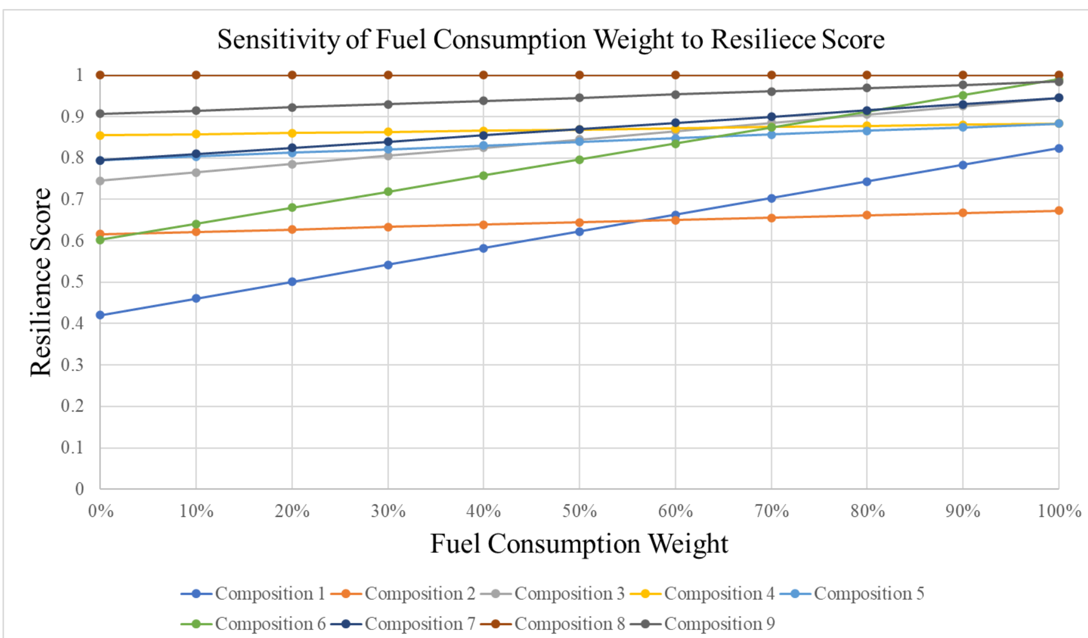


Figure 29. Sensitivity Analysis for Fuel Consumption.

G. CASE STUDY

As the backup diesel generators located at NAVSTA Rota, Spain draw closer to their end of service life, the Rota power manager and commander are seeking recommendations regarding cost and purchasing strategies for their eventual replacement. The installation is seeking solutions that span 30–40 years in support of a new military construction project submission with the goals of energy efficiency, reliability, and resilience.

Chiefly, the installation is interested whether multiple smaller diesel generators will be beneficial in regard to LCCs and installation resilience. The installation's primary source of backup power generation is a centralized architecture consisting of five 2.5MW diesel generators connected in parallel at the installation power plant. Currently, these diesel generators are used as the emergency power system in case of an outage and are used for peak shaving. Rota has an agreement with the Spanish power utility to supply 16MW of power. If demand exceeds 16MW, the utility charges an additional fee for all power over 16MW. The installation is currently in the process of acquiring a 6MW photovoltaic farm that will assist in reducing the overall energy cost to the base and ensuring the total power demanded from the utility remains below 16MW.

Rota has an additional 46 building-tied, stand-alone diesel generators attached to facilities across the installation, including the hospital and the air traffic control tower. For the purposes of this capstone, these building-tied stand-alone diesel generators are considered to be redundant to the centralized power provided by the power station and will not run in parallel during an outage.

1. Demand Assessment

Analysis of the Rota power consumption for 2019 revealed that the average demand was 10,829 kW per day, seen in Figure 30. There are three instances in the data that show power surging to beyond 23MW and almost to 29MW. The team assumed that these were errors in the data because of their short duration and rarity. Thus, the typical max demand is in the mid 17MW range.

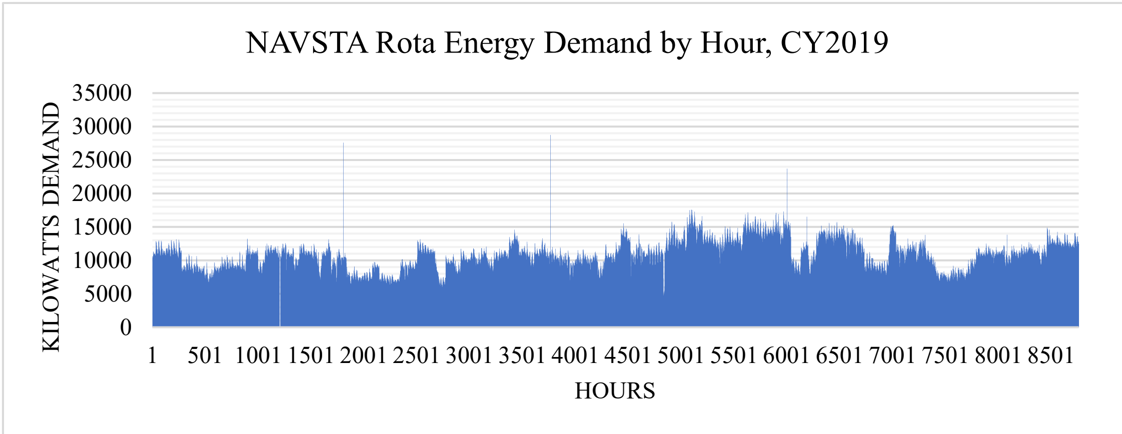


Figure 30. NAVSTA Rota Energy Demand by Hour, Calendar Year 2019.

To find the critical load, the team used information from the Energy Security Assessment Tool to conduct an analysis of the Rota installation. This analysis revealed that the total load capability of the 46 diesel generators is slightly over 6MW. Further examination of the data shows that the EDGs are oversized by approximately 100%, with the actual priority load demand estimated to be somewhere between 3 and 4MWs (Ronald Giachetti, unpublished data, May 3, 2021).

2. Problem Solution through Infrastructural Modifications

NREL's finding that a large number of networked EDGs could be used to significantly increase an installation's energy resilience was a major driver for this capstone (Marqusee, Ericson, and Jenket 2020). It examined the statistical likelihood of a network of EDGs successfully supporting the critical load throughout a power disruption without examining the size of the EDGs. The EDG sizing is a key part of analysis because most building-tied diesel generators operate at a low voltage, typically 480v. Conversely, EDGs required to transmit over long distances commonly use medium voltage because low voltage cabling is cost prohibitive. This led to the exploration of two medium voltage options when examining networked EDGs: EDGs can be tied directly into the installations distributions system, which commonly utilizes 12.47kilovolt (kV): or alternatively, a redundant network of 4160v distribution lines can be installed and tied to the EDGs.

a. *Option 1: EDG Tie-in*

When we examined the first option, we found that this solution was constrained by engine size in EDGs. Specifically, distribution lines sized at 12.47kV, which are considered medium voltage, require large engine EDGs, i.e., above 1500 kW. Caterpillar provided the reasoning for this sizing requirement explaining that EDGs below the 1500 kW threshold do not possess engines large enough to run the 12.47kV rotor necessary to push medium voltage (D. Lewis, email to author, September 3, 2021). On NAVSTA Rota, all EDGs that are tied to buildings are below the 1500 kW size. Because they do not possess a large enough engine to utilize the medium voltage rotor, they cannot connect into the medium voltage distribution lines. This makes connecting the current inventory of diesel generators to the electrical distribution system infeasible.

b. *Option 2: Distribution Network Augmentation using 4160v Cable*

The second option is to install a secondary distribution network that would mirror the 12.47kV distribution network already in place in order to transmit emergency power across the base from the existing building-tied EDGs. This option must account for the cost of extensive distribution cabling. Siemens estimates that the cost to utilize 480v cabling for 100 feet is nearly ten times more than the cost to utilize medium voltage 4160v (Siemens 2018). In light of this observation, the use of 4160v cable seems the economical choice between the two lines. This type of cable would require a retrofit for every EDG on NAVSTA Rota, enabling them to produce medium voltage power. While a redundant distribution network for the EDGs would strengthen the security and redundancy of the installation energy system, consultation with generator manufacturers revealed feasibility concerns. Specifically, Cummins expressed doubts about whether paralleling EDGs from different manufactures and ages would be feasible or cost effective (Brian Pumphrey, Zoom call, September 3, 2021). As such the team estimates this option would not be economically feasible and would be highly disruptive to base operations.

3. Problem Solution Using Replacement EDG Architecture

The feasibility limitation of utilizing the existing distribution network or creating a redundant network significantly influenced our selection of EDG compositions when examining the centralized and decentralized architectures. Each of these architectures has benefits and drawbacks. We examined the survivability, RTCL, and the fuel consumption of multiple compositions for both architectures and assessed the qualitative benefits and drawbacks to each.

a. *Replacement Using a Centralized Architecture*

The first architecture examined was the current centralized power posture at Rota. Three centralized alternatives were assessed for cost and resiliency. The alternatives' compositions are, three 3500 kW EDGs, four 2500 kW EDGs, and seven 1500 kW EDGs. These alternatives are compatible with the existing power distribution network on the base and provide over 10MW of power.

b. *Replacement Using a Decentralized Architecture*

The second architecture examined was a decentralized strategy using clusters of smaller EDGs, with each cluster supporting multiple buildings but were not tied together. We assessed clusters comprised of varying numbers of EDG but limited EDG size to the 500 kW and 600 kW range as these sizes were found to be the most economical. The total power provided by each of the cluster configuration was equal to or exceeded 10MW to ensure an equal comparison however, these sizes are not compatible with existing distribution lines.

c. *Comparison of Centralized and Decentralized Architectural Solutions*

Having developed centralized and decentralized architectures, we then applied the methods outlined in Chapter III to draw comparisons between architectures and their respective compositions. Table 6 shows the raw data from the calculations for comparison and shows the comparative results.

Table 6. Raw Data for EDG Architectures and Compositions.

Alternative		LCC	Probability of Survival (14 Day)	RTCL (14 Day)	Fuel Consumption (GAL 14 Day)
Composition A (Decentralized)	3x 3500kW DG	$19,074,804	0.545	0.260	220080
Composition B (Decentralized)	4x 2500kW DG	$17,736,579	0.445	0.441	213696
Composition C (Decentralized)	7x 1500kW DG	$18,484,663	0.658	0.793	231706
Composition D (Centralized)	3 Clusters (4x 600kW) + 1 Cluster (5x 600kW)	$17,987,664	0.858	0.976	236880
Composition E (Centralized)	3 Clusters (6x 600kW)	$18,777,612	0.732	1.042	216048
Composition F (Centralized)	5 Clusters (3x 600kW) + 1 Cluster (2x 600kW)	$18,987,664	0.565	0.976	239904
Composition G (Centralized)	7 Clusters (3x 500kW)	$20,560,974	0.937	1.037	242726
Composition H (Centralized)	5 Clusters (4x 500kW)	$18,827,325	0.876	0.935	231168
Composition L (Centralized)	4 Clusters (5x 500kW)	$18,927,325	0.806	0.935	231168

This raw data was scaled between 0 and 1 as described earlier and placed into a weighted matrix in Table 7 where each of the categories of survivability, RTCL, and fuel consumption can be weighted by the customer. For this analysis, $Survivability = 60\% \mid RTCL = 30\% \mid Fuel\ Consumption = 10\%$ were selected as the weighting criteria for the resilience score attributes. Table 7 depicts the results from this weighting approach.

Table 7. Weighted Resilience Matrix.

Attribute	Weight	Composition A	Composition B	Composition C	Composition D	Composition E	Composition F	Composition G	Composition H	Composition L
Probability of Survivability @ 2 weeks	60%	0.582	0.475	0.702	1.000	0.935	0.860	0.916	0.781	0.603
RTCL	30%	0.250	0.423	0.761	0.995	0.897	0.897	0.937	1.000	0.937
Fuel Consumption	10%	0.971	1.000	0.922	0.880	0.924	0.924	0.902	0.989	0.891
Weighted Score (Resilience Score)	100%	**0.521**	**0.512**	**0.742**	**0.987**	**0.922**	**0.877**	**0.921**	**0.867**	**0.732**

d. *Comparison Results and Conclusions*

Our analysis of the centralized vs decentralized architecture revealed that the decentralized architecture was the most resilient model in the analysis. While the centralized architecture model had the lowest overall LCC cost, we are seeking the most cost-effective balance between LCC and resilience, the team examined the cost against resilience in Figure 31. Figure 31 and Table 8 highlight the efficient frontier for cost effective resiliency solutions when analyzing EDG compositions. It is up to the stakeholder to determine the criteria for which they intend to purchase. There are many options for compositions of EDGs that could have been evaluated, but it's the process by which cost efficiency is achieved when calculating resilience with this approach.

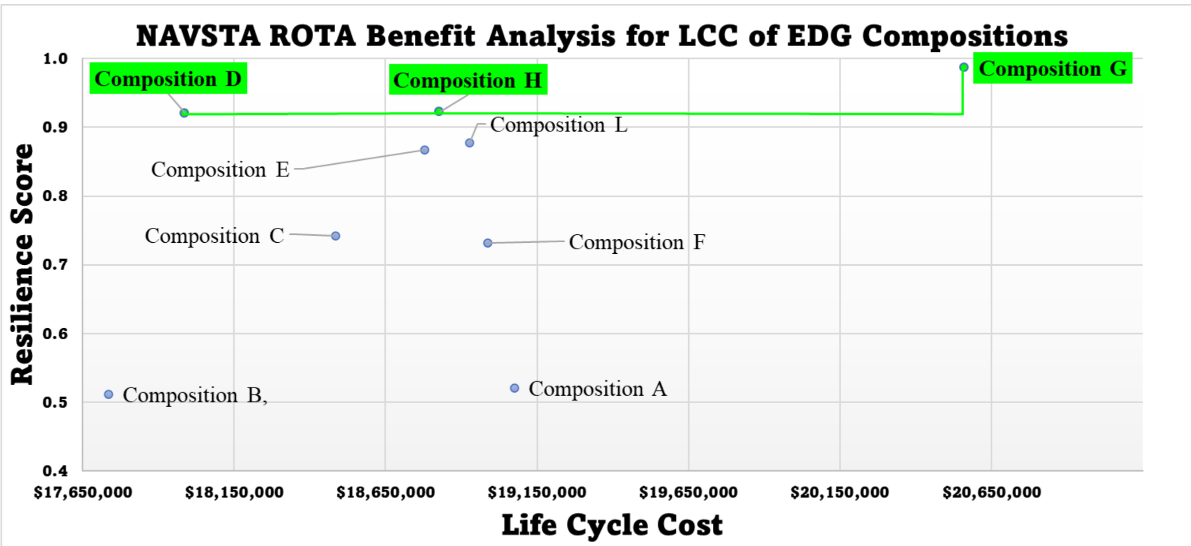


Figure 31. NAVSTA Rota Benefit Analysis.

Table 8. Solution Space for Comparison of Resilience and LCC.

Architecture Type	Alternative	Resilience Score	Life Cycle Cost	Cost per % of resilience
Centralized	Composition A	0.521	$19,074,804	$366,134
Centralized	Composition B	0.512	$17,736,579	$346,317
Centralized	Composition C	0.742	$18,484,663	$249,234
Decentralized	**Composition D**	**0.921**	**$17,987,664**	**$195,329**
Decentralized	Composition E	0.867	$18,777,612	$216,502
Decentralized	Composition F	0.732	$18,987,664	$259,301
Decentralized	**Composition G**	**0.987**	**$20,560,974**	**$208,392**
Decentralized	**Composition H**	**0.922**	**$18,827,325**	**$204,107**
Decentralized	Composition L	0.877	$18,927,325	$215,716

H. CHAPTER SUMMARY

This chapter discussed the processes and reasoning for choosing the methods and approach we used and applied to two case studies, one at NPS, Monterey, California, and the other at NAVSTA Rota. We developed a resiliency metric for different compositions and architectures of EDGs and compared those metrics to cost, which tells the stakeholder the most cost-effective EDG solution for purchasing energy resilience. Using these findings, customers are able to make decisions for their specific needs to guide them in their purchasing decision for EDGs as a standby energy source.

V. CONCLUSION

This chapter summarizes the findings of this capstone. From our literature review and analysis of diesel generator architectures, we made several findings. Regarding diesel generator architectures, the key finding is that decentralized architectures are the most cost-effective strategy for enhancing system resilience while the centralized architecture was the least expensive in LCC but at the expense of degrading system resilience. We also developed a general methodology and step-by-step approach to assessing and developing backup power systems with an emphasis on resilience and LCC. In doing so, we provide installation energy mangers with an approach to developing diesel generator replacement strategies supporting DOD and DON energy goals. Lastly, we identified knowledge and capability gaps for future work.

A. SUMMARY OF FINDINGS

The decentralized architecture is the most cost-effective strategy for resilience, but it does have its drawbacks. Decentralized architectures developed in this capstone use smaller EDGs in clusters to power a group of adjacent buildings. Our findings suggest that resilience and fuel efficiency benefits increase as higher numbers of diesel generators in an EDG architecture share the load.. This is because the system can more effectively tailor the power output against a given power need. However, resilience and efficiency benefits are subject to limitations. For example, in the case of NAVSTA Rota, EDG size cannot drop below a specific threshold without requiring extensive and cost-prohibitive modifications to the current power distribution system. To use the utility distribution network at 12.47kV, a generator must be sized to 1500 kW at a minimum to drive the required rotor. The use of EDGs below the 1500 kW size in an installation-wide network would require the installation of 4160v cabling as an augmentation to the 12.47kV cabling already installed. Additionally, to utilize the existing EDGs, each generator would need to be retrofitted to transmit power at 4160v and updated with current digital controllers. We estimated that such a modification of existing infrastructure would be prohibitively expensive to implement and highly disruptive to base operations. As such, we explored alternative architectures to most effectively utilize the cost-effective EDGs under the 1500 kW level in a decentralized manner.

1. The Decentralized Architecture Argument

In our decentralized architecture, clusters of EDGs are considered “islanded” and therefore are not connected to one another nor to any other power generating network. This works as both a benefit and a drawback. One benefit is that each cluster is independent from the next and, as such, can operate most efficiently for the demand from the connected buildings. Another benefit is that each cluster represents a power requirement distinct from others. As a result, generator sizing is tailorable to each cluster’s power requirement, enabling every cluster to be assembled for maximum efficiency against its respective power requirement. From an energy security perspective, this ensures that weather, accidents, or intentional acts have a much lower probability of disrupting the entire emergency power system. Given of these benefits, the decentralized architecture is especially useful for installations that have groups of buildings that are geographically dispersed or small groups of critical facilities.

A drawback to this architecture lies in its independence or lack of mutual support. For example, if a cluster loses part or all of its generator capacity, the demand cannot be transferred to another cluster. From a power manager’s perspective, this reduces flexibility in powering critical systems. Another drawback stems from infrastructural challenges. The decentralized cluster concept requires installation of cabling from the EDGs to all of its supported buildings. Installation of cabling sounds relatively straightforward, but the scale and variability of such an installation may prove expensive and time consuming. Given these drawbacks, the decentralized architectures may not be ideal for larger installations, or projects requiring many EDG clusters.

2. The Centralized Architecture Argument

The centralized architecture was the least expensive in LCC but had a much lower resilience score when compared to decentralized models. However, a centralized architecture has many advantages. To begin with, it has the least number of generators to maintain, reducing the requisite personnel and time to ensure adherence to a proper maintenance schedule. A centralized architecture can also be easily housed within a single building that protects the EDGs from the elements, increasing their lifespan. The co-location of EDGs and the personnel to monitor and maintain them also reduce the time between failure and the start of repairs because of their proximity. This is particularly beneficial for EDGs that are supporting critical or priority loads because they must be repaired and brought back online quickly in the event of a failure. Additionally, architectures comprised of a smaller number of EDGs have a lower statistical probability of failure as a system with fewer components lowers the overall probability of failure. Given these benefits, the centralized architecture is especially useful for installations that prioritize maintainability over resilience.

A centralized architecture is not without cost, however. While using fewer EDGs translates to a lower statistical probability of failure when utilized in the centralized architecture, any failure results in a significant loss of total capacity. For example, the loss of a single generator out of a four-generator configuration would result in a 25% loss of capacity. From an energy security perspective, the centralized architecture also represents a vulnerability. The co-location of all backup power generation creates a single high value target the destruction of which would result in a complete collapse of energy resilience for an installation, whereas a decentralized architecture reduces vulnerability by dispersing backup power generation

3. Forecasting Capacity

The DON (2020) *Installation Energy Resilience Strategy* states "installation energy plans shall account for the power and transmission demands needed to support the introduction of new weapons systems" (p. 7). Sizing EDGs for today's demand while considering the capability requirements of the future is difficult. Oversizing gensets to meet future loads increases the likelihood of underloading, as indicated by our research. The data from this capstone suggests that utilizing numerous smaller EDGs will provide the capability to add additional EDGs in the future, as the need for capacity increases, at a much more economical scale. This will ensure that a properly sized backup system is utilized for the current load without sacrificing the flexibility to expand as needed.

B. RECOMMENDATIONS

Having conducted a literature review and analysis of diesel generator architectures, we developed a number of recommendations for implementation when considering backup power system upgrade or replacement. Chiefly, we determined that a structured procedural approach to planning was critical in determining installation needs while simultaneously supporting DOD and DON energy goals. To assist installation energy managers in this process, we proposed a step-by-step process. Moreover, we applied the general methodology outlined in Chapter III to a case study for NAVSTA Rota, Spain; this section summarizes the findings of that analysis and provides recommendations regarding replacement considerations for NAVSTA Rota.

1. Guidance for Installation Energy Managers

When assessing EDG backup power generation, it is critical that the installation energy manager consider the circumstances unique to their installation. We recommend that installation energy managers follow a deliberate process when analyzing their diesel generator standby power systems. There is not a single correct architecture, nor composition, that will fit all situations and locations. Each installation and requirement are unique, as emphasized in *Power Begins at Home: Assured Energy for U.S. Military Bases* which stated, "when you've seen one base, you've seen one base" (Marqusee et al. 2017, p. 4). The steps developed in this capstone represent a deliberate process that an installation energy manager can use to frame their respective problem and develop cost-effective energy solutions that also consider energy resilience.

a. ***Step 1. Gather information***

To frame an installation's backup energy problem and develop cost-effective solutions that also consider energy resilience, it is necessary to first gather information. We recommend the following information be gathered before proceeding to the next step.

1) Identify and map critical and priority buildings. Installations may differ on which buildings they consider priority or critical, so it is necessary for the installation energy manager to work with stakeholders to identify which buildings are considered critical and priority. Identifying these buildings and

their locations is crucial for determining the most beneficial architecture for the installation.

2) Capture load data for the installation and individual critical and priority buildings if possible. This will ensure that any solution will be optimally sized for the demand produced, whether that be for the entire base or for a group of buildings.

3) Identify existing systems and infrastructure. This means determining what systems are already on hand, how old they are, and what their general condition is. When examining the installation's requirement for EDGs, the power manager should inventory all energy resources to capture a comprehensive understanding of the base's energy security. This analysis will include any energy resources that can provide power during an outage, including battery energy storage systems, solar, or wind. If a solar array cannot provide power during an outage, it should not be considered in the standby power resilience. Finally, this step should include an examination of any additional systems planned for the future. The length of time until a new system will be operational should be considered when examining future systems as part of the installation energy security. Whether a new system will be available in 12 months, 5 years, or 10 years will drive how robust or comprehensive the diesel generator network will need to be. This will require good judgement and risk management by the installation power manager.

b. *Step 2. Analyze Architectures*

The next step is to analyze which architectures are feasible and realistic. Installation load demand will be a significant driver in determining which architecture will be most appropriate. Geographical dispersion will be another major driver in the analysis. Once the critical and priority buildings are mapped, we recommend that the geographical spread and dispersion of the buildings be examined. The geographical spread of the buildings may inform whether a centralized architecture or decentralized architecture suits the installation's needs more appropriately. If either architecture is feasible, this provides more flexibility in balancing cost and reliability.

c. *Step 3. Determine best location for generators*

Once a centralized or decentralized architecture is selected, the next step is to determine the best locations for the EDG architecture. Utilizing the map of critical and priority facilities, the power manager can select the location/s where the EDGs will most effectively support the demand. The number of possible locations will most likely be reduced by available space, access to the power distribution network, distance to the facilities, number of facilities served, or unit and host nation requirements.

d. *Step 4. Assess demand and EDG requirement*

With the EDG locations selected, assess the peak load that the buildings attached to the node will require. We recommend using no less than 12 months of hourly load data as this will provide a load profile comprising all seasonal changes. Moreover, we recommend incorporating a buffer into the peak load. This capstone utilized a 25% buffer, however circumstances may differ for other case studies. Using the peak load and buffer, estimate the required number of EDGs. For the centralized architecture, if the power manager has the ability to selectively power critical facilities, combine the total required power for all critical facilities plus buffer. This should give a list of various EDG configurations to start with. Our research showed that the 500 and 600 kW range for smaller loads was a good starting point and 1500 kW and 2500 kW was the best starting point for high loads.

e. *Step 5. Analyze Cost and Resilience analysis of alternatives*

Next, conduct a quantitative analysis of the configurations, using the cost and resilience analysis methods outlined in Chapter III. This will show if there are any tradeoffs between cost and resilience that can be captured specific to the installation's unique situation.

f. *Step 6. Conduct Reassessment with proposed solution*

Reassess the proposed solution to ensure that it meets the energy requirements and increases the installation's energy security. Note, this is not a sensitivity analysis. The sensitivity analysis exists as part of the cost and resilience analysis methods outlined in Chapter III.

2. Recommendation for NAVSTA Rota, Spain

The recommended solution for NAVSTA Rota is contingent on whether the installation will require the diesel generators to provide peak shaving. The team examined the specific situation at NAVSTA Rota in depth and had to make some assumptions because of incomplete data.

If the base requires peak shaving capability from the diesel generators, even with the addition of the solar farm, a centralized architecture is the logical and recommended solution. To use the legacy 12.47V distribution system provided by the grid utility, any EDG must be at a minimum of 1500 kW in size. The analysis indicates that smaller but more numerous EDGs are more resilient than fewer larger ones. Our recommendation is to examine the use of seven 1500 kW diesel generators in place of the existing 2.5MW EDGs at the power station. While the 1500 kW option costs nearly $750,000 dollars more over 25 years, it provides 23% higher resilience according to our metrics.

If the installed solar farm fulfills the peak shaving requirement, then the most cost-effective and resilient solution would be to utilize the decentralized architecture model. We recommend exploring the utilization of 600 kW EDGs as the most cost-effective model. While the decentralized model does not have the lowest LCC, the cost for the level of resilience is lower than the centralized model. The decentralized model provides direct power to critical facilities around the installation, improving redundancy and resilience when compared to the centralized model. Under a centralized architecture, if the utility distribution networks are disrupted for any reason, power would not make it to the critical facility. The capstone assumes that for this reason, utilizing a centralized network would cost the DOD more money over the long term as tenet units purchase stand-alone systems to power the building in case of a disruption to the power station or the utility grid, which represents the current posture of energy security at NAVSTA Rota.

Implementation of a decentralized architecture deters tenet units from purchasing additional energy assets. The decentralized model not only replaces the current power station gensets but also the 46 stand-alone systems that are building-tied across the installation. These EDGs could be phased out or resold to recoup funding for replacement systems. Additionally, utilizing the energy security steps outlined in section 1 the NAVSTA Rota power manager can reassess which buildings require standby power and which do not.

C. FUTURE WORK

This section outlines several areas of study that were outside the scope of the capstone but have significant impacts upon the future of installation security energy studies and analysis. The three areas of future study are the use of smart systems for installation energy management, the reuse of existing assets to improve installation energy security, and an examination of the UFC requirement for backup power generation.

1. Smart Systems

An emergent technology that may prove valuable in the future of energy security and resilience is smart systems. These systems monitor energy consumption and system efficiency in real time. This capstone did not incorporate the use of smart systems in our analysis, but much of the material in our literature review referenced their use and integration into power generation systems. The utilization of smart systems to monitor real-time utilization of energy and the ability to control load shedding from a central control point allows for maximum flexibility. Moreover, they could provide a significant advantage when utilizing a centralized power strategy combined with the ability to selectively shed specific buildings when critical and non-essential facilities are intermixed, as is standard on most military installations. A cost-benefit analysis for the use of smart devices across the entirety of installation would provide good insight for future development of the DOD smart grids and microgrid work.

2. Use of Existing Infrastructure

While connecting all of the existing generators into a single installation-wide network was considered unrealistic by the engineers due to the differences in age, size, and manufacturer, the team was not able to explore the concept of utilizing existing gensets rearranged into power nodes in the decentralized model. This concept would take oversized building-tied EDGs and rearrange them into decentralized power nodes as explored in this capstone. Doing so would potentially capitalize on existing infrastructure while realizing significant cost savings by reducing the requisite cost of acquisition. There are several aspects to this concept that would need to be explored in detail, including what would be required to retrofit existing generators with updated digital control modules as well as the cost to disconnect, move, and reconnect them in a new location.

3. United Facilities Criteria

When examining the concept of centralized power generation, a question arose from the analysis of the UFC. Would the requirement to have backup power generation to critical facilities be satisfied by a centralized power resource or would these buildings still require an additional backup power source tied directly to the building? The capstone was unable to answer this question, and this aspect of the UFC should be re-examined and clearly articulated as the utilization of microgrids and distributed energy resources increases in frequency across military installations.

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