2022-12

MOVEABLE, DEPLOYABLE MICROGRID ANALYSIS

Drake, Jordan M.; Hardman, Graham D.; Kimble, William C.; Rodriguez, Andrea; Smith, Bradley I.

Monterey, CA; Naval Postgraduate School

https://hdl.handle.net/10945/71597

NAVAL
POSTGRADUATE
SCHOOL

MONTEREY, CALIFORNIA

SYSTEMS ENGINEERING
CAPSTONE REPORT

MOVEABLE, DEPLOYABLE
MICROGRID ANALYSIS

by

Jordan M. Drake, Graham D. Hardman, William C. Kimble,
Andrea Rodriguez, and Bradley I. Smith

December 2022

Advisor:	Douglas L. Van Bossuyt
Co-Advisor:	Anthony G. Pollman
Co-Advisor:	Corina L. White

Approved for public release. Distribution is unlimited.

THIS PAGE INTENTIONALLY LEFT BLANK

REPORT DOCUMENTATION PAGE	*Form Approved OMB No. 0704-0188*

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington, DC 20503.

1. AGENCY USE ONLY *(Leave blank)*	**2. REPORT DATE** December 2022	**3. REPORT TYPE AND DATES COVERED** Systems Engineering Capstone Report

4. TITLE AND SUBTITLE MOVEABLE, DEPLOYABLE MICROGRID ANALYSIS	**5. FUNDING NUMBERS**
6. AUTHOR(S) Jordan M. Drake, Graham D. Hardman, William C. Kimble, Andrea Rodriguez, and Bradley I. Smith	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000	**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A	**10. SPONSORING / MONITORING AGENCY REPORT NUMBER**

11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release. Distribution is unlimited.	**12b. DISTRIBUTION CODE** A

13. ABSTRACT (maximum 200 words)

This report focuses on the assessment of the feasibility of Moveable, Deployable Microgrids (MODEMs) from an interoperability and sustainment perspective as an alternative solution to traditional backup power methods aimed at bringing critical loads back online after installation microgrid failures or operational energy needs. Prior research into microgrid solutions by MAJ Daniel Varley in his paper “Feasibility Analysis of a Mobile Microgrid Design to Support Department of Defense (DOD) Energy Resilience Goals” identified MODEM as a potential solution. This report utilized the work done by MAJ Varley and further assesses system feasibility.

Base and operational energy managers will benefit from MODEMs by having access to multi-energy source systems that are both easily moveable and relatively simplistic in design. As concerns surrounding energy resiliency of defense critical infrastructure by both the DOD and Department of Energy (DOE) mount, as expressed in a March 2022 report by the Electricity Advisory Committee (EAC) titled “Strengthening the Resilience of Defense Critical Infrastructure,” there is a push to identify cost-effective solutions that utilize alternative energy sources in order to improve the overall resiliency of this infrastructure. The MODEM system has the potential to be a viable solution to the resiliency problem.

14. SUBJECT TERMS microgrids, nanogrids, renewable energy, energy resilience, electricity infrastructure, defense critical electrical infrastructure, systems engineering, Department of Defense, DOD, feasibility and interoperability, sustainment engineering	**15. NUMBER OF PAGES** 149
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT Unclassified	**18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT** UU

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18

THIS PAGE INTENTIONALLY LEFT BLANK

MOVEABLE, DEPLOYABLE MICROGRID ANALYSIS

Jordan M. Drake, Graham D. Hardman, William C. Kimble,
Andrea Rodriguez, and Bradley I. Smith

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN SYSTEMS ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL
December 2022

Lead Editor: Andrea Rodriguez

Reviewed by:

Douglas L. Van Bossuyt Advisor	Anthony G. Pollman Co-Advisor
Corina L. White Co-Advisor	

Accepted by:
Oleg A. Yakimenko
Chair, Department of Systems Engineering

THIS PAGE INTENTIONALLY LEFT BLANK

ABSTRACT

This report focuses on the assessment of the feasibility of Moveable, Deployable Microgrids (MODEMs) from an interoperability and sustainment perspective as an alternative solution to traditional backup power methods aimed at bringing critical loads back online after installation microgrid failures or operational energy needs. Prior research into microgrid solutions by MAJ Daniel Varley in his paper “Feasibility Analysis of a Mobile Microgrid Design to Support Department of Defense (DOD) Energy Resilience Goals” identified MODEM as a potential solution. This report utilized the work done by MAJ Varley and further assesses system feasibility.

Base and operational energy managers will benefit from MODEMs by having access to multi-energy source systems that are both easily moveable and relatively simplistic in design. As concerns surrounding energy resiliency of defense critical infrastructure by both the DOD and Department of Energy (DOE) mount, as expressed in a March 2022 report by the Electricity Advisory Committee (EAC) titled “Strengthening the Resilience of Defense Critical Infrastructure,” there is a push to identify cost-effective solutions that utilize alternative energy sources in order to improve the overall resiliency of this infrastructure. The MODEM system has the potential to be a viable solution to the resiliency problem.

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

LIST OF FIGURES

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF TABLES

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF ACRONYMS AND ABBREVIATIONS

AC	Alternating Current
Ao	Operational Availability
AoA	Analysis of Alternatives
BESS	Battery Energy Storage System
CONOPS	Concept of Operations
COTS	Commercial-Off-the-Shelf
DC	Direct Current
DCEI	Defense Critical Electrical Infrastructure
DER	Distributed Energy Resource
DOD	Department of Defense
DOE	Department of Energy
EAC	Electricity Advisory Committee
EDG	Emergency Diesel Generator
GHI	Global Horizontal Solar Irradiance
ICD	Interface Control Document
INCOSE	International Council on Systems Engineering
IRA	Inflation Reduction Act
ISO	International Standards Organization
ITC	Investment Tax Credit
JCIDS	Joint Capabilities Integration and Development System
KPP	Key Performance Parameter
KSA	Key System Attribute
LCC	Life-Cycle Costs
LCCA	Life-Cycle Cost Analysis
LORA	Level of Repair Analysis
LSCO	Large Scale Combat Operations
MBSE	Model-Based Systems Engineering
MMA	Multi-MODEM Architecture

MODEM	Moveable, Deployable Microgrid
MOE	Measure of Effectiveness
MOP	Measure of Performance
MSOSA	Magic Systems of Systems Architect
MTBF	Mean Time Between Failure
MLDT	Mean Logistics Delay Time
MTTR	Mean Time to Repair
NAVFAC	Naval Facilities Engineering Systems Command
NIST	National Institute of Standards and Technology
NPS	Naval Postgraduate School
NSC	Net Surplus Compensation
OEM	Original Equipment Manufacturer
O&S	Operations and Sustainment
PPE	Personal Protective Equipment
PTC	Production Tax Credit
PV	Photovoltaic Array
RBD	Reliability Block Diagram
RM&A	Reliability, Maintainability, and Availability
ROI	Return on Investment
SE	Systems Engineering
SIOH	Supervision Inspection and Overhead
SIR	Savings to Investment Ratio
SoS	System of Systems
SPV	Single Present Value
StRS	Stakeholder Requirements Specification
SysML	Systems Modeling Language
TriCon	Triple Container
UPV*	Modified Uniform Present Value
US	United States
WTP	Water Treatment Plant

EXECUTIVE SUMMARY

Energy resilience is becoming more important to the Department of Defense (DOD) due to DOD's increasing reliance on technology. This increasing reliance on the availability of power to operate critical loads represents a potential risk adversaries could target to weaken the DOD's ability to operate both at DOD installations and in combat operations. Recent research conducted at Naval Postgraduate School (NPS) by MAJ Daniel Varley introduced the idea of using Moveable, Deployable Microgrids (MODEM) to support DOD critical loads as a backup source of power during periods of electrical service interruption (Varley, Van Bossuyt, and Pollman 2022). The proposed MODEM system would provide a mobile "nanogrid" to power critical loads during periods of power interruption by utilizing a combination of solar energy and diesel generators. The system is designed so that all components can fit into a single triple container (TriCon) storage unit and be easily transported to the site of the critical load.

The MODEM team capstone project aimed to continue the work of MAJ Varley and provide additional feasibility analyses of the system through the development of a Systems Modeling Language (SysML) model and conducted analyses to determine the acquisition, Life-Cycle Costs (LCC), potential life-cycle energy savings for MODEM units, and safety protection for installation and implementation analysis. Additionally, support costs were evaluated through a Reliability, Maintainability, and Availability (RM&A) analysis (Varley, Van Bossuyt, and Pollman 2022). To achieve this goal, the MODEM team developed a tailored Systems Engineering approach, which consisted of six phases: project planning, mission analysis, stakeholder needs and requirements decomposition, system requirements definition, architecture and design definitions, and the project's system analysis processes. The team also defined the project's constraints, assumptions, and research questions to help focus the scope of the project. Additionally, throughout the project the team identified risks and safety considerations for the system.

Extensive research focused on microgrids, and the implementation of the system components fed the development of the MODEM system model. The MODEM system model provides a baseline for future projects to start from that defines the MODEM

Measures of Effectiveness (MOEs), Measures of Performance (MOPs), stakeholder needs, system, subsystem, and component requirements, and system logical, functional, and physical architectures. The model was developed utilizing the MODEM team's current understanding of the system and is designed so that it may be iteratively refined as new information is learned through further research and development.

The system analysis processes included analyses on system interoperability, operations and sustainment planning, performance analysis, and life-cycle cost analysis (LCCA). The system interoperability analysis focused on identifying the external and internal interfaces of the MODEM system. This analysis helped the team to determine interface requirements and identify additional physical components necessary to integrate the system. Through this analysis the team was able to determine the need for a direct current (DC) to alternating current (AC) inverter, combiner box, electrical bus, and charge bus components internal to the MODEM system, which are necessary to deliver the generated power to the critical load. The external interfaces necessary to integrate the MODEM to the critical load will vary depending on the load itself.

The operations and sustainment planning focused on two use cases: continuous use and service interruption. The continuous use case was assessed to show the system's reliability of the span of a year, while the service interruption use cases only simulated a system utilization of 12 hours per day over 14 days per the prior research and use cases identified by MAJ Varley's research (Varley, Van Bossuyt, and Pollman 2022). Through the reliability analysis, the team was able to verify the system requirements for reliability and sustainment. The results of the reliability analysis ultimately found that the MODEM system had an overall system reliability of 92% for the service interruption use case and 1% for the continuous use case. The emergency diesel generator was found to be the biggest determinant of system reliability, and the prolonged operation of the generator over the duration of the continuous use case caused a drastic reduction in overall system reliability. These results indicate that the MODEM system meets the desired reliability requirements for the service interruption use case but is not feasible for continuous usage to support a critical load. The team also identified preliminary maintenance strategies for all MODEM system components which consisted of a combination of corrective and preventative maintenance.

Additionally, the MODEM team performed system performance analysis and a system LCCA focused heavily on use cases discussed with a base energy manager for Naval Air Station (NAS) Sigonella. The team also conducted research to determine the initial costs necessary to procure the components necessary for the system. Through the discussions with the OCONUS Base Energy Manager the team decided to center the life-cycle analyses on two specific use cases. The first use case focused on the MODEM system being connected directly to the installation microgrid at NPS in Monterey, California. In this use case, the system was not powering a specific critical load, but instead providing supplemental energy to the installation microgrid using only the energy generated from the photovoltaic (PV) arrays. The second use case involved deploying the MODEM system for continuous usage at the site of a remote pump house used to feed water to a water treatment plant at NAS. The goal of the LCCA was to identify the system's Savings to Investment Ratio (SIR) to help determine the cost effectiveness of the MODEM system. The outputs of the performance analysis fed into the LCCA and identified that the MODEM system had an SIR of –6.19 for the NPS Monterey use case and 0.22 for the NAS Sigonella pump house use case. These SIR values led the team to conclude that the current system design is not economically viable to provide a satisfactory return on investment for the identified use cases. However, there are additional factors (monetary quantification of increased resilience, additional renewable energy credits) that were not included in the analyses that could affect the SIR values.

Finally, the MODEM team identified areas for each of the analyses and system model which could be expanded upon for future projects and research. In this section the team identified problem areas which require further research and ideas for expansion of the analyses and model developed for this project. MODEM undoubtedly can be effective in increasing energy resilience for the DOD, but further research is needed to determine the best way to make the system financially and reliably feasible.

References

Varley, Daniel W., Douglas L. Van Bossuyt, and Anthony Pollman. “Feasibility Analysis of a Mobile Microgrid Design to Support DOD Energy Resilience Goals.” *Systems* 10, no. 3 (2022): 74. https://doi.org/10.3390/systems10030074.

ACKNOWLEDGMENTS

The Moveable, Deployable Microgrid (MODEM) team would like to express our gratitude to MAJ Daniel Varley and OCONUS Base Energy Manager for the groundwork that they laid so that we could succeed in the continuation of the MODEM project. The knowledge and tools that they shared with the MODEM team was extremely valuable. Furthermore, the team would like to express our appreciation for our advisors, Dr. Douglas Van Bossuyt and Corina White, for the guidance they provided over the course of our capstone project and for reassuring us of our work and capabilities. Their assistance, as well as Rabia Khan’s during our last quarter, was essential to our success. Additionally, the MODEM team would like to extend our thanks to Naval Postgraduate School (NPS), and more specifically, the Systems Engineering (SE) Department, for the incredible opportunity to go through the Master’s of Systems Engineering (MSSE) program. It was a challenging and extremely rewarding experience that we will never forget. The MODEM team greatly appreciates all the wonderful professors in the SE Department who imparted their wealth of knowledge to us. The MODEM team would like to express our sincerest gratitude to our home command, NSWC Crane, and our respective Divisions for believing in us and investing in our development. Finally, the MODEM team would like to whole-heartedly thank our families and friends who supported us on this four-year journey to earn our MSSE degree.

THIS PAGE INTENTIONALLY LEFT BLANK

I. PROJECT PLANNING AND MISSION ANALYSIS

A. INTRODUCTION

1. Background

The United States (US) Department of Energy (DOE) defines a microgrid as "a group of interconnected loads and distributed energy resources (DER) within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the [utility] grid to enable it to operate in either grid-connected or island mode." U.S. Department of Defense (DOD) installations are built upon microgrids to provide power to their infrastructure. Energy resilience for installation power grids is an increasing concern for the DOD (Anuat, Van Bossuyt, and Pollman 2022, 4). Much of this concern stems from an aging energy grid here within the U.S., an increasing trend in energy and other infrastructure related cyber-attacks, issues related to supply chain networks, and the relatively low reliability of grid systems in some areas of operation outside of the US.

The use of MODEMs has been identified as a subject meriting research to help address resilience concerns for both DOD installations and operational environments. Currently, base and operational energy microgrid systems are not easily interoperable. In the event of an equipment failure, operational energy equipment cannot easily be plugged into a base microgrid to resume critical missions. Similarly, assets cannot easily be pulled from base microgrids to supply operational energy needs. This leads to lower resilience of DOD microgrids. Installation energy managers, tenant commands, and operational energy users will all benefit by having microgrid electrical equipment that is interoperable.

Previous work on the subject matter by MAJ Daniel Varley has identified the potential for MODEM to help improve installation energy resilience. The concept of MODEM is to give base energy managers a single box solution to provide power to critical loads during periods of interruption of the operational utility grid and base microgrid. MODEM creates a "nanogrid" for critical loads to reduce the amount of downtime in the event of a power disruption due to inclement weather, supply chain disruptions, and the like. MODEM relies on a combination of Photovoltaic (PV) Arrays, Battery Energy Storage System (BESS), and Emergency Diesel Generators (EDGs) to supply power at the critical load with all necessary equipment able to be stored in a single International Standards Organization (ISO) Triple Container (TriCon) (Varley, Van Bossuyt, and Pollman 2022). This capability allows MODEM to be easily moveable and deployable using readily available DOD assets. The MODEM BESS interfaces with critical loads via low-voltage connections at the point of the critical loads to supply necessary power to keep the affected critical loads in an operational state.

2. Problem Statement

In a March 2022, report titled "Strengthening the Resilience of Defense Critical Infrastructure," the Electricity Advisory Committee (EAC) outlines five findings and four recommendations aimed at the U.S. DOE. In this report, the committee emphasizes the importance of "bolstering the resilience of Defense Critical Electrical Infrastructure (DCEI)" and the role DCEI resilience plays in the executing our nation's national defense strategy (EAC 2022). While the scope of this report and the findings contained within it are much broader than the scope of this project, Finding 3 "Sponsoring the development of DCEI-specific resilience assessment tools, standards, and metrics," outlines the necessity for better assessment capabilities for existing infrastructure resiliency and related requirements, better modeling tools for assessing threats and the infrastructures reaction to these threats, and the reliance currently on natural gas and other traditional fuel sources. Additionally, ongoing research looking specifically at mobile hybrid microgrids to address energy resiliency issues in support of DOD installations, outlines similar concerns to that of the EAC report as well as others more specific to operational situations (Varley, Van Bossuyt, and Pollman 2022). MODEM has been identified as a potential solution to address some of the concerns and findings outlined by the EAC report and the ongoing research specific to hybrid microgrid solutions, but additional analyses for feasibility, interoperability, and sustainment are necessary. To date, there have been no research findings that show feasibility, interoperability, and sustainment analysis on hybrid microgrid solutions.

3. Project Scope

The intent of the MODEM project team is to provide analysis of the feasibility of the proposed MODEM solution. To accomplish this, the team utilized architecture modeling to perform interoperability and sustainment analyses. The team also utilized and expanded upon existing tools developed for microgrid analysis to assess the level and ease of interoperability with existing infrastructure, assess the power requirements for DOD critical loads, and determine the acquisition, Life-Cycle Costs (LCC), potential life-cycle energy savings for MODEM units, and safety protection for installation and implementation analysis. Additionally, support costs were evaluated through a Reliability, Maintainability, and Availability (RM&A) analysis.

The MODEM project team identified and documented viable use cases for MODEM with DOD installations, operational forces, and potential use in humanitarian efforts and developed a Concept of Operations (CONOPS) for those use cases. Another intent of the team was to explore non-combat operations use cases such as disaster response and humanitarian efforts, time permitting. The team leveraged previous CONOPS developed for DOD installation usage and potential usage in large-scale combat operations (LSCO). The team also identified and documented functionalities which require verification.

For the MODEM physical architecture, the project team performed interoperability assessments, identified and documented system test points, and identified and documented acceptable system, subsystem, and interface performance specifications.

4. Constraints

The project was undertaken as a part of an NPS capstone project and the MODEM project team was on a strict nine-month schedule for completion. This time constraint limited the amount of Analysis of Alternatives (AoA) that was able to be performed with respect to system architectural design. The project team decided to focus on a subset of applicable variations and alternatives for interoperability analyses. The scope for the analyses that were performed was limited to the most common and standardized interfaces for both base and operational energy grids.

5. Assumptions

The MODEM project is a continuation of work from previous projects. Previous efforts have provided initial assumptions that established a baseline for the purpose of this project. These initial assumptions included the following:

- Previous projects performed an exhaustive analysis of alternatives of varying microgrid technologies and viable solutions. The design under consideration was the most suitable for further analysis.

- Assumptions regarding sustainment factors (mission cycles, operation energy grid equipment reliability, and the like) were necessary to conduct sustainability analyses. These are documented within CONOPs.

- “Power outages may be accompanied by a fuel constrained environment (e.g., natural disaster that restricts fuel transport), an existing installation microgrid is in place, and the risk of outages does not warrant the development of redundant customized single load microgrids for each critical load” (Varley, Van Bossuyt, and Pollman 2022, 11).

- Because this project continues previous work some of the Systems Engineering (SE) processes are already completed. The MODEM team did not perform those processes in full due to the restricted project schedule.

6. Research Questions

Research questions the MODEM team addressed, posed by the project originator for their thesis work are as follows:

- “Can mobile microgrids (one size fits all) effectively meet an average 10kw critical load while reducing the reliance on diesel fuel for power generation?” (Varley, Van Bossuyt, and Pollman 2022, 2)

- “What are the trade-offs between a mobile microgrid and a single load specific microgrid (e.g., resilience, time, cost, over or under utilization, load shedding)?” (Varley, Van Bossuyt, and Pollman 2022)

After review of MAJ Varley's work and related material, the MODEM team had insight into the future direction of the project and formulated the following research questions:

- When, if at all, is utilizing a solar-powered microgrid financially advantageous in comparison to using a diesel fueled generator? When does return on investment (ROI) yield cost savings?
- What is the LCC of a MODEM unit?
- What objective/threshold power levels are necessary for most DOD critical loads?
- What long-term supportability requirements exist for MODEM units?
- Are MODEM units feasible to provide forward deployment power capabilities for LSCO?

Throughout the team's SE process, the research questions were a key driving factor for formulating answers and conclusions.

7. Project Goals and Objectives

The original intent of the MODEM project team was to further analyze the feasibility of using MODEM units to increase DOD energy resilience and capture systems engineering data previously generated in support of this overarching effort. At the conclusion of the MODEM project, the team aimed to provide the analyses and deliverables in the following bulleted list:

- Develop a Systems Modeling Language (SysML) Systems Architecture Model
    - Capture requirements
    - Capture functional and allocated system baselines
    - Document viable use cases / CONOPs
        - Installation

        - Operational Usage
    - Identify and document functionality requiring verification
    - Interface interoperability assessment
    - Identify and document system test points
    - Identify and document acceptable system/subsystem/interface performance specifications
- Comparison of life-cycle support costs and realized energy savings from identified moveable microgrid system
    - Consider support costs from a reliability, maintainability, and availability analysis
    - Utilize physics-based modeling previously done to show cost benefit of microgrid as a supplemental power source

B. SYSTEMS ENGINEERING PROCESS

The Systems Engineering Process section identifies the various steps within the SE Process in alignment with those identified by the International Council on Systems Engineering (INCOSE) in the Systems Engineering Handbook (2015). The project team reviewed INCOSE's SE process and determined the applicable processes for the project; the applicable SE processes were sectioned into a six-phase iterative process that aligns to the project schedule. The six-phase process divided the work into more manageable segments that provided the best odds of project success. The project's six-phase SE process flow is provided in Figure 1.

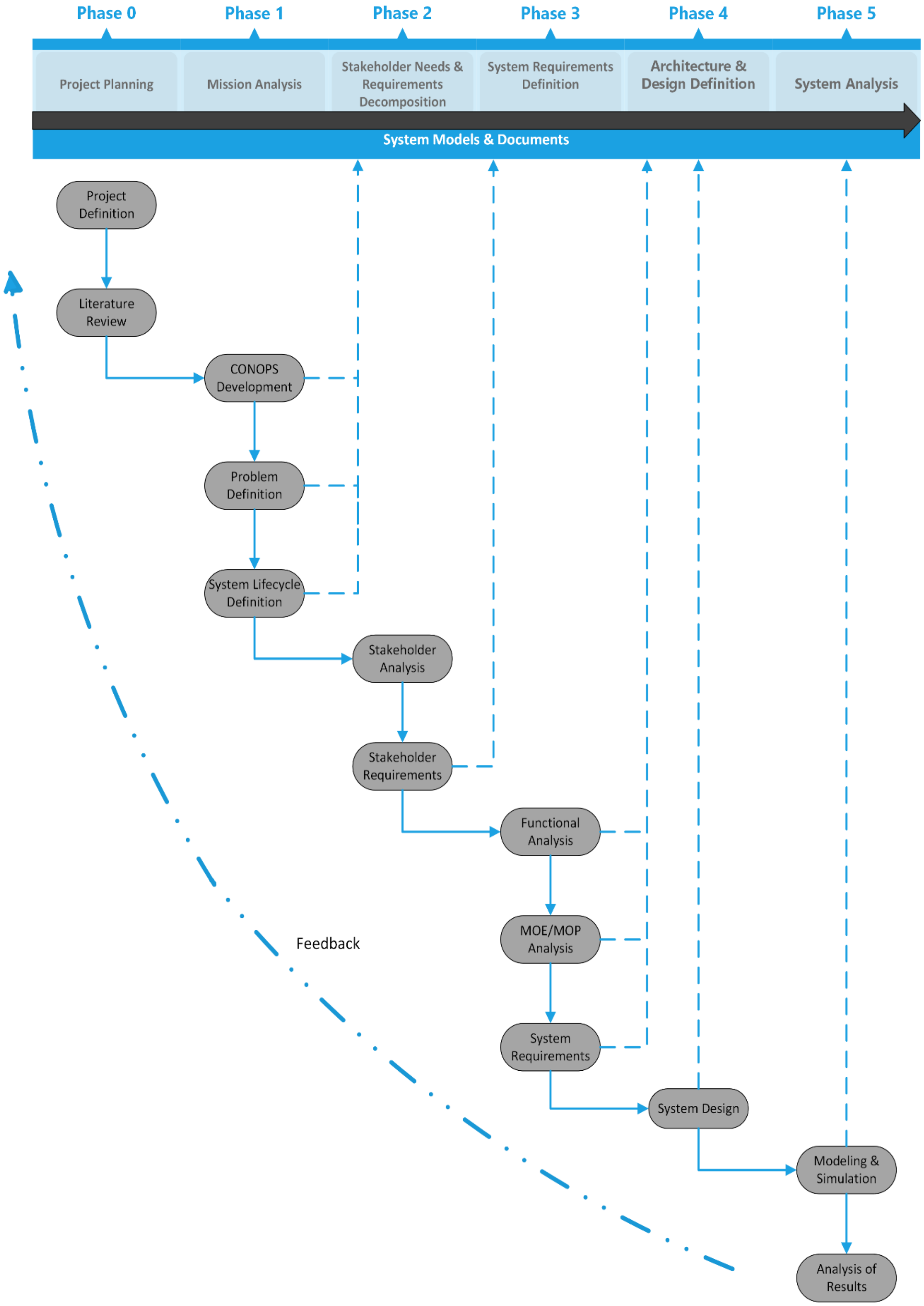


Figure 1. SE Process for MODEM Project. Adapted from INCOSE (2015).

This section elaborates on the project planning, mission analysis, stakeholder needs and requirements decomposition, system requirements definition, architecture and design definitions, and the project's system analysis processes. This section also further defines the life-cycle of the system and how these SE processes align with those cycles.

1. Project Planning

The purpose of the project planning process was to perform a detailed analysis of the previous work on the MODEM project and all relevant information in relation to MODEM. Initial findings provided foundational knowledge to aide decision making going into the Mission Analysis process and definition of the project scope.

2. Mission Analysis

The INCOSE SE Handbook identifies the purpose of the Mission Analysis process as "defining the specific mission problem or opportunity, characterizing the solution space, and determining the potential solutions that would address the identified problem or take advantage of an identified opportunity" (INCOSE 2015, 49). This process was the inception of the life cycle of the system or solution that addressed the identified problem or area of opportunity. During this process, the problem and opportunity were defined through the review of identified gaps within the target organization, and the solution space was scoped and characterized through the identification of preliminary CONOPS and the definition of preliminary life-cycle concepts. Traditionally, this process also includes the identification and assessment of alternative solutions, but due to the nature of this project, this step had already been completed by another party. The focus of this step, within the context of this project, was to clearly identify and define the problem and opportunity the identified solution addresses and the capability gaps it fills. The MODEM team's tailored approach for the Mission Analysis is communicated in Figure 2.

Figure 2. IPO Diagram for the Mission Analysis Process. Adapted from INCOSE (2015).

3. Stakeholder Needs & Requirements Decomposition

INCOSE identifies the purpose of the Stakeholder Needs & Requirements Decomposition process as "defining the stakeholder requirements for a system that can provide the capabilities needed by users and other stakeholders in the defined environment" (INCOSE 2015, 52). This step in the overall SE process is crucial to the success of a project and its assessment throughout the various stages of the life cycle. During this process, the relevant users and stakeholders were identified to begin the development of requirements, stakeholder needs were identified and prioritized, the CONOPs and other life-cycle concepts were further refined, the stakeholder needs were translated to specific system requirements, and these requirements were assessed and assigned validation criteria. The MODEM team's tailored approach for the Stakeholder Needs & Requirements Decomposition process is communicated in Figure 3.

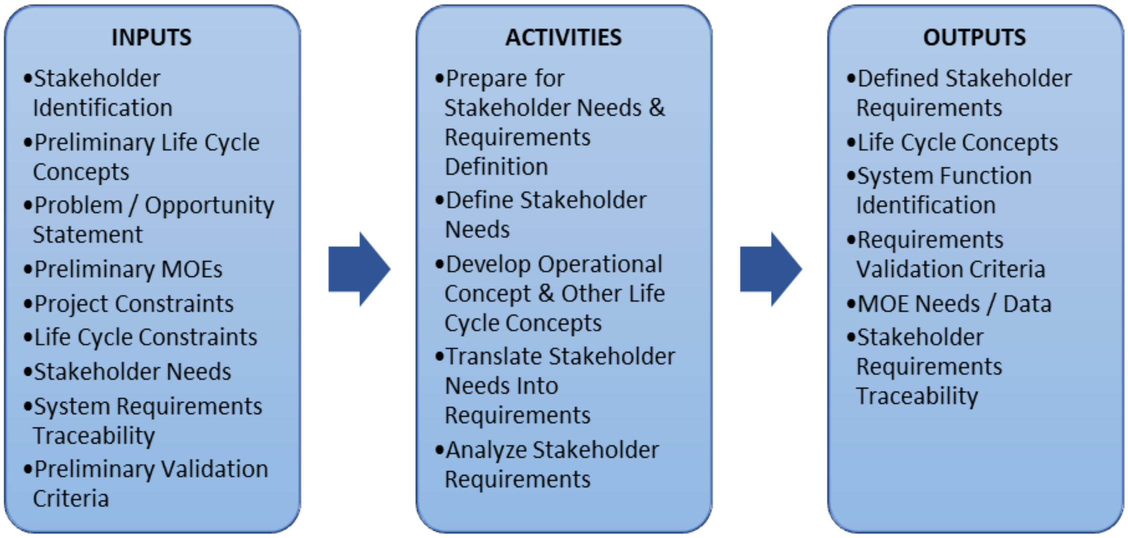


Figure 3. IPO Diagram for the Mission Stakeholder Needs & Requirements Decomposition. Adapted from INCOSE (2015).

During this stage, the system requirements began to be tracked for future SE purposes as well as future life-cycle processes. For this project, the requirement capture took place within a SysML environment—specifically, Magic System of Systems Architecture (MSOSA).

4. System Requirements Definition

The purpose of the Systems Requirements Definition process was to translate the desired stakeholder and user capabilities into a technical view of a solution that achieved the identified operational need and opportunity gap (ISO 2015). Much like the Stakeholder Needs & Requirements Decomposition process where the stakeholder and user needs began to form the requirements, this step was just as important to the formation of system requirements which system effectiveness are measured throughout its operational life. These requirements are foundational in all aspects of the systems life—from the preliminary stages of design and development to the operation and support phase. It was expected that the requirements definition process be both iterative and recursive to achieve the maximum level of success. During this process, the methods in which the system requirements definition took place were identified, the system functions were identified and defined, any relevant technical risks were accounted for, system requirements were further defined, system requirements were analyzed for integrity and that they adequately reflect the needs of the stakeholders, and Measures of Performance (MOPs) were identified and traced back to Measures of Effectiveness (MOEs). As before, the system requirements were tracked and managed throughout the various iterations in such a way to support future life-cycle phases. The MODEM team's tailored approach for the System Requirements Definition Process is communicated in Figure 4.

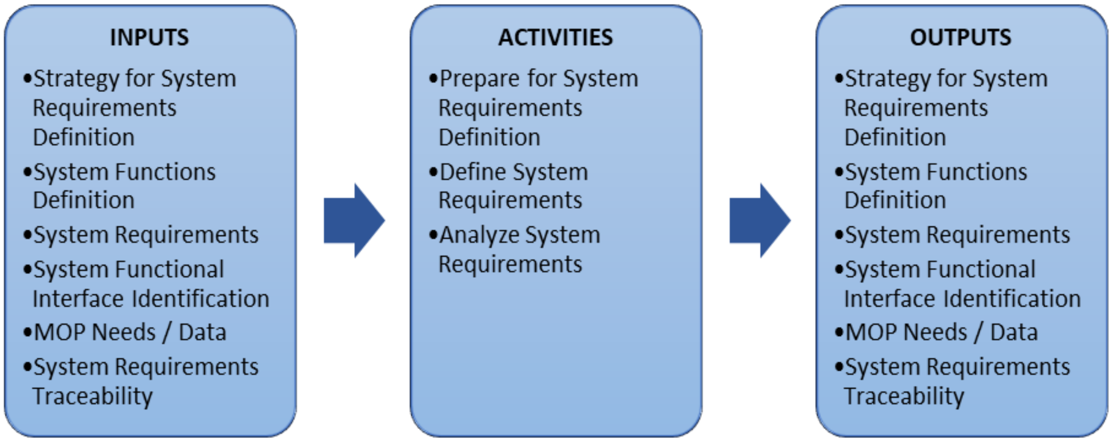


Figure 4. IPO Diagram for the System Requirements Definition Process. Adapted from INCOSE (2015).

5. Architecture Definition

INCOSE defines the Architecture Definition process as "generating system architecture alternatives, to select one or more alternative(s) that frame stakeholder concerns and meet system requirements, and to express this in a set of consisted views" (INCOSE 2015, 64). It was within this step of the overall SE process that the SE team identified the methodology and tools they utilized to capture and maintain the system requirements and operational concepts, and then trace them to the original stakeholder requirements. This process was dependent on the design activities of the system but should be utilized in support of the design definition process. While this step in the process traditionally has the SE team evaluating and comparing alternative approaches to modeling the system architecture, the primary focus within this step for the MODEM project was on the identification of the specific views—the architecture viewpoint development step. A SysML model was developed to capture and view all relevant requirements, and to trace these requirements back to stakeholder needs and requirements. Once the team captured the system architecture through the identified views, the system architecture was then mapped to a system design in preparation for the next step within the SE process. The MODEM team's tailored approach to the Architecture Definition process is communicated in Figure 5.

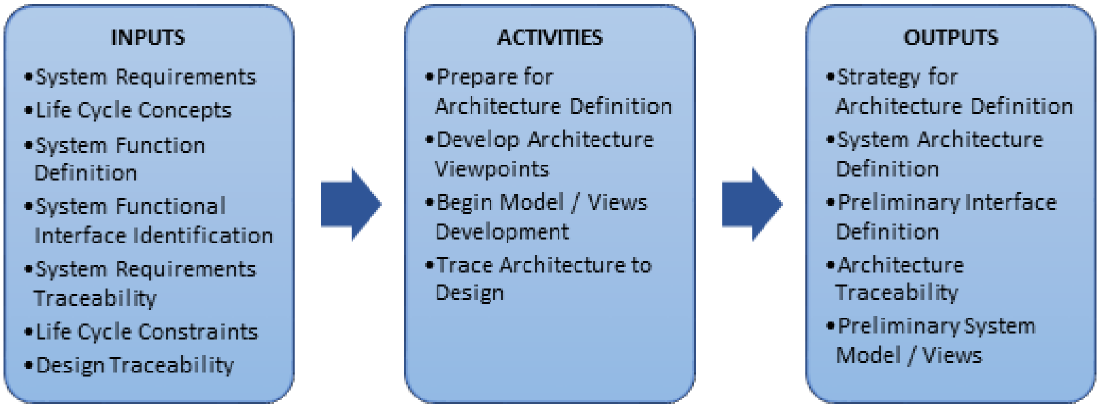


Figure 5. IPO Diagram for the Architecture Definition Process. Adapted from INCOSE (2015).

6. Design Definition

INCOSE defines the Design Definition process as "providing sufficient detailed data and information about the system and its elements to enable implementation consistent with architectural entities as defined in models and views of the system architecture" (INCOSE 2015, 70). It was during this step that the system began to be mapped and allocated to physical characteristics and hardware from the identified system elements and functions. While this step was not the actual physical system design nor the implementation of a physical system element, it was crucial for the eventual Implementation Process step of the SE process. During this phase, the team identified technologies that achieve design objectives and meet system requirements, design characteristics were identified and established, requirements were allocated to specific system elements, design characteristics were mapped to architectural characteristics, and AoA for the various system elements were performed. The nature of this project had the team already set on a specific physical system design, therefore an AoA was not conducted, but the allocation of system requirements to system elements, the mapping of system architecture to the system elements, and the technologies that are contained within the identified system were discussed within the context of this process and managed appropriately. The MODEM team's tailored approach to the Design Definition process is communicated in Figure 6.

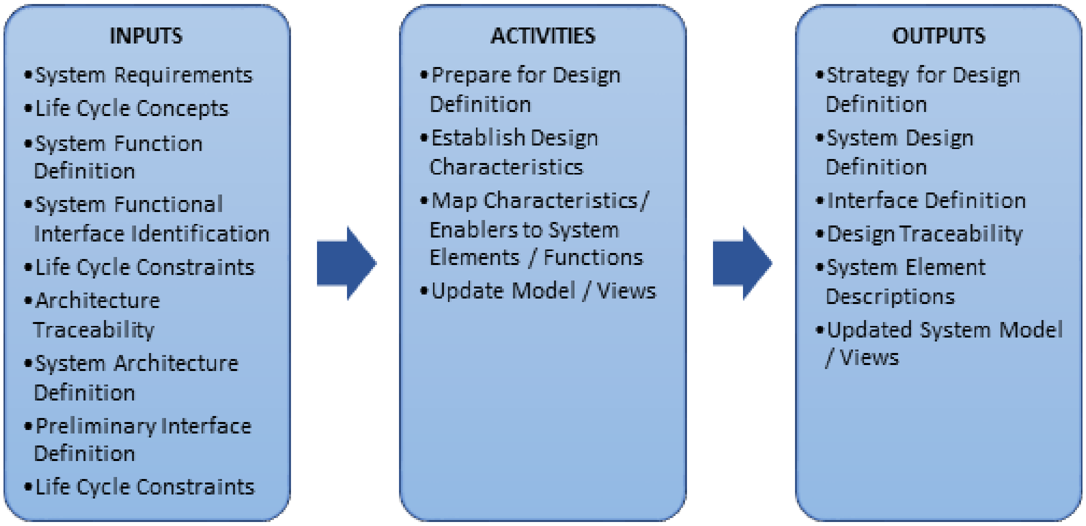


Figure 6. IPO Diagram for the Design Definition Process. Adapted from INCOSE (2015).

7. System Analysis Processes

The purpose of the System Analysis Process was to provide data and information for a technical understanding of the system and its elements to aid in the various decisions that required across the life of the system (ISO, 2015). It was during this phase that assessments and estimates based on various analyses were performed to provide information necessary to make various technical decisions. Analyses such as cost analysis, return on investment, affordability analysis, effectiveness analysis, and supportability analysis are a few such analyses that are typically provided to management to drive various decisions that can aid in selecting alternatives, drive design and support decisions, and help to measure the systems success. Additionally, the outputs of this process can be used in other steps in the SE process such as the Mission Analysis phase, the Stakeholder Needs & Requirements Decomposition phase, the Architecture Definition phase, and the Design Definition Phase to name a few. While there are many additional steps and processes that accompany the System Analysis process, as well as the overall SE process, most of the work on this project focused on the Integration Planning, Operation Planning, and the Maintenance Planning of the identified system. The INCOSE Systems Engineering Handbook breaks out these processes separately from the Systems Analysis process, but the team chose to account for them as subsets of the overall Systems Analysis process. The MODEM teams tailored approach to the System Analysis process is communicated in Figure 7. The following sections outline each of these and provide details within the context of the MODEM project.

Figure 7. IPO Diagram for the System Analysis Process (including Integration, Operation, and Maintenance Planning). Adapted from INCOSE (2015).

a. Integration Planning

Building from the Systems Analysis process, the Integration Planning process brought together all the system elements into a cohesive system that satisfied all the system and stakeholder requirements, the identified architecture, and the finalized design. The focus of this process was on both the internal and external interfaces to the system that allow it to function as designed and to the requirements. Ensuring full integration within the system itself as well as the identified CONOPs is crucial to the system's success. Because the technology that was identified for the system is commercial-off-the-shelf (COTS) and not designed by one original equipment manufacturer (OEM) from the ground up, interoperability is a risk. The team assessed the identified technologies for their ability to be successfully integrated. Additionally, the team assessed the identified area of operations to ensure maximum usability. For each component and integrated assembly, the team considered safety protection, measures, and standards to validate for usability and realistic implementation of the system. Physical tests were not within the scope of this project. The team conducted simple analyses of the hardware in place of actual physical testing—i.e., ensuring a power supply that supplies 120V is not integrated with hardware that requires 48V resulting in degraded performance.

b. Operation Planning

The purpose of the Operation Planning process was to identify the means and methods in which the system will be operated. Often executed concurrently with the Maintenance Planning phase, the Operation Planning phase is primarily done in preparation for fielding the system and making it operational within its environment. This includes preparing for personnel necessary to use the system, the measuring of system performance, standing up the infrastructure necessary to sustain the system, enabling applicable systems, products, and services required for operation, and identifying process for addressing deficient performance. Most DOD programs spend the majority of their useful life within the Operations & Sustainment (O&S) phase of the life cycle. This is also the phase in which a system will incur most of the LCC. Additionally, operation enabling systems such as the operational environment, training systems, technical data, facilities and infrastructure, and sustainment engineering, to name a few, must be accounted for. For this planning phase, the team focused on identifying the operational environments within which the system operates and what facilities are necessary to support the implementation, while abiding by safety and facility standards. Any additional changes to existing infrastructure that are necessary were identified.

c. Maintenance Planning

The Maintenance Planning and Operation Planning phases are often done simultaneously due to the relationship between operations and support from a fielded system. The Maintenance Planning phase is targeted at sustaining and maintaining a system. This includes planning for the various types of maintenance, the levels of maintenance, outlining any predetermined maintenance actions, addressing logistics needs across the entirety of the systems life cycle, and incorporating system health feedback processes into support capabilities. For the Maintenance Planning phase, the team will focus on analyzing the system from a reliability, maintainability, and availability perspective to assess operational availability (Ao) at cost. Ao is identified by the Manual for the Operations of the Joint Capabilities Integration and Development System (JCIDS) as a Key Performance Parameter (KPP) within the area of sustainment (Department of Defense 2018). It is the Ao value that the system will most often be assessed for performance, from a sustainment perspective. Additionally, JCIDS identifies and mandate's reliability, maintainability, and cost as Key System Attributes (KSAs)—reliability and maintainability being key pieces to Ao. Assessing the system's ability to meet requirements related to sustainment, all while meeting performance-based requirements, is key to assessing the likelihood of the system's success.

8. System Life Cycle

The DOD Acquisition Life Cycle as directed by DOD Instruction 5000.85 "Major Capability Acquisition" outlines the policies principles that define the acquisition and associated phases for all DOD programs (Department of Defense 2021). This framework identifies the specific documentation, reports, and other deliverables necessary for the program to advance from one phase to the next. Each point in which a program transitions from one phase to the next is marked by what is called a Milestone. At each milestone a specific set of criteria must be met in order for the program to advance to the next phase. Traditionally, these phases are Material Solution Analysis, Technology Maturation & Risk Reduction, Engineering & Manufacturing Development, Production & Deployment, Operations & Support, and lastly Disposal. The three major Milestones are Milestone A, which occurs between the Material Solution Analysis and Technology Maturation & Risk Reduction phases, Milestone B, which occurs between the Technology Maturation & Risk Reduction and Engineering & Manufacturing Development phases, and finally Milestone C, which occurs between the Engineering & Manufacturing Development and Production & Deployment phases. Additionally, there are decision points and major reviews that are done within each of these phases to ensure the program can successfully transition through the life cycle. An SE process is traditionally employed throughout the system acquisition process with special emphasis in the early phases, though all phases can greatly benefit from SE applications.

The MODEM project primarily focused on the early phases of the acquisition process. Specifically, the team took advantage of prior work related to the subject to complete many of the processes typically associated with the Material Solution Analysis and the Technology Maturation & Risk Reduction phases utilizing an SE approach (Varley, Van Bossuyt, and Pollman 2022). Within the team's modified SE process, these phases of the acquisition life cycle aligned to Phases 0 through 3, as depicted in Figure 1. Utilizing these previous works, the team's primary focus within the acquisition life cycle was on the Production & Deployment phase as well as analysis to support the Operations & Support phase. While the Operation & Support phase is typically the fielding and supporting of a system, assessments and analyses should be performed prior so that the system can successfully be supported within this phase. Within the team's modified SE process, these phases will encompass Phase 4 and 5.

II. STAKEHOLDER NEEDS AND REQUIREMENTS DECOMPOSITION

As noted in the project's problem statement, the primary focus of the MODEM team was the feasibility, interoperability, and sustainment analysis of the MODEM system. As such, many of the upfront SE activities, such as those in this section, were performed by leveraging the many prior studies and projects conducted on microgrids. These prior efforts performed extensive research and analyses on these activities. Specifically, many of the resources and stakeholders identified in these prior works were those with whom the MODEM team were consistently in contact with. Within the scope of the stakeholder analysis and various requirements analyses, it was the goal of the MODEM team to assess and capture all prior work relevant to the overall goal of this project through SysML methodologies. The MODEM team also derived additional needs and requirements not previously captured by other efforts.

A. STAKEHOLDER ANALYSIS

Prior research focused on DOD energy resilience has identified stakeholders who would benefit from the implementation of MODEM. Communication with members of previous efforts as well as referencing their material helped the MODEM team communicate with key stakeholders identified in Figure 8. Communication with the key stakeholders expanded the MODEM team's knowledge and understanding of needs and requirements. Continued research conducted through literature review helped the MODEM team to further identify and refine the list of stakeholders. Research coupled with further interviews with key stakeholders allowed the MODEM team to establish a thorough understanding of stakeholder needs, motivations, and current limitations regarding installation microgrids.

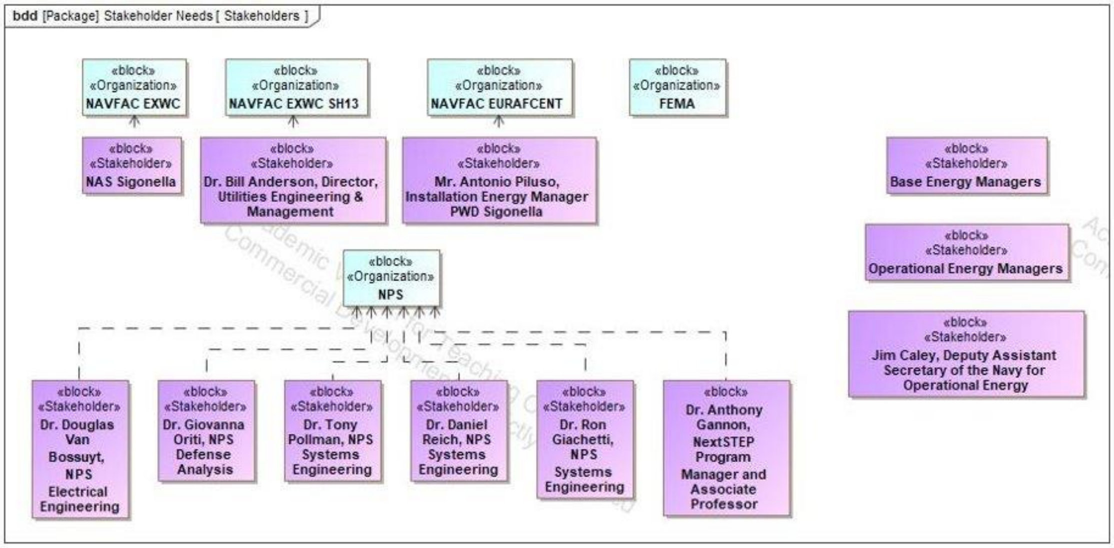


Figure 8. MODEM Project Stakeholders

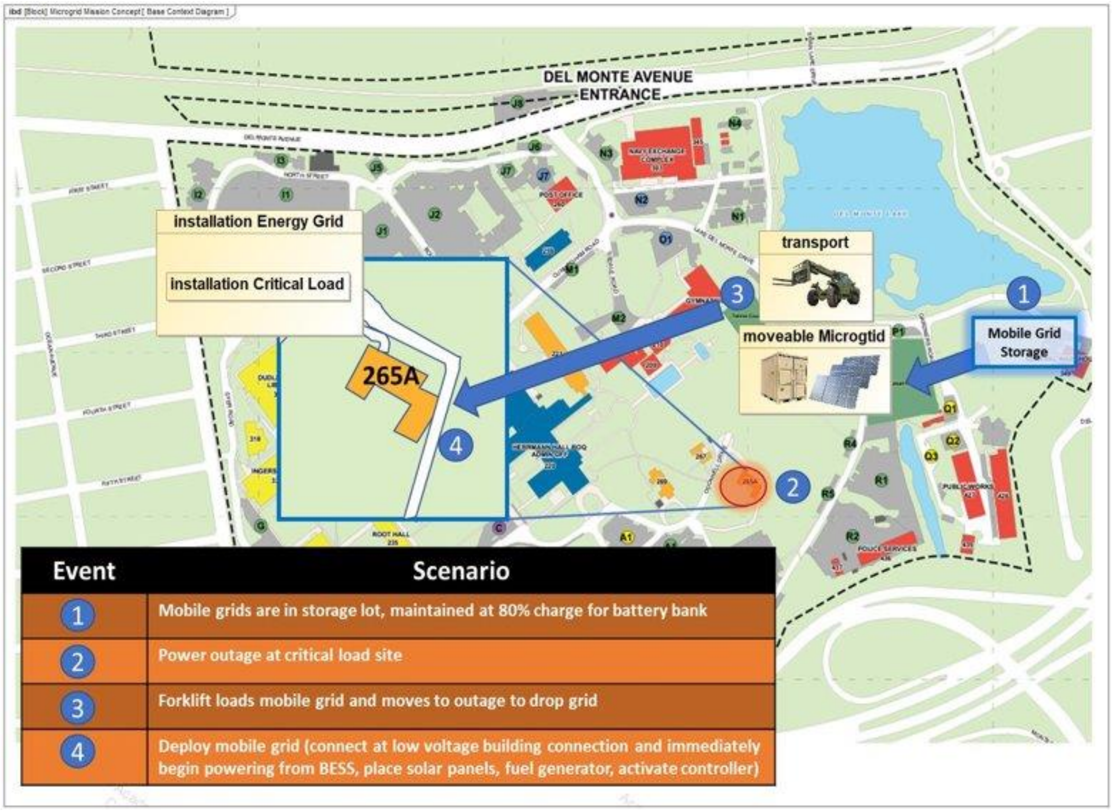
The MODEM project deliverables will benefit base energy managers, operational energy managers, and users at the points of critical loads to better assess and determine the feasibility of implementing MODEM units to improve energy resilience for DOD installations. The MODEM units also present potential opportunities to support critical civilian infrastructure (hospitals, emergency services, and the like) and provide an option for powering LSCO critical loads that are less reliant on fuel supply chains. Additional stakeholders may be identified through the different mission scenarios and use cases of the MODEM units.

B. NEEDS ANALYSIS

During the needs analysis process, the problem and opportunity were defined through the review of identified gaps within the target organization, and the solution space was scoped and characterized through the identification of preliminary CONOPS and the definition of preliminary life-cycle concepts. Traditionally, this process also includes the identification and assessment of alternative solutions, but due to the nature of this project, that step had already been completed by another party. The focus of this step, within the context of the MODEM project, was to clearly identify and define the problem and opportunity the identified solution addresses and the gaps it fills.

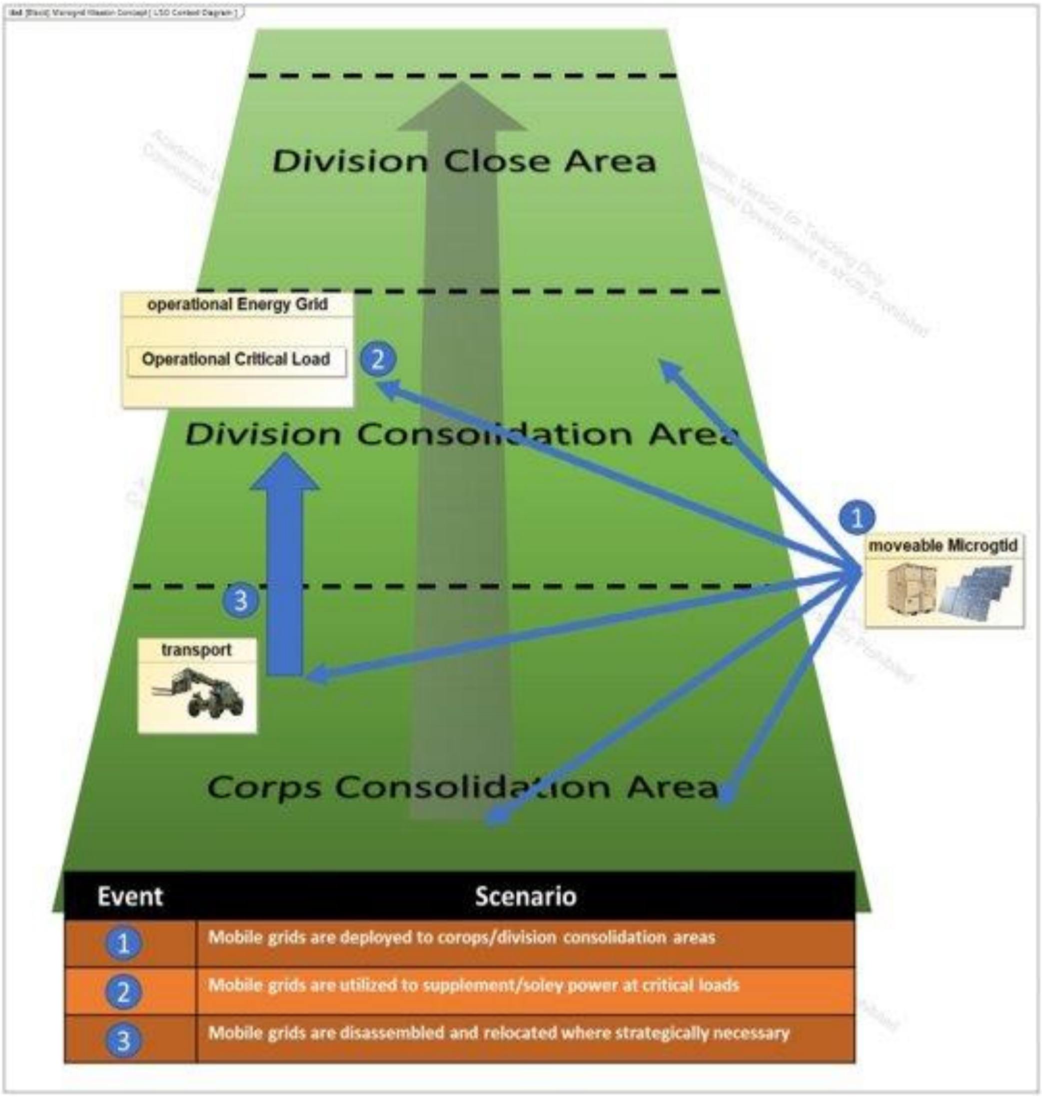
Due to the numerous previous projects focused on installation microgrids and increased energy resiliency for DOD installations, many of the stakeholder needs had already been identified. Figures 9 and 10 show the context diagrams for MODEM installation and LSCO mission scenarios. Through additional discussions with an OCONUS Base Energy Manager, the team identified an additional use case in which the MODEM systems would need to be setup and ran continually as additional power input into the grid. The stakeholder expressed that this use case would be key in funding the project and getting a good return on investment. Undoubtedly, there is more work to be done, but the MODEM team believes by documenting and incorporating the stakeholder needs into a model that it will allow stakeholders to visualize other potential needs that have not been captured. Based on the identified stakeholders within this report, the team identified a set of stakeholder needs that have been captured within the MODEM system SysML model and are outlined:

- Increase installation Power Grid Resiliency
- A Commercial Off-the-Shelf (COTS) system solution
- Can be quickly moved and setup
- Interoperable with current grids
- Can be transported by common fixed and rotary wing military aircraft with no alterations to system or transport
- Aligns to common DOD shipping and transportation methods
- Supports permanent DOD installations
- Supports contingency operations
- Supports Large-Scale Combat Operations (LSCO)
- Provides power generation and storage
- Provides sufficient return on investment



Event	Scenario
1	Mobile grids are in storage lot, maintained at 80% charge for battery bank
2	Power outage at critical load site
3	Forklift loads mobile grid and moves to outage to drop grid
4	Deploy mobile grid (connect at low voltage building connection and immediately begin powering from BESS, place solar panels, fuel generator, activate controller)

Figure 9. Base Context Diagram. Adapted from Varley (2022).



Event	Scenario
1	Mobile grids are deployed to corops/division consolidation areas
2	Mobile grids are utilized to supplement/soley power at critical loads
3	Mobile grids are disassembled and relocated where strategically necessary

Figure 10. LSCO Context Diagram. Adapted from Varley (2022).

Because the MODEM team built upon previous works there were already several artifacts that had been produced to help facilitate discussions with stakeholders. INCOSE states that “using the enterprise-level ConOps from the acquiring enterprise and the system-level preliminary OpsCon from the development enterprise as guidance, requirements engineers lead stakeholders from business operations through a structured process to elicit stakeholder needs (in the form of a refined system-level OpsCon and other life-cycle concepts). Stakeholder needs are then transformed by requirements engineers into a formal set of stakeholder requirements, which are often captured in a Stakeholder Requirements Specification (StRS)" (INCOSE 2015, 48).

The MODEM team documented and modeled the stakeholder needs that had been identified in previous works to assist with gap analyses, understanding of the interfaces required of the MODEM system, and to establish a baseline for further research to build upon. The MODEM team discussed the needs that were identified in previous works with available stakeholders through interviews and questionnaires to refine and expand upon the stakeholder needs.

III. SYSTEM REQUIREMENTS DEFINITION

A. REQUIREMENTS ANALYSIS

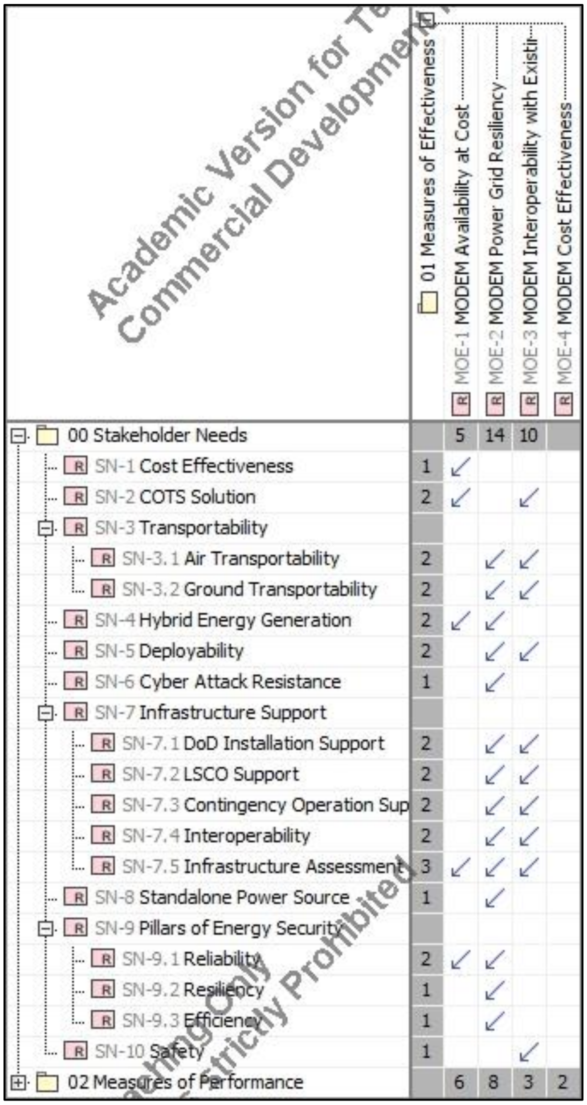
The purpose of the Stakeholder Needs & Requirements Decomposition process is to define the requirements from the stakeholder perspective that algin to measures of success of the system under the intended use case (INCOSE 2015). This step in the overall SE process is crucial to the success of a project and its assessment throughout the various stages of the life cycle. During this process, the relevant users and stakeholders are identified to begin the development of requirements, stakeholder needs are identified and prioritized, the CONOPs and other life-cycle concepts are further refined, the stakeholder needs are translated to specific system requirements, and these requirements are assessed and assigned validation criteria. It is during this stage that the system requirements begin to be tracked for future SE purposes as well as future life-cycle processes. For this project, requirements tracking took place within a SysML environment—specifically MSOSA.

The MODEM team documented and modeled requirements that had been identified in previous works including MAJ Daniel Varley's "Feasibility Analysis of a Mobile Microgrid Design to Support Department of Defense (DOD) Energy Resilience Goals" and Giachetti's "Systems Engineering Issues in Microgrids for Military Installations" and used the modeling of the stakeholder needs to derive requirements that may have been overlooked or ill-defined in the past. The goal of the MODEM team was to formally document and model requirements that had been identified of the potential MODEM system through extensive literature review of past projects, articles, and models to establish a baseline requirements model for future research into the MODEM system. These requirements helped facilitate feasibility analyses and aid in the definition of the logical and physical system architectures for the MODEM system.

Once the logical and physical system architectures were defined, the MODEM team then further decomposed the stakeholder needs down to system, subsystem, and component level requirements. These lower-level requirements were derived from the higher-level stakeholder needs and MOPs. The full decomposition of requirements down to the component level helps to establish and define the necessary performance for each part of the system. These requirements also helped the MODEM team with the identification and modeling of value properties that can be used to facilitate simulation in future projects.

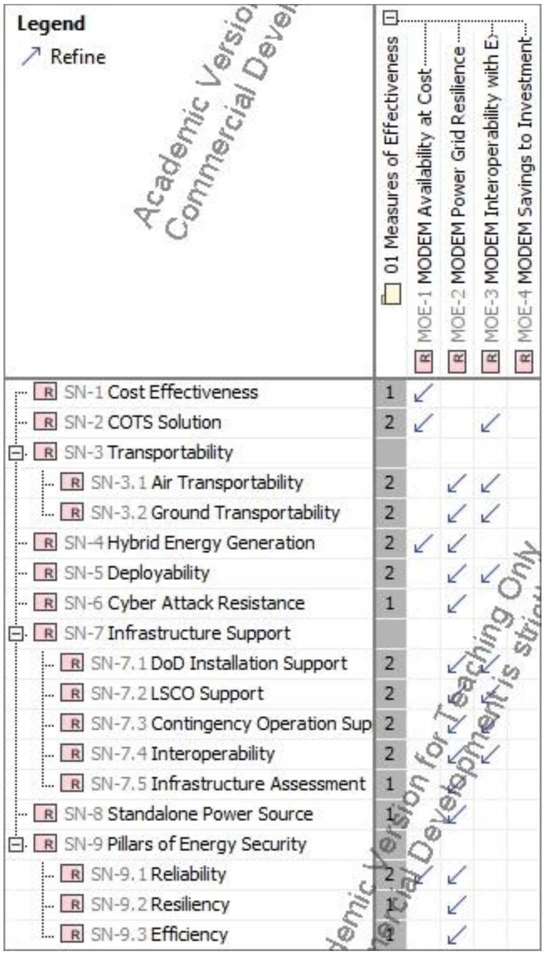
B. REQUIREMENTS TRACEABILITY

To further elaborate on the requirement decomposition process, the MODEM team ensured that each requirement in the system model was traceable to a higher-level requirement from the stakeholder needs down to component requirements. This traceability ensures that each requirement is rooted in trying to achieve a higher-level goal and contributes to the overall system performance. Figure 11 (Stakeholder Needs to MOEs), Figure 12 (MOEs to MOPs), Figure 13 (Stakeholder Needs to System Requirements), Figure 14 (System Requirements to Subsystem Requirements), and Figure 15 (Subsystem Requirements to Component Requirements) show the requirements traceability from the highest level down to the lowest level and demonstrate that each requirement in the system model is traceable.



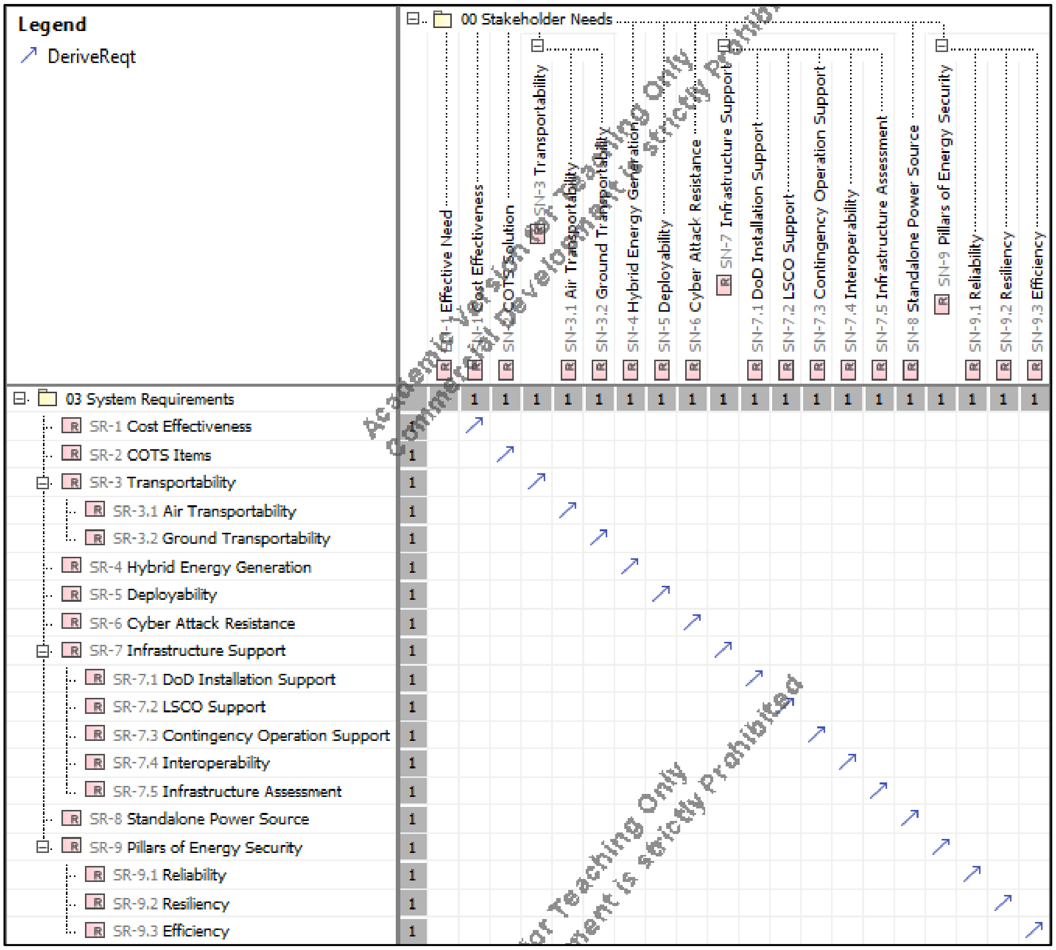
	01 Measures of Effectiveness	MOE-1 MODEM Availability at Cost	MOE-2 MODEM Power Grid Resiliency	MOE-3 MODEM Interoperability with Existi	MOE-4 MODEM Cost Effectiveness
00 Stakeholder Needs		5	14	10	
SN-1 Cost Effectiveness	1	↙			
SN-2 COTS Solution	2	↙		↙	
SN-3 Transportability					
SN-3.1 Air Transportability	2		↙	↙	
SN-3.2 Ground Transportability	2		↙	↙	
SN-4 Hybrid Energy Generation	2	↙	↙		
SN-5 Deployability	2		↙	↙	
SN-6 Cyber Attack Resistance	1		↙		
SN-7 Infrastructure Support					
SN-7.1 DoD Installation Support	2		↙	↙	
SN-7.2 LSCO Support	2		↙	↙	
SN-7.3 Contingency Operation Sup	2		↙	↙	
SN-7.4 Interoperability	2		↙	↙	
SN-7.5 Infrastructure Assessment	3	↙	↙	↙	
SN-8 Standalone Power Source	1		↙		
SN-9 Pillars of Energy Security					
SN-9.1 Reliability	2	↙	↙		
SN-9.2 Resiliency	1		↙		
SN-9.3 Efficiency	1		↙		
SN-10 Safety	1			↙	
02 Measures of Performance		6	8	3	2

Figure 11. Requirements Traceability Matrix—Stakeholder Needs → MOEs



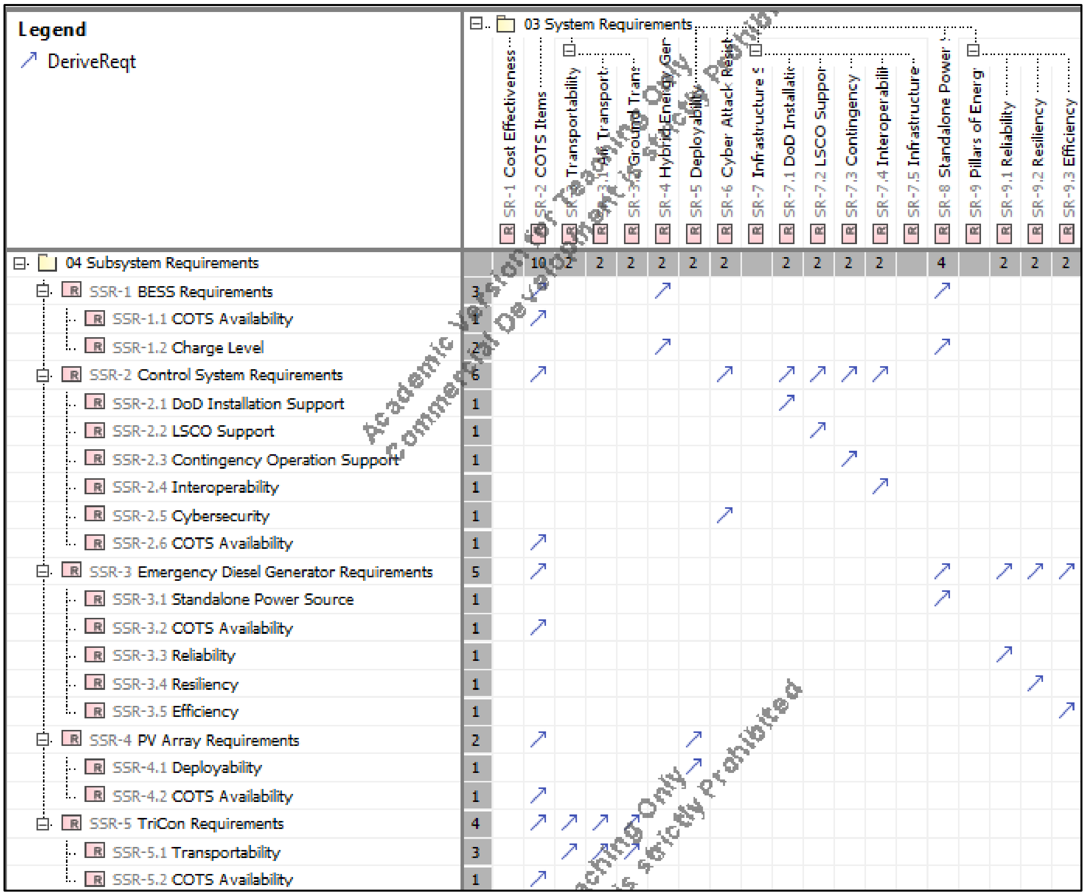
	01 Measures of Effectiveness	MOE-1 MODEM Availability at Cost	MOE-2 MODEM Power Grid Resilience	MOE-3 MODEM Interoperability with E…	MOE-4 MODEM Savings to Investment
SN-1 Cost Effectiveness	1	✓			
SN-2 COTS Solution	2	✓		✓	
SN-3 Transportability					
SN-3.1 Air Transportability	2		✓	✓	
SN-3.2 Ground Transportability	2		✓	✓	
SN-4 Hybrid Energy Generation	2	✓	✓		
SN-5 Deployability	2		✓	✓	
SN-6 Cyber Attack Resistance	1		✓		
SN-7 Infrastructure Support					
SN-7.1 DoD Installation Support	2		✓	✓	
SN-7.2 LSCO Support	2		✓	✓	
SN-7.3 Contingency Operation Sup	2		✓	✓	
SN-7.4 Interoperability	2		✓	✓	
SN-7.5 Infrastructure Assessment	1		✓		
SN-8 Standalone Power Source	1		✓		
SN-9 Pillars of Energy Security					
SN-9.1 Reliability	2	✓	✓		
SN-9.2 Resiliency	1		✓		
SN-9.3 Efficiency	1		✓		

Figure 12. Requirements Traceability Matrix—MOEs → MOPs



		00 Stakeholder Needs																		
		SN-1 Effective Need	SN-1.1 Cost Effectiveness	SN-1.2 COTS Solution	SN-3 Transportability	SN-3.1 Air Transportability	SN-3.2 Ground Transportability	SN-4 Hybrid Energy Generation	SN-5 Deployability	SN-6 Cyber Attack Resistance	SN-7 Infrastructure Support	SN-7.1 DoD Installation Support	SN-7.2 LSCO Support	SN-7.3 Contingency Operation Support	SN-7.4 Interoperability	SN-7.5 Infrastructure Assessment	SN-8 Standalone Power Source	SN-9 Pillars of Energy Security	SN-9.1 Reliability	SN-9.2 Resiliency	SN-9.3 Efficiency
03 System Requirements			1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
SR-1 Cost Effectiveness	1		↗																		
SR-2 COTS Items	1			↗																	
SR-3 Transportability	1				↗																
SR-3.1 Air Transportability	1					↗															
SR-3.2 Ground Transportability	1						↗														
SR-4 Hybrid Energy Generation	1							↗													
SR-5 Deployability	1								↗												
SR-6 Cyber Attack Resistance	1									↗											
SR-7 Infrastructure Support	1										↗										
SR-7.1 DoD Installation Support	1											↗									
SR-7.2 LSCO Support	1												↗								
SR-7.3 Contingency Operation Support	1													↗							
SR-7.4 Interoperability	1														↗						
SR-7.5 Infrastructure Assessment	1															↗					
SR-8 Standalone Power Source	1																↗				
SR-9 Pillars of Energy Security	1																	↗			
SR-9.1 Reliability	1																		↗		
SR-9.2 Resiliency	1																			↗	
SR-9.3 Efficiency	1																				↗

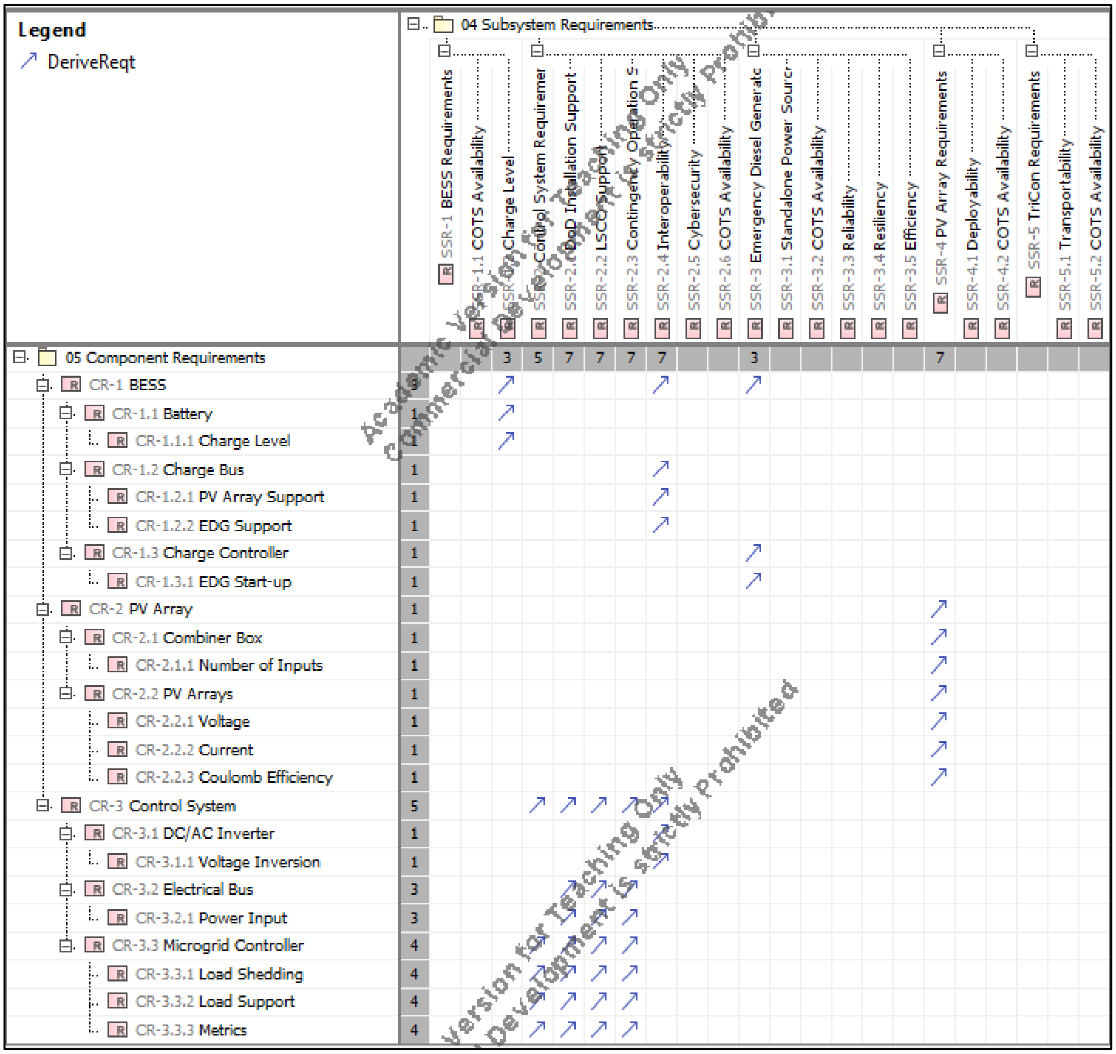
Figure 13. Requirements Traceability Matrix—Stakeholder Needs → System Requirements



Legend
↗ DeriveReqt

		SR-1 Cost Effectiveness	SR-2 COTS Items	SR-3 Transportability	SR-3.1 Air Transport	SR-3.2 Ground Trans	SR-4 Hybrid Energy Ger	SR-5 Deployability	SR-6 Cyber Attack Resist	SR-7 Infrastructure S	SR-7.1 DoD Installatic	SR-7.2 LSCO Suppor	SR-7.3 Contingency	SR-7.4 Interoperabilit	SR-7.5 Infrastructure	SR-8 Standalone Power	SR-9 Pillars of Energ	SR-9.1 Reliability	SR-9.2 Resiliency	SR-9.3 Efficiency
04 Subsystem Requirements			10	2	2	2	2	2	2		2	2	2	2		4		2	2	2
SSR-1 BESS Requirements	3		↗				↗									↗				
SSR-1.1 COTS Availability	1		↗																	
SSR-1.2 Charge Level	2						↗									↗				
SSR-2 Control System Requirements	6		↗						↗		↗	↗	↗	↗						
SSR-2.1 DoD Installation Support	1										↗									
SSR-2.2 LSCO Support	1											↗								
SSR-2.3 Contingency Operation Support	1												↗							
SSR-2.4 Interoperability	1													↗						
SSR-2.5 Cybersecurity	1								↗											
SSR-2.6 COTS Availability	1		↗																	
SSR-3 Emergency Diesel Generator Requirements	5		↗													↗		↗	↗	↗
SSR-3.1 Standalone Power Source	1															↗				
SSR-3.2 COTS Availability	1		↗																	
SSR-3.3 Reliability	1																	↗		
SSR-3.4 Resiliency	1																		↗	
SSR-3.5 Efficiency	1																			↗
SSR-4 PV Array Requirements	2		↗					↗												
SSR-4.1 Deployability	1							↗												
SSR-4.2 COTS Availability	1		↗																	
SSR-5 TriCon Requirements	4		↗	↗	↗	↗														
SSR-5.1 Transportability	3			↗	↗	↗														
SSR-5.2 COTS Availability	1		↗																	

Figure 14. Requirements Traceability Matrix—System Requirements → Subsystem Requirements



Legend
↗ DeriveReqt

04 Subsystem Requirements		SSR-1 BESS Requirements	SSR-1.1 COTS Availability	SSR-1.2 Charge Level	SSR-2 Control System Requiremer	SSR-2.1 DoD Installation Support	SSR-2.2 LSCO Support	SSR-2.3 Contingency Operation S	SSR-2.4 Interoperability	SSR-2.5 Cybersecurity	SSR-2.6 COTS Availability	SSR-3 Emergency Diesel Generatc	SSR-3.1 Standalone Power Sourc	SSR-3.2 COTS Availability	SSR-3.3 Reliability	SSR-3.4 Resiliency	SSR-3.5 Efficiency	SSR-4 PV Array Requirements	SSR-4.1 Deployability	SSR-4.2 COTS Availability	SSR-5 TriCon Requirements	SSR-5.1 Transportability	SSR-5.2 COTS Availability
05 Component Requirements				3	5	7	7	7	7			3						7					
CR-1 BESS	3			↗					↗			↗											
CR-1.1 Battery	1			↗																			
CR-1.1.1 Charge Level	1			↗																			
CR-1.2 Charge Bus	1								↗														
CR-1.2.1 PV Array Support	1								↗														
CR-1.2.2 EDG Support	1								↗														
CR-1.3 Charge Controller	1											↗											
CR-1.3.1 EDG Start-up	1											↗											
CR-2 PV Array	1																	↗					
CR-2.1 Combiner Box	1																	↗					
CR-2.1.1 Number of Inputs	1																	↗					
CR-2.2 PV Arrays	1																	↗					
CR-2.2.1 Voltage	1																	↗					
CR-2.2.2 Current	1																	↗					
CR-2.2.3 Coulomb Efficiency	1																	↗					
CR-3 Control System	5				↗	↗	↗	↗	↗														
CR-3.1 DC/AC Inverter	1								↗														
CR-3.1.1 Voltage Inversion	1								↗														
CR-3.2 Electrical Bus	3					↗	↗	↗															
CR-3.2.1 Power Input	3					↗	↗	↗															
CR-3.3 Microgrid Controller	4				↗	↗	↗	↗															
CR-3.3.1 Load Shedding	4				↗	↗	↗	↗															
CR-3.3.2 Load Support	4				↗	↗	↗	↗															
CR-3.3.3 Metrics	4				↗	↗	↗	↗															

Figure 15. Requirements Traceability Matrix—Subsystem Requirements → Component Requirements

C. TECHNICAL MEASURES

For the MODEM team to effectively assess the feasibility of the proposed system, technical measures were identified that could be assessed through modeling and simulation and basic compliance. These technical measures serve to guide design decisions in early acquisition and to assess the system's performance later in the life cycle. The MODEM team established an effective need and objective based on research and stakeholder feedback. Based on those needs and the established objective, the MODEM team determined these technical measures and decomposed them into two distinct categories—

MOEs and MOPs. Detailed descriptions for each of the technical measures categories can be found in their respective sections, along with the specific identified measures. A value hierarchy was constructed to show the logical flow from identified objective need to each of the MOEs and down to their subsequent MOPs. The system value hierarchy is shown in Figure 16, with the SysML equivalent shown in Figure 17.

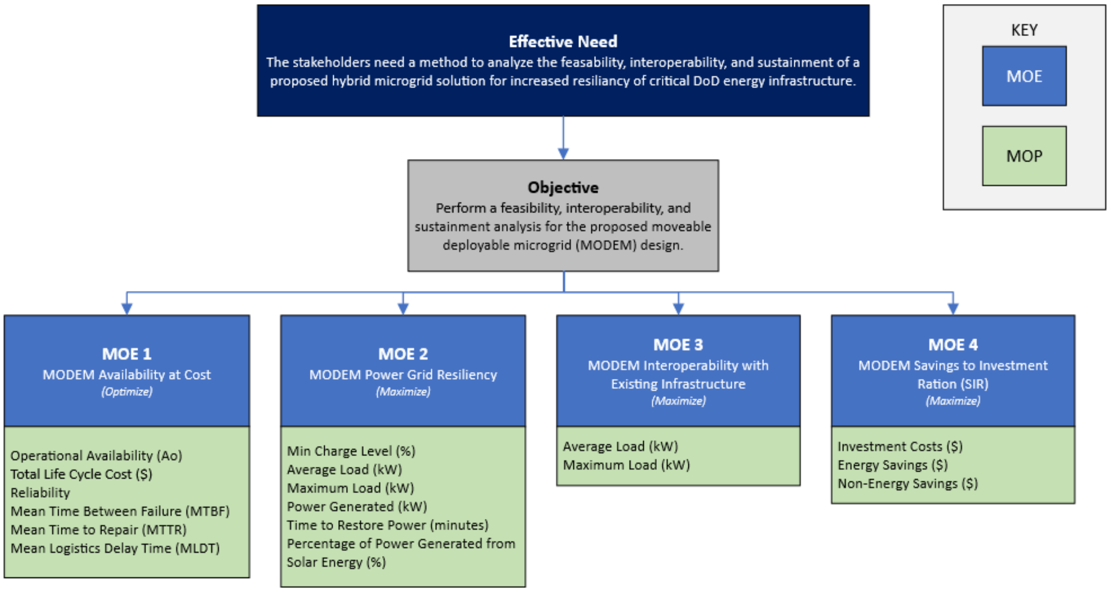


Figure 16. MODEM System Value Hierarchy

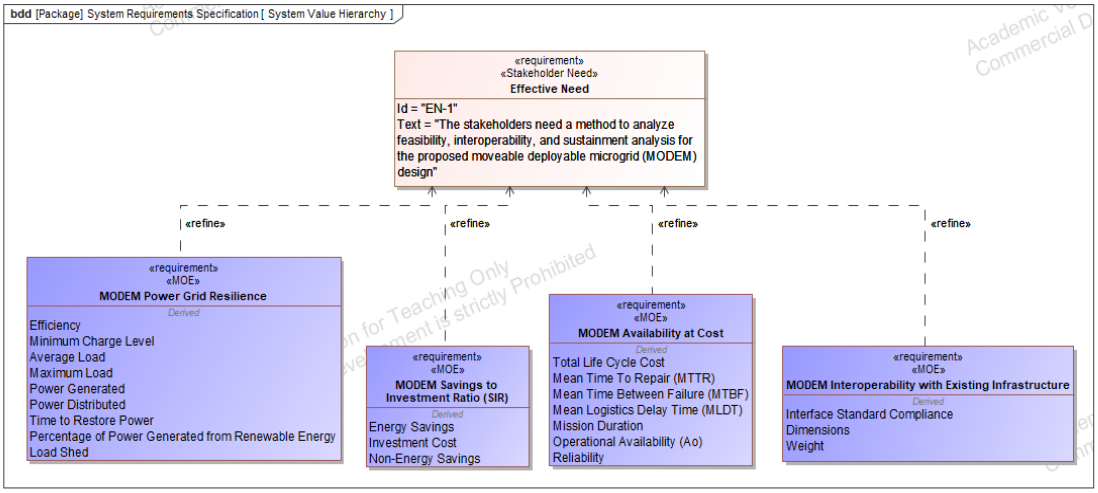


Figure 17. MODEM System Value Hierarchy in the SysML Model

1. Measures of Effectiveness

INCOSE describes Measures of Effectiveness (MOEs) as the measures of success related to the operational environment and identified mission being performed by the system under a specifically identified environment and set of conditions (INCOSE 2015). It is these measures that assess how well the identified solution achieves its intended purpose at an operational level. The team has identified four MOEs for the MODEM system that are captured in Figure 16 and Figure 17 with detailed descriptions in Table 1:

Table 1. MODEM Measures of Effectiveness Description

Measure of Effectiveness (MOE)	Description
Availability at Cost	Availability is one of the most important metrics used to gauge the effectiveness of DOD systems. It is defined as the probability a system will be capable of performing its defined mission or function under defined conditions when used. It is a function of how often the system is down and how quickly it can be restored to an operational state, all of which are functions of the reliability of the system, maintainability of the system, and the support infrastructure available to the system. LCC of the system is directly tied to availability as much of the systems cost will come from maximizing the availability. As such, system availability and cost should be optimized so that availability is maximized, and cost is minimized.
Power Grid Resiliency	Resiliency as it relates to energy is “the ability to assure access to reliable energy sources and protect and deliver the necessary amount of energy required to meet operational needs” (Varley, Van Bossuyt, and Pollman 2022, 4). Energy resiliency also includes the ability to survive outages or quickly recover from outages.
Interoperability with Existing Infrastructure	Interoperability is the ability of the system to connect and operate effectively with other systems within specified standards and conditions to deliver an identified function (Kasunic 2001).
Savings to Investment Ratio (SIR)	SIR is a cost analysis metric used to gauge how much money can be saved using alternative energy resources throughout the systems life cycle compared to the upfront costs associated with implementing these methods.

2. Measures of Performance

INCOSE describes Measures of Performance (MOPs) as critical performance measures that describe the physical and functional attributes related to a systems operational and technical achievement (INCOSE 2015). These are measures of success related to the implementation of the system and should be traceable to the identified MOEs. These MOPs allowed the MODEM team to track and measure the system's ability to achieve the identified MOEs, as well as make specific design or operational changes to better achieve the various technical measures. The team identified the following MOPs for the MODEM system captured in Figure 16 and listed in Table 2:

Table 2. MODEM Measures of Performance (MOPs) Values & Descriptions

Measure of Performance (MOP)	**Requirement**
	Description
Operational Availability (A_O)	The MODEM SHALL have a measured operational availability (Ao) of 0.90.
	Operational Availability is a measure that identifies the probability expressed as a percentage of the time a system is capable of performing a specified mission under an identified set of conditions. Specifically, operational availability considers all aspects of a system and its support infrastructure—reliability, maintainability, and supportability.
Total LCC	The MODEM SHALL have a maximum total LCC of $200 Million.
	LCC is the total cost across a systems life cycle that includes research and development, test and evaluation, production, facilities, operations and support, maintenance, and disposal.
Reliability	The MODEM SHALL have a measured system reliability of 95% for 168 hours with 90% confidence.
	Reliability is the probability that a system will perform an intended function over a specified period of time.
Mean Time Between Failure (MTBF)	The MODEM SHALL have a Mean Time Between Failure of 2,000 hours (objective) or 1,500 hours (threshold).
	Mean Time Between Failure is the average predicted amount of time between failures of a system or its components during normal operation.

Measure of Performance (MOP)	Requirement
	Description
Mean Time to Repair (MTTR)	The MODEM SHALL have a Mean Time to Repair of 2 hours (objective) or 6 hours (threshold).
	Mean Time to Repair is the average predicted amount of time it takes for a system to be brought from a failed or degraded state back to a fully operational state. This time includes time to isolate failures, make repairs, and test the system for full functionality.
Mean Logistics Delay Time (MLDT)	The MODEM SHALL have a Mean Logistics Delay Time of 48 hours (objective) or 168 hours (threshold).
	Mean Logistics Delay Time is the average predicted amount of time a system is awaiting parts due to necessary maintenance.
Minimum Charge Level	The MODEM SHALL maintain a minimum charge level greater than 80% while not in use.
	Minimum Charge Level is the minimum charge level of the systems batteries when in a stored state or not in use.
Average Load	The MODEM SHALL meet an average load of 10 kW over the mission duration.
	Average Load is the average power load measured in kW the system is capable of supporting during operation.
Maximum Load	The MODEM SHALL be capable of providing a maximum load of 12 kW over the mission duration.
	Maximum Load is the maximum power load measured in kW the system is capable of supporting during operation.
Power Generated	The MODEM SHALL be capable of generating a maximum of 15 kW.
	Power Generated is the amount of power measured in kW the system is capable of generating through the identified power sources.
Time to Restore Power	The MODEM SHALL be capable of restoring power to critical infrastructure within 30 minutes.
	Time to Restore Power is the amount of time measured in minutes it takes to restore full operational power to critical loads after loss, and includes the time to move, setup, connect, and/or start the system.
Percentage of Power Generated from Solar Energy	The MODEM SHALL generate 43.75% (objective) or 37.5% (threshold) of power from a renewable energy source.
	Percentage of Power Generated from Solar Energy is the total power generated from the solar array system divided by the sum of all generated power.
Investment Costs	The MODEM SHALL be designated as an AAP program in alignment with SECNAVINST 5000.02F, “Defense

Measure of Performance (MOP)	Requirement
	Description
	Acquisition System and Joint Capabilities Integration and Development System Implementation" and have an upfront investment cost of less than $64 Million.
	Investment Costs refers to the initial cost of procuring the COTS items and any additional material.
Energy Savings	The MODEM SHALL have energy savings ratio greater than 1.0.
	Energy Savings refers to the amount of money that can be saved on the production of energy through the use of the system versus traditional or other methods. This is a comparison of existing utility costs versus expected costs with the system.
Non-Energy Savings	The MODEM SHALL have non-energy savings ratio greater than 1.0.
	Non-Energy Savings refers to the amount of money that can be saved on costs related to aspects other than utilities cost through the use of this system. Examples of this include maintenance, support, etc.

D. FUNCTIONAL ANALYSIS

The MODEM team performed a functional analysis of the MODEM system by documenting and evaluating the proposed system's high level CONOPs and behavioral diagrams through mission analysis. Two primary use cases were chosen and expanded upon to capture functions necessary to meet stakeholder needs and to identify required interactions between the MODEM and external systems or external actors. Figure 18 and Figure 19 depict the intended system usage both from the perspective of continuous use and emergency use service interruption to a critical load. The team then further decomposed mission level functionality down into subfunctions which form the MODEM's functional architecture and functional interfaces. Figure 18 through Figure 25 illustrate the decomposition of system behavior from a CONOPs level down to system functions and subfunctions. The functional analysis of MODEM provides a means for future teams to organize and discuss MODEM requirements and design.

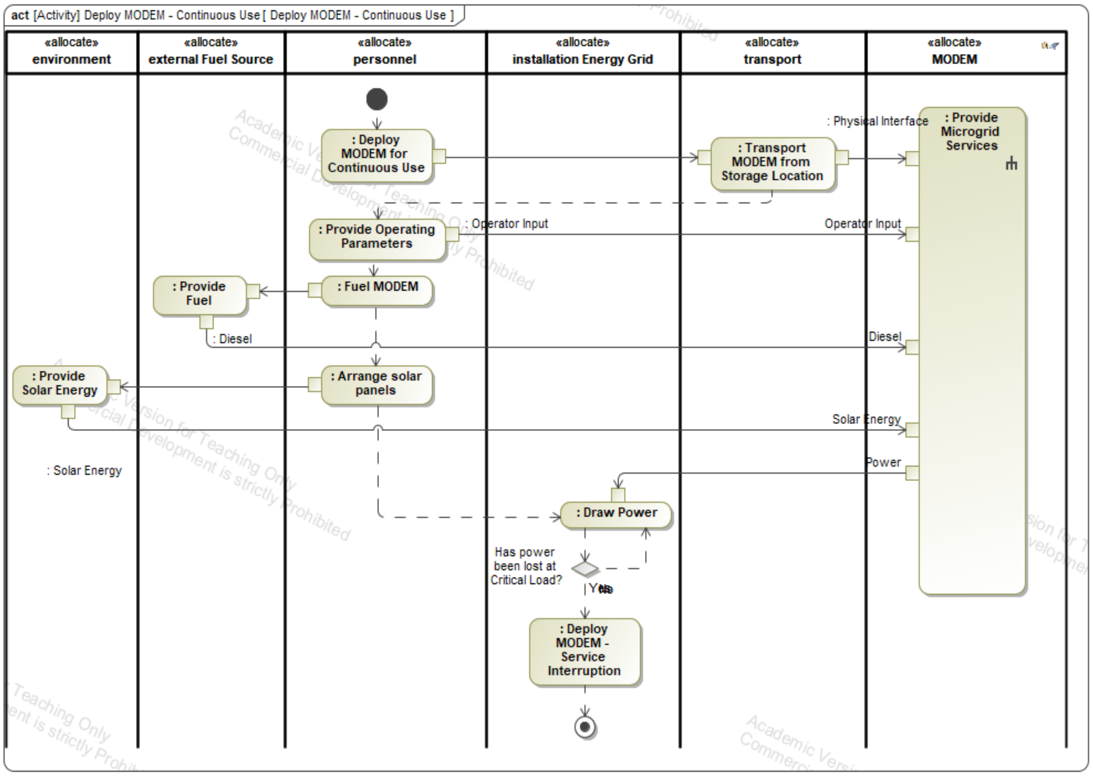


Figure 18. Deploy MODEM—Continuous Use

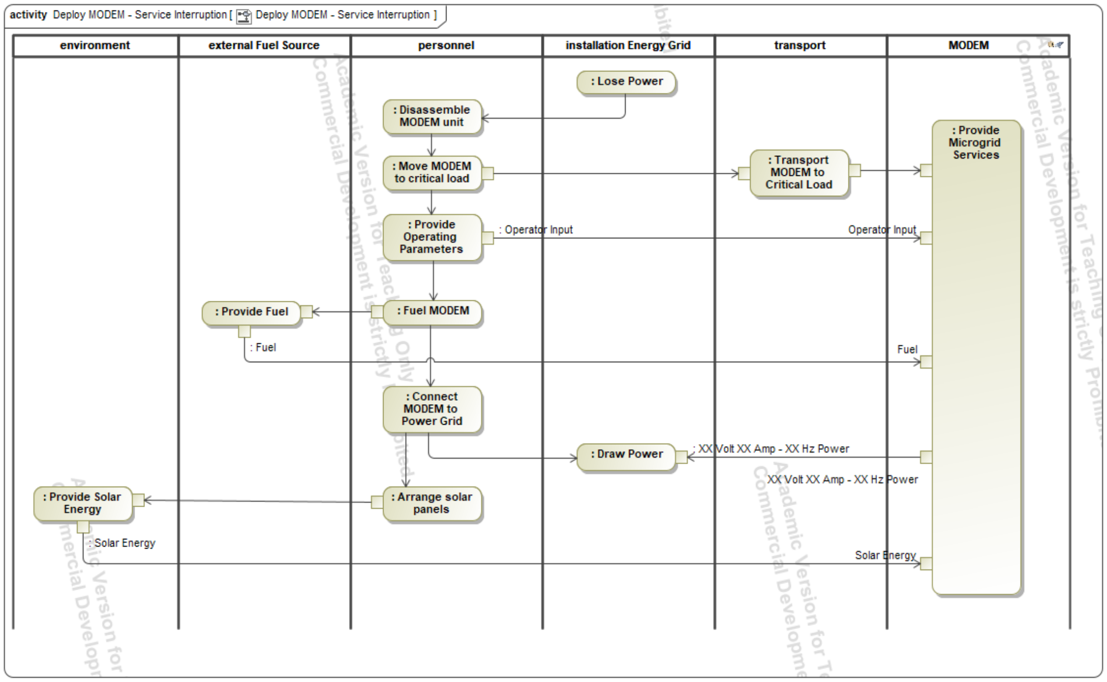


Figure 19. Deploy MODEM—Service Interrupt

Following the definition of use cases and CONOPs, the MODEM team then decomposed the mission-level behavior performed by the system into lower levels of system functionality. Although the intended usage of the system varies within each use case, the core functions remain the same and include generating power, storing energy, controlling the microgrid, and lastly distributing power (Giachetti et al. 2020). Figure 20 provides a top-down decomposition of the MODEM's functional architecture. These functions and their subfunctions are defined in greater detail in the following sections.

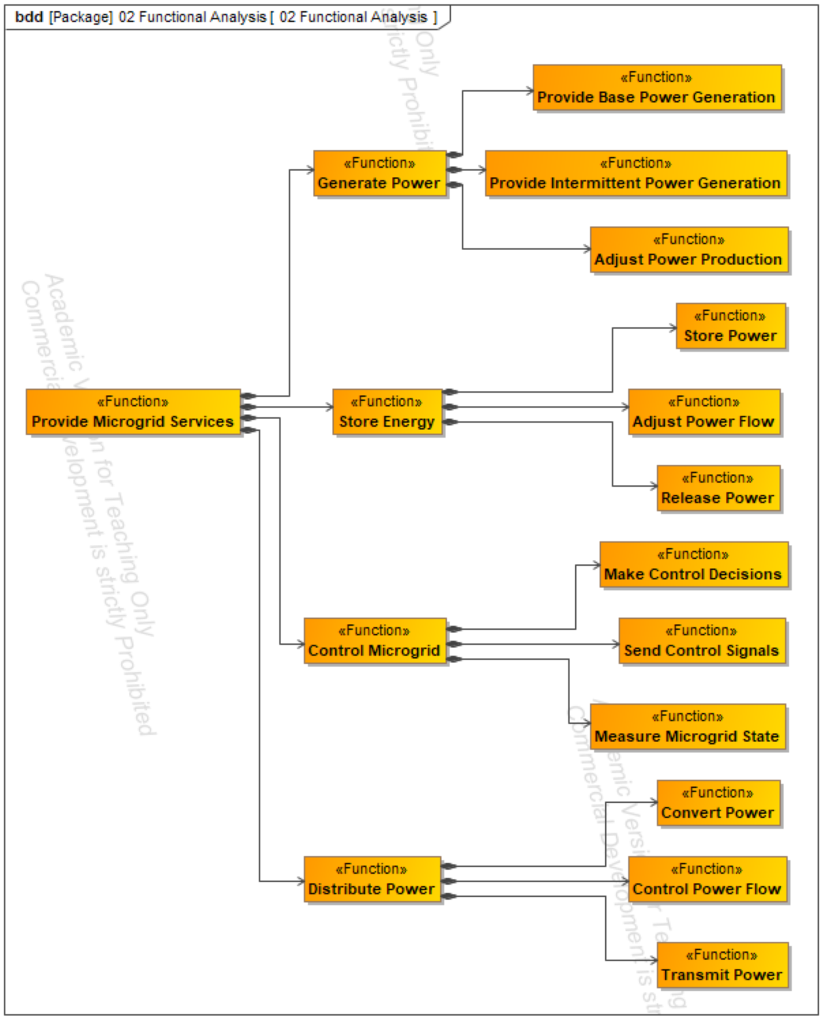


Figure 20. MODEM Functional Hierarchy

Figure 21 illustrates the decomposition and functions necessary for MODEM to provide microgrid services. The function Generate Power, Figure 22, takes in various energy sources, both renewable and non-renewable, and converts them into power to supply to other system functions. Power generated from non-renewable energy sources form the base power generation method and is supplemented by intermittent power generated from renewable sources. Other subfunctions include the ability to process control signals and provide status, which are common among all core system functions.

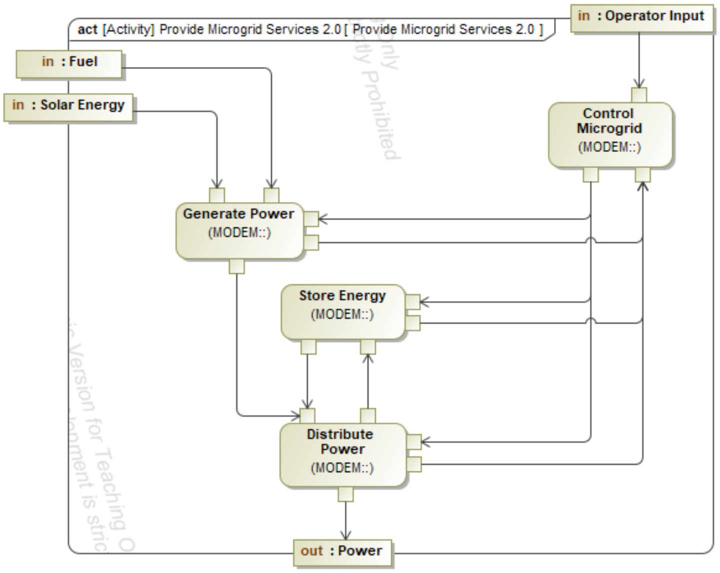


Figure 21. MODEM Functional Decomposition: Provide Microgrid Services

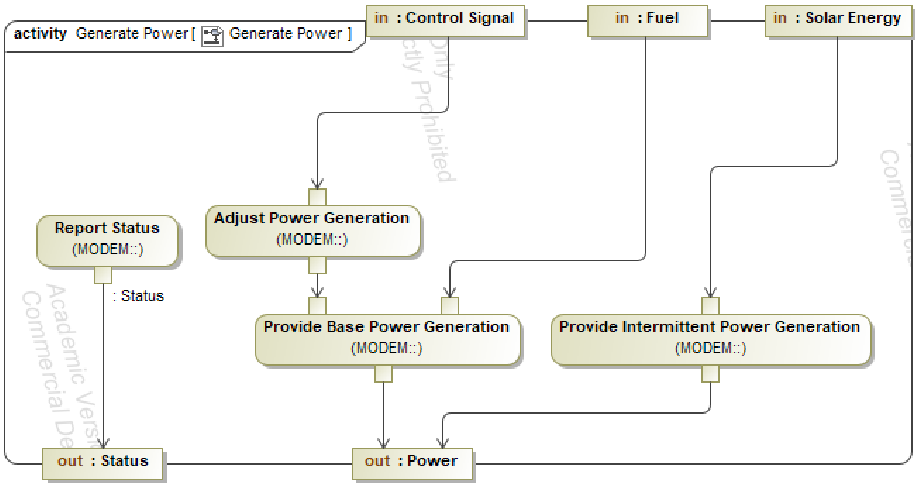


Figure 22. MODEM Functional Decomposition: Generate Power

Generated power is sent to the Distribute Power function, Figure 23, which converts, routes, and controls power flow as required. Power is then sent to either the Store Energy function or through the external system boundary. Power received by the Store Energy function, Figure 24, is accumulated via some storage method and transmitted externally as required. "The storage of energy is not an essential microgrid function, but for microgrid performance, energy storage is generally needed to help balance energy generation and loads, aid in frequency and voltage control, and to increase microgrid resiliency" (Giachetti et al. 2020).

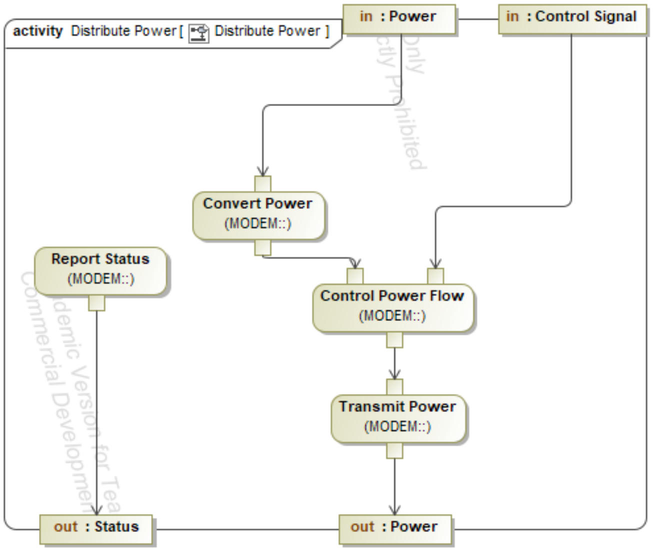


Figure 23. MODEM Functional Decomposition: Distribute Power

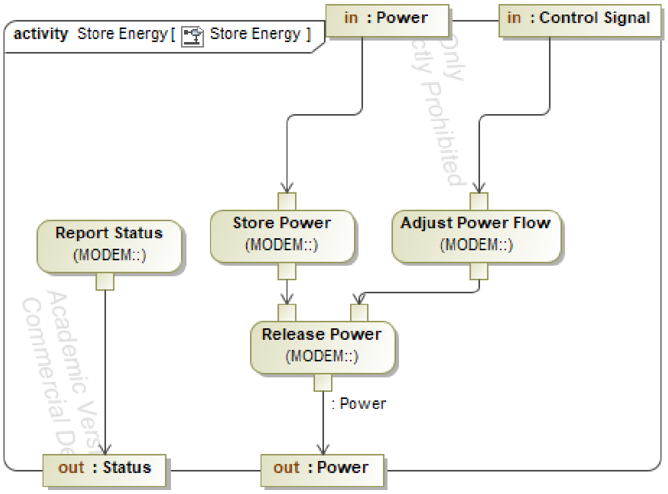


Figure 24. MODEM Functional Decomposition: Store Energy

The final core function of the MODEM functional architecture is Microgrid Control, shown in Figure 25. This function involves tracking the state and status of the MODEM, making control decisions based on those various measurements, and lastly providing control signals to various components within the system.

> Microgrid control is often conceptualized as hierarchical control at three levels of authority. Primary controllers (sometimes referred to as droop controls) operate generators and storage sources to maintaining the stability of frequency and voltage within a predefined range of values in intervals measured in milliseconds. Secondary controllers coordinate generation and storage across the microgrid for power quality control, power flow control, and synchronization. Tertiary controllers operate the grid connect/ disconnect switch and regulate if power is being taken from the grid or fed back to the grid. Tertiary control addresses the economics of operating the microgrid (Giachetti et al. 2020, 6).

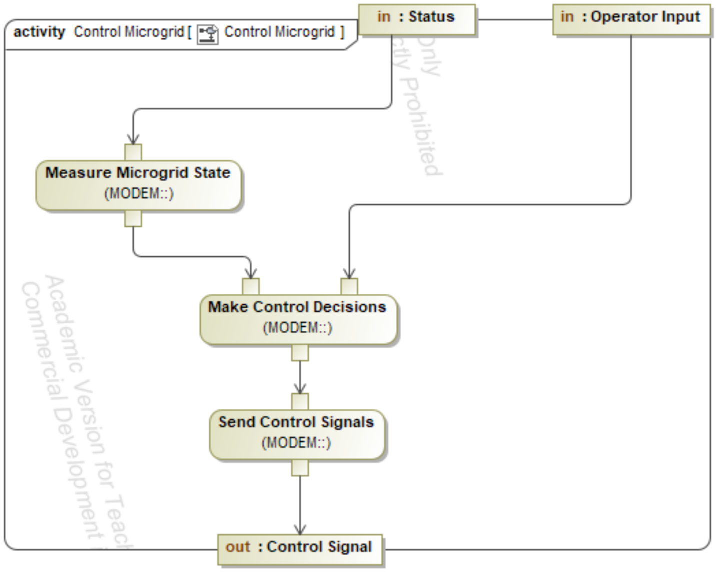
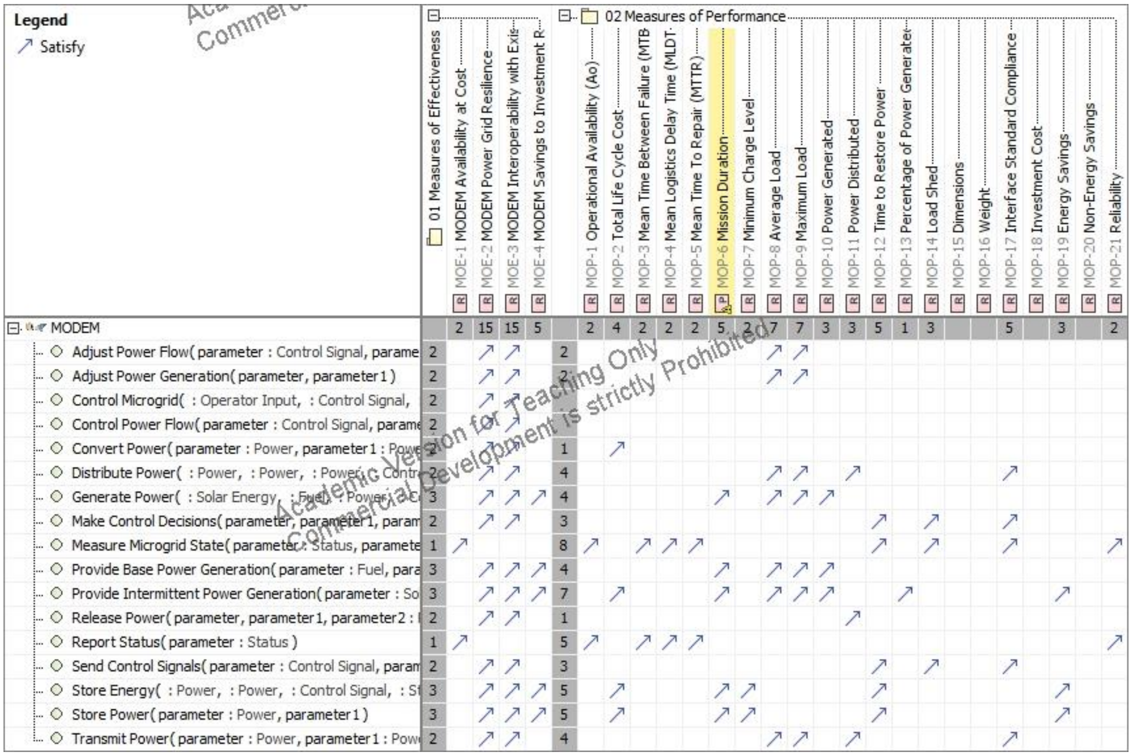


Figure 25. MODEM Functional Decomposition: Control Microgrid

The final step in the functional analysis of the MODEM system involved mapping identified system functions to system requirements. Behaviors performed by the system were traced to the various system requirements to identify how the system was satisfying those requirements and as a result, satisfying stakeholder needs. These relationships between system behavior and system requirement are mapped via a matrix, shown in Figure 26, with arrows identifying those dependencies of the behavior tracing to the requirement.



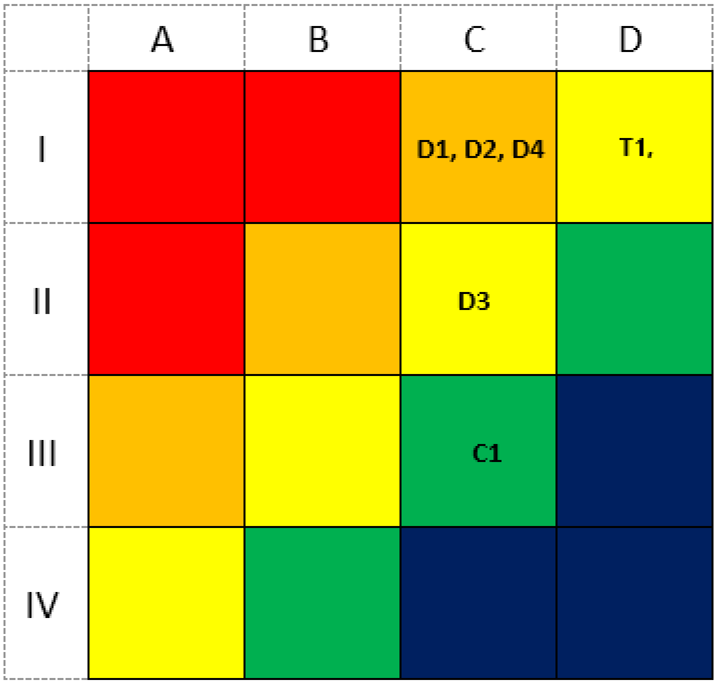
Legend
↗ Satisfy

	01 Measures of Effectiveness	MOE-1 MODEM Availability at Cost	MOE-2 MODEM Power Grid Resilience	MOE-3 MODEM Interoperability with Exis	MOE-4 MODEM Savings to Investment R	02 Measures of Performance	MOP-1 Operational Availability (Ao)	MOP-2 Total Life Cycle Cost	MOP-3 Mean Time Between Failure (MTB	MOP-4 Mean Logistics Delay Time (MLDT	MOP-5 Mean Time To Repair (MTTR)	MOP-6 Mission Duration	MOP-7 Minimum Charge Level	MOP-8 Average Load	MOP-9 Maximum Load	MOP-10 Power Generated	MOP-11 Power Distributed	MOP-12 Time to Restore Power	MOP-13 Percentage of Power Generatec	MOP-14 Load Shed	MOP-15 Dimensions	MOP-16 Weight	MOP-17 Interface Standard Compliance	MOP-18 Investment Cost	MOP-19 Energy Savings	MOP-20 Non-Energy Savings	MOP-21 Reliability
MODEM		2	15	15	5		2	4	2	2	2	5	2	7	7	3	3	5	1	3			5		3		2
Adjust Power Flow(parameter : Control Signal, parame	2		↗	↗		2								↗	↗												
Adjust Power Generation(parameter, parameter1)	2		↗	↗		2								↗	↗												
Control Microgrid(: Operator Input, : Control Signal,	2		↗	↗																							
Control Power Flow(parameter : Control Signal, parame	2		↗	↗																							
Convert Power(parameter : Power, parameter1 : Powe	2		↗	↗		1		↗																			
Distribute Power(: Power, : Power, : Power, : Contr	2		↗	↗		4								↗	↗		↗						↗				
Generate Power(: Solar Energy, : Fuel, : Power, : C	3		↗	↗	↗	4						↗		↗	↗	↗											
Make Control Decisions(parameter, parameter1, param	2		↗	↗		3												↗		↗			↗				
Measure Microgrid State(parameter : Status, paramete	1	↗				8	↗		↗	↗	↗							↗		↗			↗				↗
Provide Base Power Generation(parameter : Fuel, para	3		↗	↗	↗	4						↗		↗	↗	↗											
Provide Intermittent Power Generation(parameter : So	3		↗	↗	↗	7		↗				↗		↗	↗	↗			↗						↗		
Release Power(parameter, parameter1, parameter2 :	2		↗	↗		1											↗										
Report Status(parameter : Status)	1	↗				5	↗		↗	↗	↗																↗
Send Control Signals(parameter : Control Signal, param	2		↗	↗		3												↗		↗			↗				
Store Energy(: Power, : Power, : Control Signal, : St	3		↗	↗	↗	5		↗				↗	↗					↗							↗		
Store Power(parameter : Power, parameter1)	3		↗	↗	↗	5		↗				↗	↗					↗							↗		
Transmit Power(parameter : Power, parameter1 : Pow	2		↗	↗		4								↗	↗		↗						↗				

Figure 26. MODEM Function Mapping to System Requirements

E. RISKS ANALYSIS

MODEM can provide a great deal of capability to its connected load, but with that, there are inherent risks associated with the system, installation, interoperability, and sustainment of the system. The risks in this section have been associated with the MODEM system and have gone through a rigorous risk review board utilizing the Department of the Navy Operational Risk Management Guide to appropriately score them. The current risks fall into one of three categories, technical, cost, or design. The risks in its respective category have been identified by the team at the current state of the effort. Figure 27 captures the risks being tracked in a combined matrix. The top designation, A through D, captures the probability for frequency of occurrence. The side designation scales the severity from 1 to 4 for the effect of the risk. The colors of the matrix denote the category of the risk, blue is negligible, green is minor, yellow is moderate, orange is serious, and red is critical. As the MODEM design continues to mature, the expectation is that these risks will be negligible, converted to an issue, or lower in severity.



	A	B	C	D
I	🟥	🟥	🟧 D1, D2, D4	🟨 T1,
II	🟥	🟧	🟨 D3	🟩
III	🟧	🟨	🟩 C1	🟦
IV	🟨	🟩	🟦	🟦

Figure 27. MODEM Risk Matrix

1. Technical Risk

Technical Risk 1 (T1): If the MODEM microgrid does not abide by the Naval Facility Safety Standard, P-604, Electrical Safety Standards for Employees, then the MODEM system will not be installed at the facility.

The risk has been identified due to the nature of the system; in general, any electrical system needs to be able to demonstrate it is safe and worthy of installation. To be able to successfully install MODEM, it will have to go through a robust safety qualification to be installed in its designated location. If the location and system cannot be interoperable based on the safety standards required to be met, then the risk is considered a 3, for moderate.

2. Cost Risk

Cost Risk 1 (C1): If the MODEM microgrid does not have a savings to investment ratio of 1, then the microgrid is not suitable to be installed in a DOD installation.

This risk has been identified as it is critical for an electrical microgrid be able to generate a positive savings to investment ratio. A microgrid is a big financial effort that needs to be able to provide back its investment. Otherwise, the funding for this could have been applied to other DOD mission critical efforts. For this reason, the severity has been identified as a 3, with a probability of C due to its potential occurrence over time. This then ranks this risk as a minor level 4 risk.

3. Design Risks

The first two identified design risks revolve around the generator. The first risk intends to capture the risk associated with an outage due to the reclosing procedure, the second risk is about the ventilation that could cause overheating causing an outage due to overheating. Both risks have been categorized as serious.

Design Risk 1 (D1): If a self-generator is still on the line during an outage incident, then the automatic reclosing procedure will lead to a longer than necessary outage.

The recloser provides a critical function to the system as it acts as an automatic switch that shuts off electrical power when the system is in trouble. This risk captures the essentiality of having protocol in place for an outage incident. The recloser also needs to be designed to be able to shut down as quickly as possible.

Design Risk 2 (D2): If the generator does not have adequate ventilation, then the unit will have a catastrophic failure.

The generator needs to be strategically placed in the system to get the required ventilation. Ventilation in the system leads to overheating that can then cause damage to circuit parts, such as an arc fault event, fire, explosion, and ultimately personnel injury. This risk is important to track because if the final design does not have appropriate ventilation, then the damage by overheating can be irreversible, adding cost, schedule, and safety concerns.

The next two design risks are associated with the modules in the grid connected system and the batteries. The modules need to be matched correctly so that the array output is met, and the batteries need to be in a specific environment; the risks capture the probability of the likelihood in the environment and its potential consequence.

Design Risk 3 (D3): If the design of the grid-connected system has mismatched modules, then the array output will be dropped by several percentage.

The third risk captures the possibility of mismatched modules that would inhibit the array output, hence the microgrid not reaching its optimal state. This risk has been ranked as moderate.

Design Risk 4 (D4): If the selected batteries are not fit for the operational environment, then the environmental factors, such as temperature inside the unit, could cause the batteries to explode.

The last risk being tracked captures the probability of the batteries not being designed for the operational environment they are meant to serve in. This risk covers one environmental factor and a consequence. As the project evolves and more research is gathered from the batteries, the risk is expected to change or decrease in severity. This risk is currently in the serious category.

IV. ARCHITECTURE AND DESIGN DEFINITION

A. ARCHITECTURE DEFINITION

The definition of the MODEM system’s logical, functional, and physical architectures was one of the main goals for the MODEM team’s modeling effort. While the system’s functional architecture has been previously discussed in the “Functional Analysis” section of this paper, the “Architecture Definition” section focuses on the progression of the baseline into the logical and physical architectures.

To aid in defining the system logical architecture the MODEM team developed logical design alternatives and descriptions to create a Microgrid design decision tree. Design selections made in constructing the system’s logical architecture dictated what was necessary in the system’s physical architecture. The MODEM team’s logical architecture design decisions are depicted in Figure 28 and included the following:

- Energy generation: Microgrids are composed of a singular or multiple energy resources which can be physically collocated or form a network of DER. Common energy generation sources include fossil-fuel based generators, power plants, and renewable power sources. Types of power generation sources may be peaking power generation, load following, base generation, intermittent generation, or any combination of these types (Giachetti et al. 2020).

- Power distribution: Alternatives for power distribution include alternating current (AC) or direct current (DC). Common implementations of either transmission method include power lines and buses. In some cases, transformers are utilized to step up and/or step-down voltages. For microgrids with greater distances between network nodes, AC transmission is generally preferred. For microgrids supplying power to specialized loads or sensitive electronics, DC transmission is typically utilized (Giachetti et al. 2020).

- Energy storage: Microgrids architectures often include a means of capturing excess energy through various means of energy storage. Storage systems can take the form of batteries (lead acid, lithium, flow, etc.), mechanical storage (compressed air, flywheel, pump storage hydro, etc.), or thermal (cryogenic, ice storage, molten salt storage, etc.) (US EPA (2015)).

- Control methods / protection: Microgrid control can be implemented using a central control unit or with a combination of distributed control systems. Controllers, either centralized or decentralized, may implement protection schemes to protect nodes within the network during interruptions or faults.

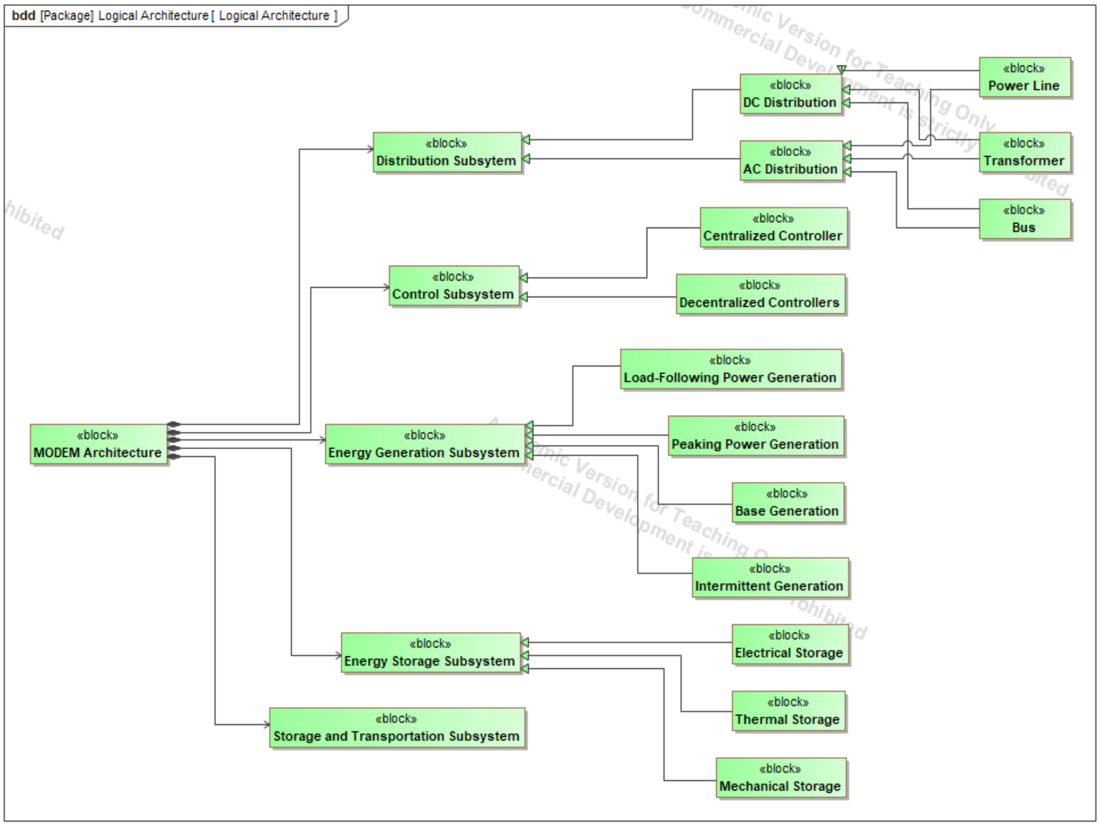


Figure 28. MODEM Logical Design Decision Tree

Figure 29 shows the MODEM team's allocations from the logical design decision tree to a physical system implementation forming the MODEM preliminary physical architecture. The system produces power by utilizing the emergency diesel generator and photovoltaic arrays. Power converted by the photovoltaic arrays is stored in the battery energy storage system and supplemented by the emergency diesel generator when necessary. During power outages, generated power stored in the battery energy storage system is converted and delivered to the critical load via a series of electrical buses via AC power, while the microgrid is controlled by multiple distributed controllers. The system elements are stored within the storage and transportation subsystem when the system is not in use or is in transit. Logical design decisions were primarily made to ensure alignment with the design previously identified by MAJ Varley. Additionally, the MODEM team used results from the stakeholder analysis, requirements definition, and functional analysis to evaluate, at a high level, the proposed physical architecture's ability to meet stakeholder needs, system requirements, and perform all necessary functionality.

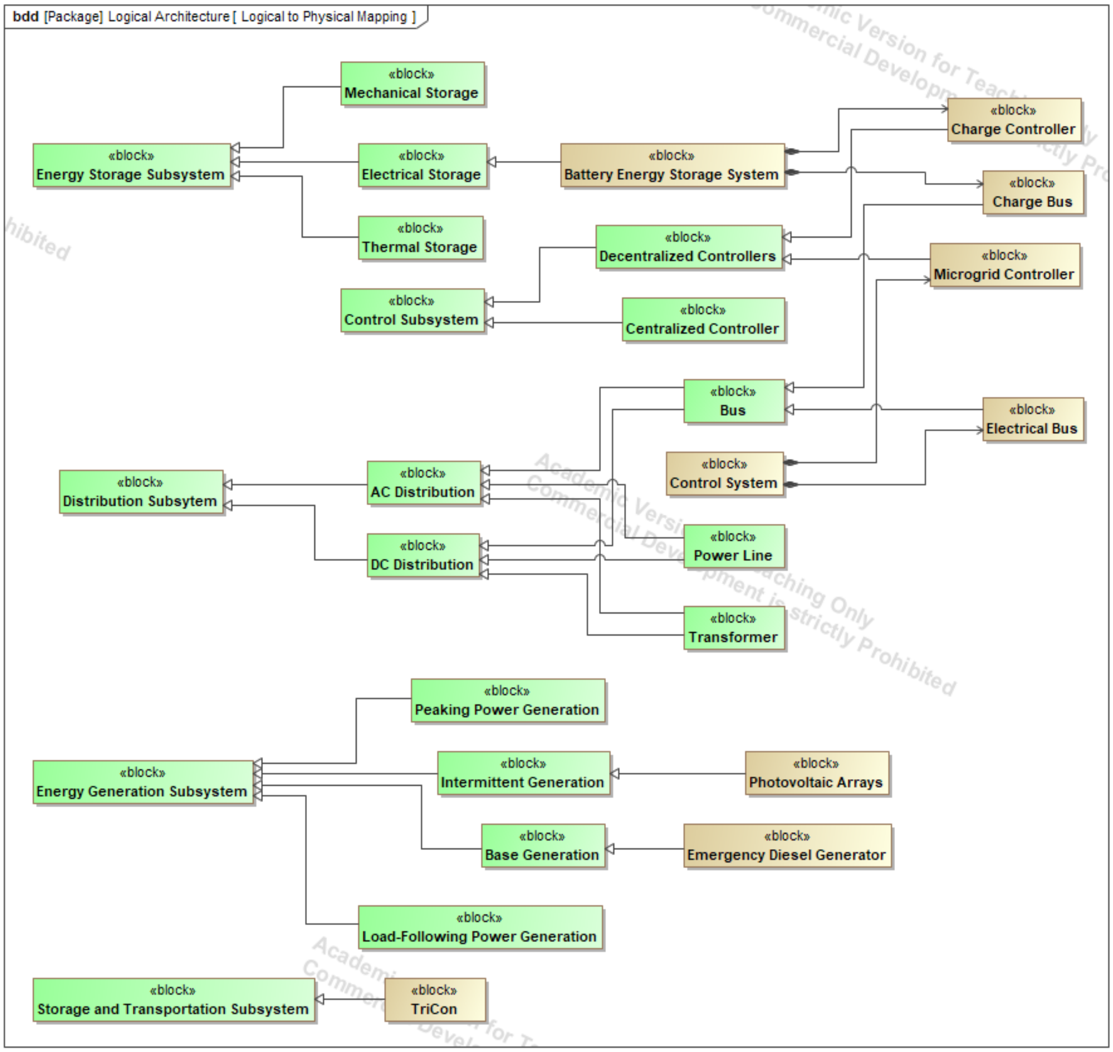


Figure 29. MODEM Logical Design Decision Tree to Physical Architecture Mapping

Figure 30 depicts the MODEM physical architecture at the subsystem level, based on the logical architecture, within the context of the larger system of systems (SoS) architecture of the proposed mission scenario. The subsystem architecture was then further decomposed into specific physical configuration items shown in Figure 31.

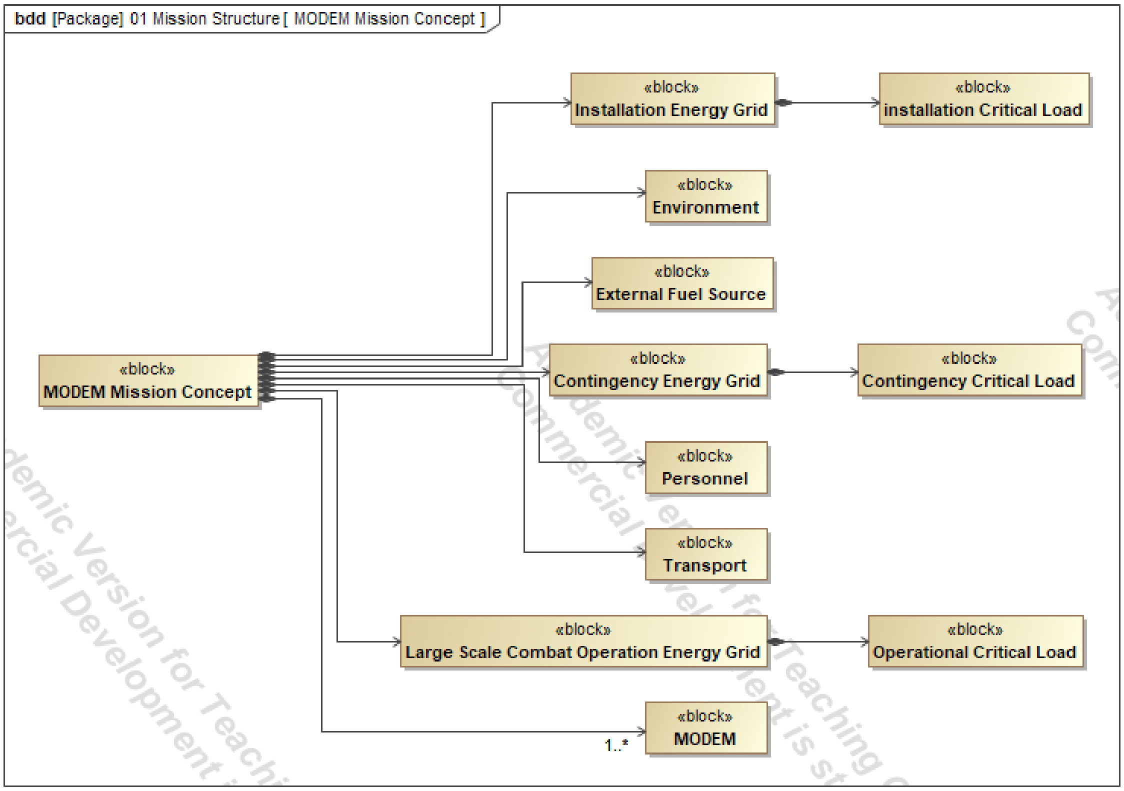


Figure 30. MODEM Mission Concept

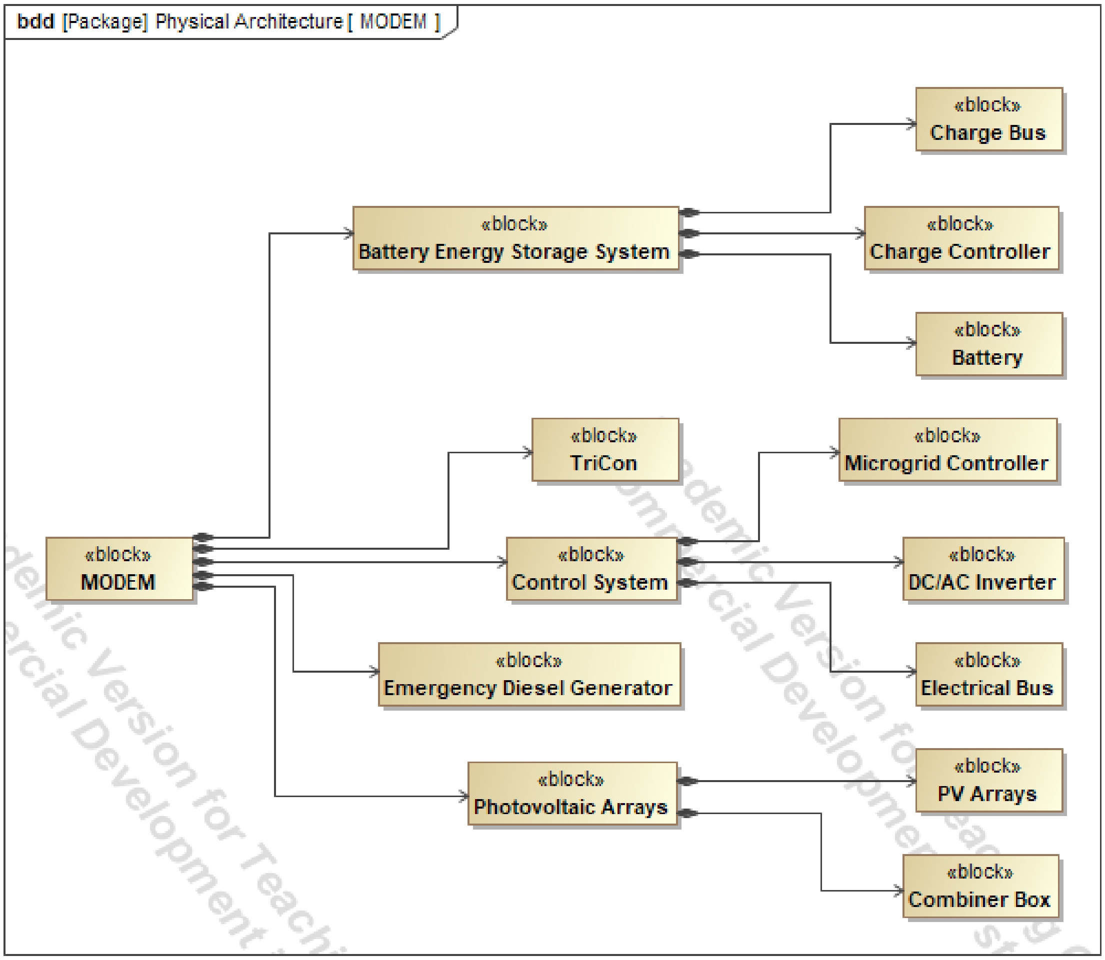


Figure 31. MODEM Physical Architecture

Figure 32 shows the inputs and outputs of the MODEM system which were previously identified in the functional analysis. The diagram provides visualization of the input and output flows that are required for the MODEM system to operate and details what the MODEM system generates and provides to the various energy grids. Allocation system level functionality to the physical architecture informs the required input and output signals for physical design elements based on the input and output parameters of the associated behaviors.

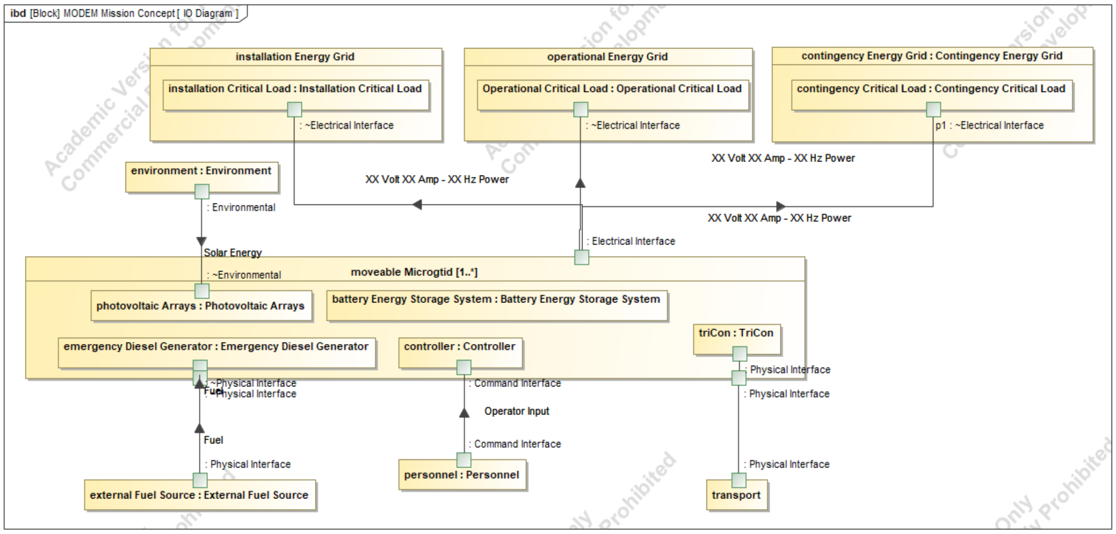


Figure 32. MODEM IO Diagram

Through stakeholder feedback, the MODEM team also considered using multiple MODEM units to support larger critical loads and created a conceptual Multi-MODEM Architecture (MMA) to show at a high level the extra components necessary to implement multiple MODEM units in parallel. The architecture includes the addition of cables necessary to connect the units in parallel as well as a high-power controller to distribute the generated power to the larger critical load. While the MODEM team determined that using multiple units in parallel should be possible, further exploration of the MMA was not in scope of this project. The MMA architecture and MMA IO diagrams are represented in Figure 33 and Figure 34, respectively.

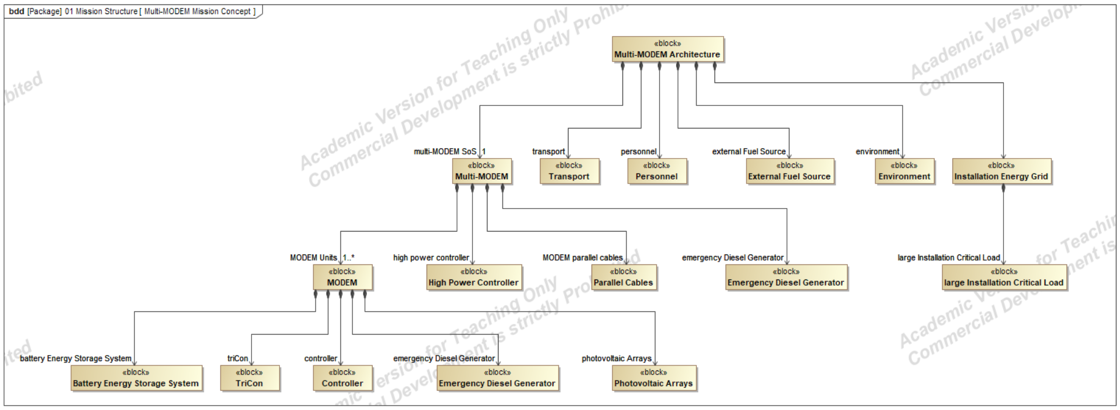


Figure 33. Multi-MODEM Architecture

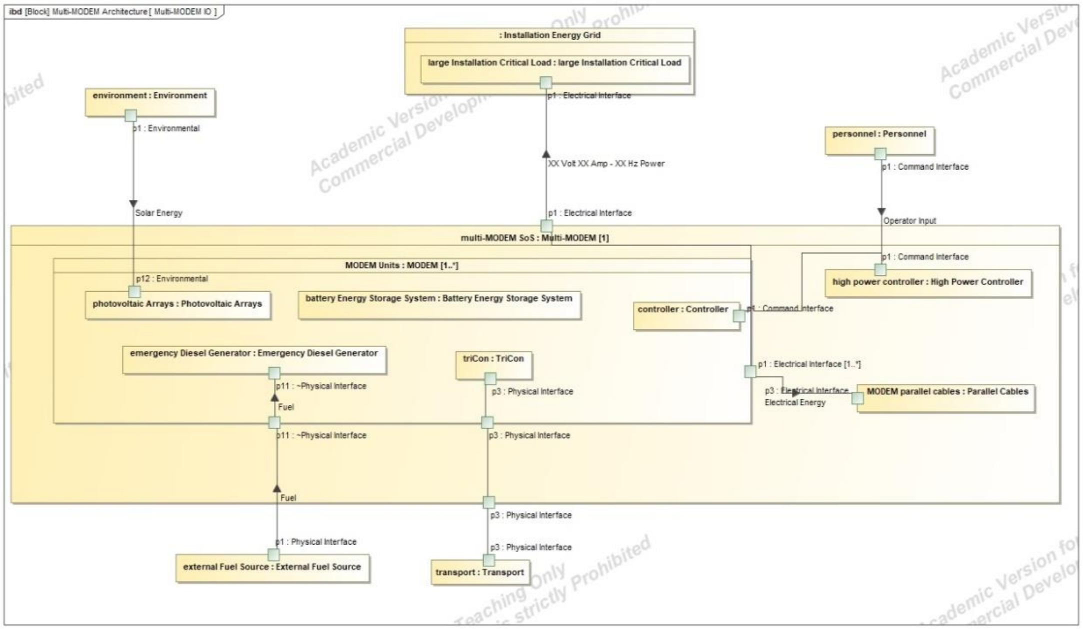


Figure 34. Multi-MODEM IO Diagram

B. DESIGN DEFINITION

The MODEM team's INCOSE-based approach to system design was "technology oriented through physical, structural, environmental, and operational properties forcing decisions for implementation by focusing on compatibility with technologies and other design elements and feasibility of construction and integration" (INCOSE 2015, 64). The MODEM team conducted research and a thorough review of previous MODEM works to understand the physical, structural, environmental, and operational properties. With this understanding, the MODEM team established a baseline design largely developed on the research conducted by MAJ Daniel Varley looking at hybrid mobile microgrids for military applications. MAJ Varley analyzed various microgrid configurations with the following base requirements, "…constrained within an International Standards Organization (ISO) TriCon and not to exceed 10,000 lbs., to provide power in a fuel constrained environment for DOD small critical loads (average loads of 10 kW)" (Varley 2022). MAJ Varley proposed specified batteries, photovoltaic panels, and a diesel generator based on simulated analyses looking at operational effectiveness. The MODEM team reviewed MAJ Varley's proposed design and captured the work in MSOSA, as shown in Figure 35 and adapted that design to model the MODEM internal interfaces as shown in Figure 36:

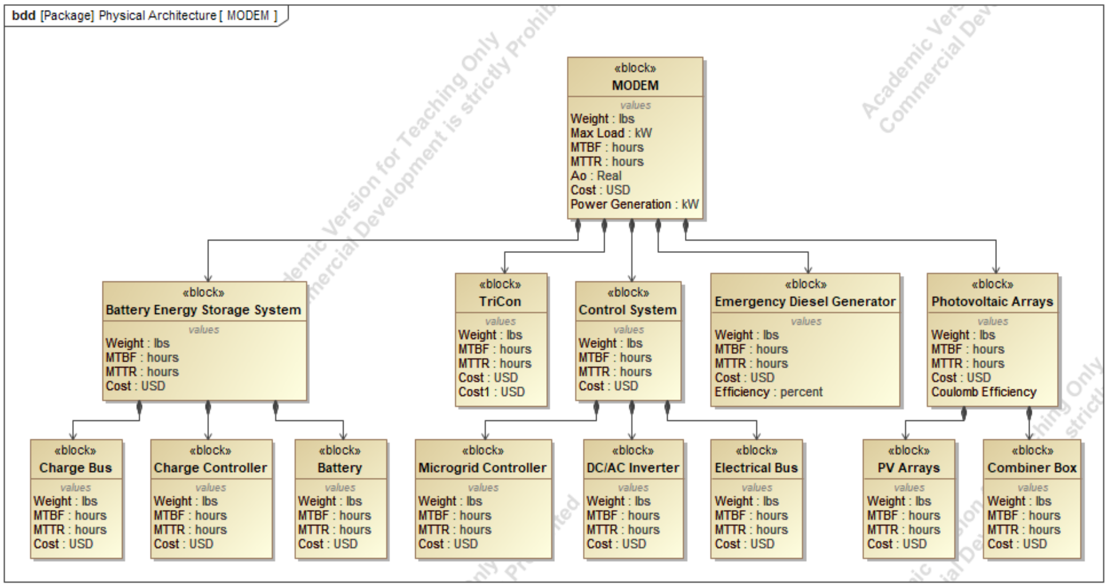


Figure 35. MODEM Baseline Design

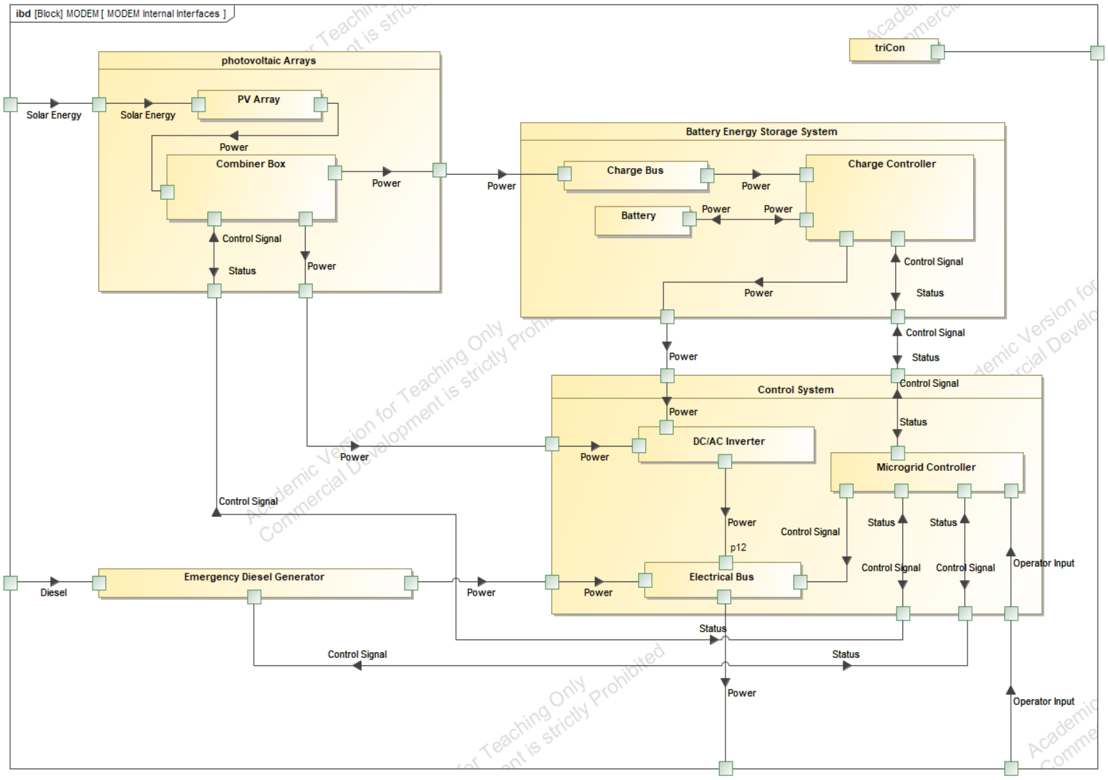


Figure 36. MODEM Internal Interfaces

After establishing a baseline MODEM design, the MODEM team continued to conduct research and capture additional feedback and needs from key stakeholders. The additional information assisted the team in identifying shortfalls in the design and where to focus further development.

C. SAFETY CONSIDERATIONS

A key aspect to implementing microgrids across Naval Facilities is safety. The microgrid needs to be operationally safe for the humans interfacing with it but it also must comply with the facility safety standards. The current MODEM system is currently designed for 48 V. This voltage was chosen due to the DOD safety standards for untrained personnel to work on the system. This voltage was designed into as a precaution but ultimately Naval Facilities must abide by the “P-604 Safe Acts for Employees” (Naval Facilities Engineering Command [NAVFAC] 2019) for electrical components. Below is a breakout of applicable considerations the implementation of microgrids must account for.

Employee Qualifications: An employee handling the microgrid needs to be trained in understanding the purpose and function of the energy control program, the employee should also have some understanding in the hazardous energy source, type and magnitude of energy, and necessary methods to isolate and control the system. The employee should also be able to distinguish the exposed energized parts from other parts in the electrical system. The employee managing the microgrid should also know proper techniques for electrical precaution, they should also know any Personal Protective Equipment (PPE) that they might need, in addition to insulating and shielding materials for self and system protection, and lastly they should have knowledge of any insulated tools for working on or near unprotected energized components (NAVFAC 2019).

Low Voltage Outage Procedures: An employee must be familiar and comfortable by the Low Voltage Outage Procedure outlined in the P-604 Safe Acts for Employees guide under section 2.3.3. The procedure is detailed enough to account for the general preparation, de-energization of circuit and equipment, the testing of no voltage and application of temporary personal protective grounds, guidance to brief out, the verification of no voltage, and the performance of a lock out tag out (NAVFAC 2019).

Arc Flash Precautions: Employees working on MODEM need to be trained and qualified for any activity that needs to be performed on an energized control circuit. Because the system is a 48V system, PPE clothing to manage the arc flash is optional (NAVFAC 2019).

While there is a large variety of COTS items available to design an optimal micro grid, there will always be a struggle to balance out the cost, efficient integration, safe distribution protection, and following all the industry and DOD safety standards. The above considerations account for a low voltage system; the system as a result has lesser restrictions and less rules to abide by. The selected voltage also provides versatility in the type of employee that can be hired or placed in, to work and maintain this system. As the design of MODEM continues to develop, the safety standards need to be revisited and ensure that the designated protocols are considered per the system specifications.

THIS PAGE INTENTIONALLY LEFT BLANK

V. SYSTEM ANALYSIS

A. SYSTEM ANALYSIS PROCESSES

The System Analysis Process within our identified SE Process is where the majority of the work performed on this project lies. The work and analyses performed are discussed in the following sections and are critical in the overarching assessment of the MODEM's ability to be a feasible solution to increasing DOD energy resiliency. It is within this process that the MODEM team determined the ability of the components within the MODEM solution to be interoperable with one another from a functional perspective. Additionally, the team determined whether the components within the MODEM solution are capable of meeting mission related requirements—this is largely based in reliability and sparing analysis.

For our analyses the MODEM team focused on compiling information for the individual system components and then utilizing that data to perform preliminary system-level analyses. These system-level analyses were conducted to assess the MODEM system's ability to meet the system MOEs as the system is currently designed. The criteria and use cases that were analyzed by the MODEM team were selected based upon stakeholder input and availability of data.

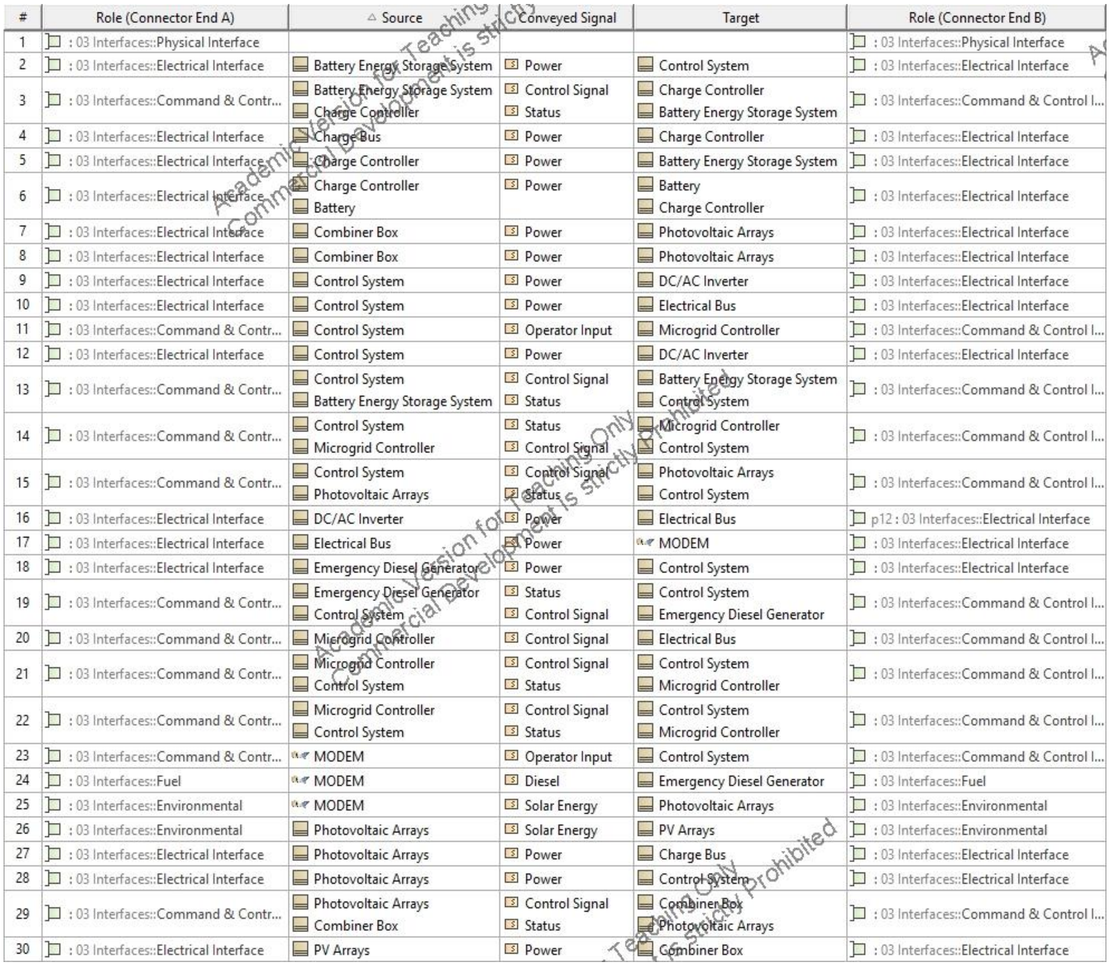
1. Integration Planning Foundation (Interoperability Analysis)

The MODEM team's interoperability analysis activities focused on identifying and documenting both internal and external system interfaces throughout the functional, logical, and physical architecture definition phases. Integration planning activities also included identifying necessary equipment to facilitate integration of the various COTS components and determining areas within the physical architecture that require further exploration to address potential integration or interoperability issues based on research of the technologies implemented in the MODEM design.

The MODEM design represents a system of unique systems that must be able to exchange information to support the safe, secure, efficient, and reliable operation of the microgrid system. This functional necessity represents a small-scale example of the growing complexity in interoperability requirements for electrical grids based on the growing number of devices and systems utilized (NIST 2021).

Although undesirable, interoperability and integration issues often require custom one-off solutions, or point-to-point integration. Point-to-point solutions are typically time consuming and have high associated costs but are usually necessary when interfacing new and legacy equipment or when integrating components that do not adhere to a common published communication standard or interface protocol (NIST 2021).

The output of the team's preliminary interoperability analysis was foundational in nature and intended to enable more in-depth analysis of integration requirements for any follow-on efforts in assessing or implementing the MODEM units' interface with existing infrastructure. As part of the functional analysis phase, critical system functions as well as their functional interfaces and dependencies were identified and documented via activity flows. This process aided in documenting functional inputs and outputs at both the system level, with respect to external entities, as well as internally, with respect to subsystem and component level interactions. Once logical and physical architectures of the system were completed, the functional architecture was then allocated to the various design components and formed the basis of all interface definitions both internal and external to the system. Various design needs were identified through this process including the need for a DC to AC inverter, a PV array combiner box, and various busses necessary for charging and distribution. Figure 37 summarizes the MODEM Interface Control Document which provides a wholistic summary of interfaces including those to external systems, between subsystems, and between components. This summary table is the starting point for future design activities necessary to enable implementation of the MODEM design and integration with existing infrastructure, which will likely require point-to-point solutions for many of the critical loads intended to be supported. Further details regarding proposed next steps in the system's interoperability analysis are covered in Chapter VI of this report.



#	Role (Connector End A)	Source	Conveyed Signal	Target	Role (Connector End B)
1	: 03 Interfaces::Physical Interface				: 03 Interfaces::Physical Interface
2	: 03 Interfaces::Electrical Interface	Battery Energy Storage System	Power	Control System	: 03 Interfaces::Electrical Interface
3	: 03 Interfaces::Command & Contr...	Battery Energy Storage System Charge Controller	Control Signal Status	Charge Controller Battery Energy Storage System	: 03 Interfaces::Command & Control I...
4	: 03 Interfaces::Electrical Interface	Charge Bus	Power	Charge Controller	: 03 Interfaces::Electrical Interface
5	: 03 Interfaces::Electrical Interface	Charge Controller	Power	Battery Energy Storage System	: 03 Interfaces::Electrical Interface
6	: 03 Interfaces::Electrical Interface	Charge Controller Battery	Power	Battery Charge Controller	: 03 Interfaces::Electrical Interface
7	: 03 Interfaces::Electrical Interface	Combiner Box	Power	Photovoltaic Arrays	: 03 Interfaces::Electrical Interface
8	: 03 Interfaces::Electrical Interface	Combiner Box	Power	Photovoltaic Arrays	: 03 Interfaces::Electrical Interface
9	: 03 Interfaces::Electrical Interface	Control System	Power	DC/AC Inverter	: 03 Interfaces::Electrical Interface
10	: 03 Interfaces::Electrical Interface	Control System	Power	Electrical Bus	: 03 Interfaces::Electrical Interface
11	: 03 Interfaces::Command & Contr...	Control System	Operator Input	Microgrid Controller	: 03 Interfaces::Command & Control I...
12	: 03 Interfaces::Electrical Interface	Control System	Power	DC/AC Inverter	: 03 Interfaces::Electrical Interface
13	: 03 Interfaces::Command & Contr...	Control System Battery Energy Storage System	Control Signal Status	Battery Energy Storage System Control System	: 03 Interfaces::Command & Control I...
14	: 03 Interfaces::Command & Contr...	Control System Microgrid Controller	Status Control Signal	Microgrid Controller Control System	: 03 Interfaces::Command & Control I...
15	: 03 Interfaces::Command & Contr...	Control System Photovoltaic Arrays	Control Signal Status	Photovoltaic Arrays Control System	: 03 Interfaces::Command & Control I...
16	: 03 Interfaces::Electrical Interface	DC/AC Inverter	Power	Electrical Bus	p12 : 03 Interfaces::Electrical Interface
17	: 03 Interfaces::Electrical Interface	Electrical Bus	Power	MODEM	: 03 Interfaces::Electrical Interface
18	: 03 Interfaces::Electrical Interface	Emergency Diesel Generator	Power	Control System	: 03 Interfaces::Electrical Interface
19	: 03 Interfaces::Command & Contr...	Emergency Diesel Generator Control System	Status Control Signal	Control System Emergency Diesel Generator	: 03 Interfaces::Command & Control I...
20	: 03 Interfaces::Command & Contr...	Microgrid Controller	Control Signal	Electrical Bus	: 03 Interfaces::Command & Control I...
21	: 03 Interfaces::Command & Contr...	Microgrid Controller Control System	Control Signal Status	Control System Microgrid Controller	: 03 Interfaces::Command & Control I...
22	: 03 Interfaces::Command & Contr...	Microgrid Controller Control System	Control Signal Status	Control System Microgrid Controller	: 03 Interfaces::Command & Control I...
23	: 03 Interfaces::Command & Contr...	MODEM	Operator Input	Control System	: 03 Interfaces::Command & Control I...
24	: 03 Interfaces::Fuel	MODEM	Diesel	Emergency Diesel Generator	: 03 Interfaces::Fuel
25	: 03 Interfaces::Environmental	MODEM	Solar Energy	Photovoltaic Arrays	: 03 Interfaces::Environmental
26	: 03 Interfaces::Environmental	Photovoltaic Arrays	Solar Energy	PV Arrays	: 03 Interfaces::Environmental
27	: 03 Interfaces::Electrical Interface	Photovoltaic Arrays	Power	Charge Bus	: 03 Interfaces::Electrical Interface
28	: 03 Interfaces::Electrical Interface	Photovoltaic Arrays	Power	Control System	: 03 Interfaces::Electrical Interface
29	: 03 Interfaces::Command & Contr...	Photovoltaic Arrays Combiner Box	Control Signal Status	Combiner Box Photovoltaic Arrays	: 03 Interfaces::Command & Control I...
30	: 03 Interfaces::Electrical Interface	PV Arrays	Power	Combiner Box	: 03 Interfaces::Electrical Interface

Figure 37. MODEM Interface Control Document (ICD)

2. Operations & Sustainment Planning

The Operations & Sustainment phase is when a fully identified and integrated system is fielded and operated within the identified environments. All relevant metrics are tracked to their requirements and any issues that arise are addressed by the program so the system can continue to operate as designed. Additionally, all support infrastructure and assessment begin and continue throughout this process. It is within this phase that a program will spend the majority of its life and in which a system will traditionally incur the most cost. Many of the analyses performed up to this phase and throughout are critical in ensuring the system optimizes performance and cost (i.e., Ao at Cost), as well as meeting the identified MOEs and other technical and functional requirements. The following sections discuss the background and relevancy of reliability and sustainment to the MODEM effort, the initial research and relevant calculations that were performed by the team, the relationship and validation of relevant requirements, and any associated recommendations from the analyses.

a. Reliability Analysis

Reliability is the probability, typically expressed as a percentage, that a system will perform an intended function or set of functions over a specified period of time under stated conditions. It is imperative that programs consider reliability throughout the planning and design of systems in order to deliver an effective system. All aspects of the system must be in working order if the overall system is to be able to achieve desired capabilities. Another very closely related metric to reliability is Mean Time Between Failure (MTBF). MTBF is the average predicted amount of time, often expressed in hours, between failures of a system or its components during normal operating conditions. While not a one-to-one definition, MTBF is often the metric programs use to track system performance from a reliability perspective. It should be noted that reliability is a function of MTBF, which is typically where the relationship between the two stems from.

(1) Research

The nature of this project had the team utilizing prior work that already identified a potential system and the COTS items that would encompass it (Varley, Van Bossuyt, and Pollman 2022). We began our reliability research by looking into the specific hardware identified by MAJ Varley but ran into issues with reliability data being available. Companies often restrict this type of data unless requested by a potential partner or customer. The next best solution was to utilize other research both specific to the hardware and specific to our particular scenario. We were able to identify and interpolate values for components within our system that would satisfy the initial reliability assessment the team wished to perform. Table 3 shows the final MTBF values for each of the items within the MODEM as well as the sources from which these values came.

Table 3. Identified System MTBF Values

Subsystem	Component	Reliability (MTBF) (hours)	Source
Battery Energy Storage System	Charge Bus	28,177	Baschel, Koubli, Roy, and Gottschalg 2018
Battery Energy Storage System	Charge Controller	131,400	Gerken and Welsh 1997
Battery Energy Storage System	Battery	131,400	EG4 Battery
Control System	DC/AC Inverter	65,707	Alfano 2011
Control System	Electrical Bus	28,177	Baschel, Koubli, Roy, and Gottschalg 2018
Emergency Diesel Generator	Generator	1,662	Marqusee and Jenket II 2020
Photovoltaic Arrays	PV Array	719,114	Collins, Dvorack, Mahn, Mundt, and Quintana
Photovoltaic Arrays	Combiner Box	2,469,136	NREL 2017

(2) Calculations

Once the component reliability values were established, the team could then begin rolling these values up to both the subsystem and system level to identify the overall expected reliability in terms of both metrics. First, the MTBFs of each component were converted into reliability using Equation 1. Once each component was expressed in terms of reliability, rolling up to the subsystem and system level could be done using Equation 2 and Equation 3 respectively. The final results of the calculations and rollup can be seen in the system tree found in Table 4. It should be noted that a factor was placed on the diesel generator to simulate the fact that it would not be running constantly over the timeframe for each use case. The generator is functionally supposed to ensure adequate charge of the BESS and to provide supplemental power if the PV arrays cannot maintain sufficient charge against the load. A generator usage of 65% was determined based off the calculations done by MAJ Varley in his model (Varley 2022).

$$R(t) = e^{-\lambda t} = e^{-t/MTBF} \qquad \text{(Equation 1)}$$

$$R(t)_{SUBSYSTEM} = \prod R(t)_{COMPONENTS} \qquad \text{(Equation 2)}$$

$$R(t)_{SYSTEM} = \prod R(t)_{SUBSYSTEM} \qquad \text{(Equation 3)}$$

Table 4. System Tree with Calculated Reliability for Both Use Cases

		Service Interruption Use Case (t = 168 hours)	Continuous Use Case (t = 8,760 hours)
Indenture Level	Item	Reliability	Reliability
1A	System	92.00%	1.00%
1A1	BESS	99.15%	64.13%
1A1A1	Charge Bus	99.41%	73.28%
1A1A2	Charge Controller	99.87%	93.55%
1A1A3	Battery	99.87%	93.55%
1A2	Control System	99.15%	64.13%
1A2A1	DC/AC Inverter	99.74%	87.52%
1A2A2	Electrical Bus	99.41%	73.28%
1A3	Emergency Diesel Generator	93.64%	3.25%
1A3A1	Generator	93.64%	3.25%
1A4	Photovoltaic Arrays	99.97%	98.44%
1A4A1	PV Array	99.98%	98.79%
1A4A2	Combiner Box	99.99%	99.65%

Additionally, a simple series reliability block diagram (RBD) was utilized for these calculations. Figure 38 shows the MODEM RBD at the subsystem level with each subsystem being in series. Within each of the subsystem blocks, the subsequent components are also in series. In cases where there are multiple instances of a component, such as the batteries and the PV Arrays, these components have an n:n have-need relationship where n represents the number of these components within the system. In this configuration, a single failure of any part of the MODEM system will cause a critical failure and full functionality of the system will not be available.

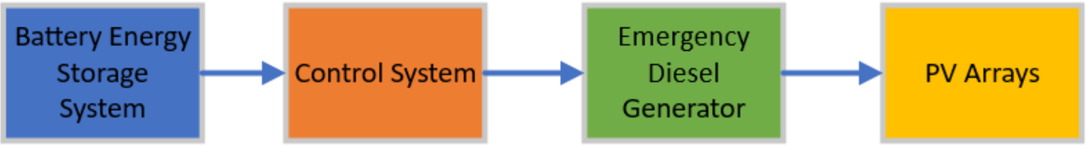


Figure 38. MODEM Subsystem Series RBD

(3) Reliability Analysis

After performing the calculations and getting values from component level up to the MODEM system level, the team was then able to assess these results within the context of system requirements. We were able to verify the system reliability requirements, both reliability and MTBF, as well as assist in the verification of other sustainment related requirements, such as Ao, MLDT, and MTTR.

The two high level use cases of continuous use and service interruption use, have significantly different parameters, and the team fully expected the outcomes of the reliability analysis to vary greatly between the two. Again, the primary difference between the two is the time in which the system operates, which has a drastic impact on the system's reliability. The continuous use case was assessed to show the system's reliability over the span of a year (8,760 hours), while the service interruption use cases would only simulate a system utilization of 12 hours per day over 14 days (168 hours) per the prior research and use cases identified by MAJ Varley (Varley, Van Bossuyt, and Pollman 2022).

Figure 39 shows the reliability for each component of the MODEM over the 168 hours, and Figure 40 shows the rolled-up reliability values for the subsystems and the overall system. Figure 40 also includes a threshold line at 90% to show the system level requirement the MODEM aims to achieve. From these two figures, the team deduced that, overall, the system is capable of meeting the reliability and MTBF requirements that have been identified. Additionally, we can see where the system is likely to have the most issues from a reliability perspective—in this case, the diesel generator is our primary concern. Even at a reduced usage rate compared to the other components, the generator is likely to be the primary cause of critical failures to the overall MODEM system in service interruption use cases. We can also deduce this from the MTBF values in Table 3 as the generator has the lowest MTBF of any other by a good amount.

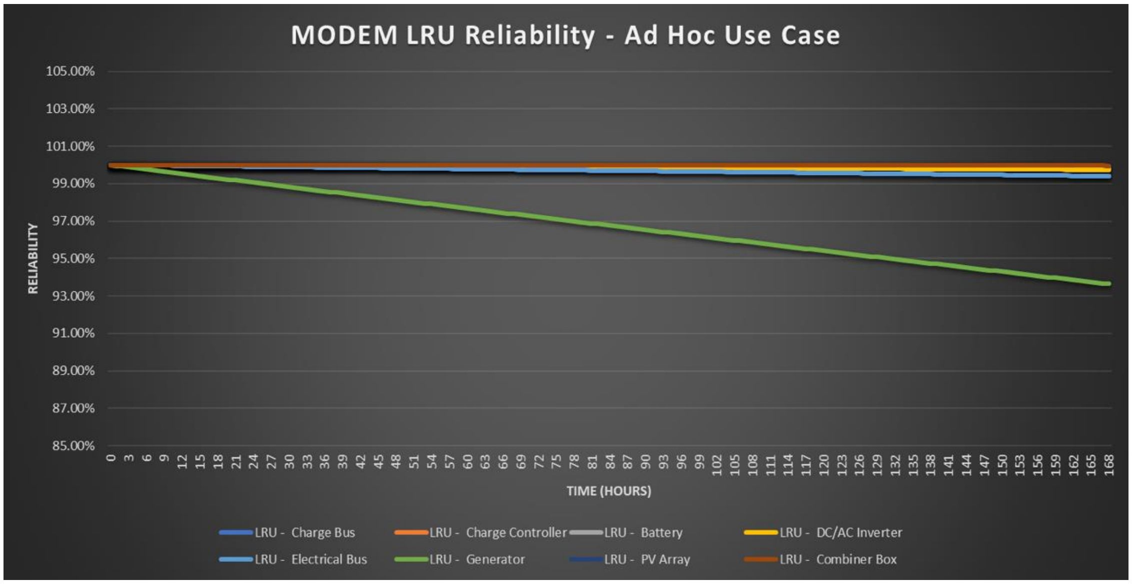


Figure 39. MODEM Component Reliability for Service Interruption Use Case

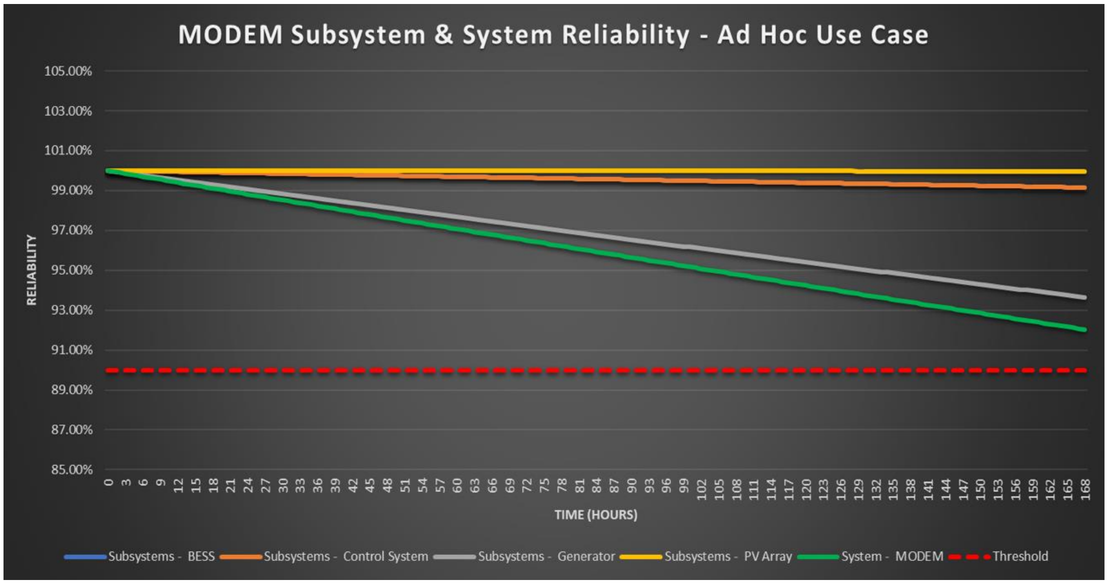


Figure 40. MODEM Subsystem & System Reliability for Service Interruption Use Case

Similar to the service interruption use case, Figure 41 shows the reliability for each component of the MODEM over 8,760 hours, and Figure 42 shows the rolled-up reliability values for the subsystems and the overall system for the continuous use case. Figure 42 also includes a threshold line at 90% to show the system level requirement the modem aims to achieve. As expected, the results of the continuous use case are very different from the service interruption use case. From the figures, we can see that, overall, the system is not capable of meeting the reliability and MTBF requirements that have been identified. In fact, the system reliability quickly goes below the 90% threshold and even reaches below a 50% reliability before the halfway point in the overall operational timeframe. Again, we can see the diesel generator is our primary cause of this, but we also see that other subsystems are likely to reduce the overall reliability. Not easily seen from the figure—both the BESS and the Control System are areas of concern for the team. Even still, the generator is likely to be the primary cause of critical failures to the overall MODEM system in the continuous use case. These outcomes are, again, somewhat expected as the MTBF values of the generator are the lowest. Additionally, we can see from the reliability values in Table 4, which subsystems are cause for concern.

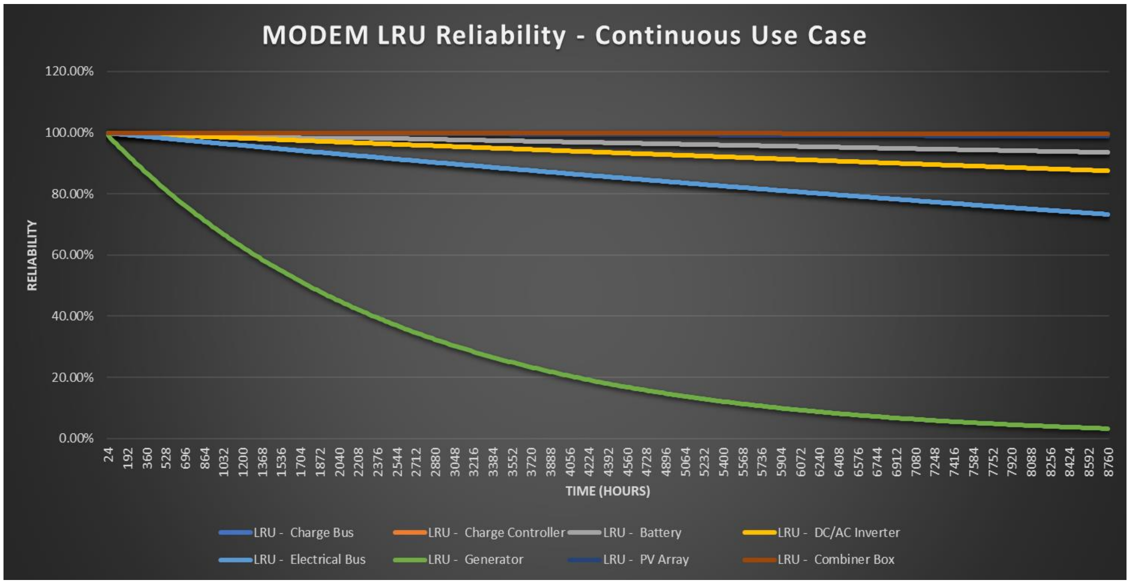


Figure 41. MODEM Component Reliability for Continuous Use Case

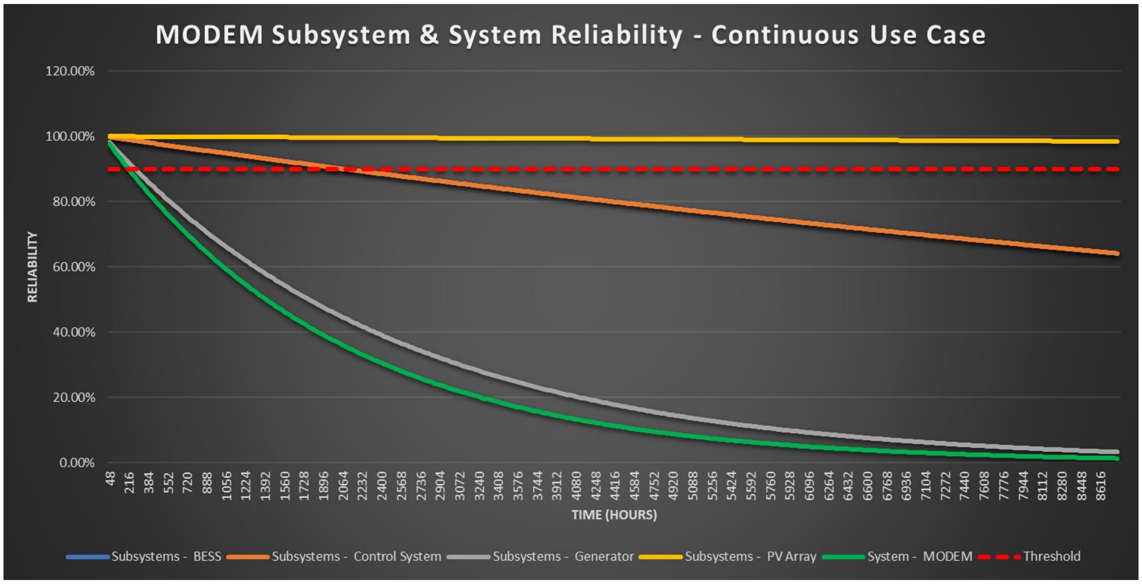


Figure 42. MODEM Subsystem & System Reliability for Continuous Use Case

b. *Maintenance Analysis*

Maintenance is one of the most important aspects of the O&S phases of a systems life cycle—both from a cost and execution perspective. Maintenance goes hand-in-hand with reliability in the overall goal of fielding an operationally capable system at cost, and, like reliability, maintenance should be planned out well in advance of the O&S phase. At the very least, a program should begin considering the strategies they might employ for the system, the infrastructure necessary, and, of course, the associated costs. The primary purpose of the maintenance analysis for the MODEM team was to leverage the reliability analysis that was performed to begin this preliminary planning. This combination of reliability and maintenance strategies further the possibility of a capable system.

(1) Types of Maintenance Philosophies

While there are many types of maintenance and many types of strategies across both the DOD and private industry, the two primary forms which all other types likely fall under are preventative maintenance and corrective maintenance. A few, though not all, of the subsets of both maintenance strategies will be discussed and utilized for this analysis.

Preventative maintenance is a maintenance strategy in which maintenance is performed on a system prior to failure occurring. A common example of this would be changing the oil in a car. Within the context of this effort, the team will focus on two subsets of preventative maintenance known as time-based maintenance and condition-based maintenance. Time-based maintenance is maintenance that is performed at set intervals—typically time or cycles. The car oil example mentioned previously is an example of time-based maintenance. Condition-based maintenance is slightly more complicated than time-based in that it relies heavily on a system being able to report its conditions effectively and correctly prior to failure. A program would set thresholds based on performance of the system and perform maintenance when the system fell outside of these thresholds. A simple example of this would be the light on a flashlight dimming due to the charge level of its batteries deteriorating.

Corrective maintenance is a maintenance strategy in which maintenance is performed on a system after a failure has occurred and aims to restore full or partial system capability. While corrective maintenance might seem cheaper and easier since you are essentially running the system and its components until there is a failure, it is actually the opposite. Using a corrective maintenance strategy can be more costly in the long run and takes much more planning. Systems that are less sophisticated, that have cheaper lower-level components, or are more reliable can sometimes benefit from a corrective maintenance strategy. The key with corrective maintenance is ensuring adequate spares are available when needed and that operators are trained to perform these maintenance tasks in a timely manner.

(2) Analysis & Strategy

After analyzing the results from our reliability analysis, we were able to begin identifying the best methods for supporting the various hardware within the MODEM system. It should be noted that the assessment done by the team is very preliminary and should serve as a jumping off point for further assessment and analysis—these are discussed in Chapter VI, "Recommendations and Future Work." The team has identified both a primary and a secondary strategy for each of the components. This primarily serves as a backup strategy but also because some of the strategies are dependent on the actual COTS items in the final design. The primary will serve as the most general and readily accessible with the secondary being a potential solution. This being said, all components could simply be swapped with all new hardware, which would be similar to corrective maintenance. Table 5 shows the strategies that were chosen for each component.

Of the eight components, six utilize corrective maintenance as the primary strategy with no secondary solution. As mentioned above, the corrective maintenance strategy of simply replacing the components with all new ones is the default. The main reasoning for choosing just corrective maintenance for these items is largely due to their cost and overall reliability. The busses (charge and electrical) are two of the more expensive items but are relatively simple and it's highly likely a full replacement would not be necessary. The charge controller, the combiner box, and the PV arrays are relatively inexpensive so simply keeping spares on-hand would be a feasible option. The reliability of these components is also relatively high which would mean they wouldn't need replacing often—especially the PV arrays. The DC/AC inverter is one of the more expensive items, but it also has relatively high reliability so swapping out spares would not occur often. Overall, the suggested strategy for these five components would be to identify a specific sparing strategy that would allow spares of these components to be shipped and kept with the system.

Table 5. Proposed Component Maintenance Strategies & Costs per Item

Subsystem	Component	Maintenance Strategy	Cost per Item ($)	Source
Battery Energy Storage System	Charge Bus	Primary: Corrective Secondary: N/A	$3,250.00	Electrical.com
Battery Energy Storage System	Charge Controller	Primary: Corrective Secondary: N/A	$589.05	Northern Arizona Wind & Sun
Battery Energy Storage System	Battery	Primary: Preventative (Time) Secondary: Corrective	$2,459.80	Lithium Battery Power
Control System	DC/AC Inverter	Primary: Corrective Secondary: N/A	$3,450.00	SunWatts
Control System	Electrical Bus	Primary: Corrective Secondary: N/A	$3,250.00	Electrical.com
Emergency Diesel Generator	Generator	Primary: Preventative (Time-Based) Secondary: Corrective	$20,000.00	Ebay
Photovoltaic Arrays	PV Array	Primary: Corrective Secondary: Preventative (Condition)	$365.00	SunWatts
Photovoltaic Arrays	Combiner Box	Primary: Corrective Secondary: N/A	$663.25	Inverter.com

The other two components involve some type of preventative maintenance strategy with the secondary being corrective. Like all batteries, lithium-ion batteries degrade over time so replacing them at set intervals can help mitigate the likelihood of failures in the system. Additional spares of the batteries are also suggested. Finally, the diesel generator, which is the costliest item, will greatly benefit from routine maintenance practices. As was pointed out in the reliability analysis, this was the primary concern towards reliability due to the poor MTBF values. Doing preventative maintenance can help reduce the likelihood of failure and prolong the generators life. Since the generator was the driver towards reliability, the team wanted to simulate how preventative maintenance might impact the reliability of the overall system across the continuous use case since that scenario was where the system failed to meet requirements. Figure 43 shows three separate assessments: the first is a baseline and is the original reliability values performed in the reliability analysis, the second shows the sawtooth curves generated by the simulated maintenance on the generator, and the final simply shows the system reliability sans generator. The periodicity of service is an average based on research done by the team and was set to 450 hours. From this we can see that even with the periodic maintenance of the generator, the system is still unable to achieve the reliability requirement. We can also see that it does not meet this requirement without the generator, which indicates the other components have a part to play.

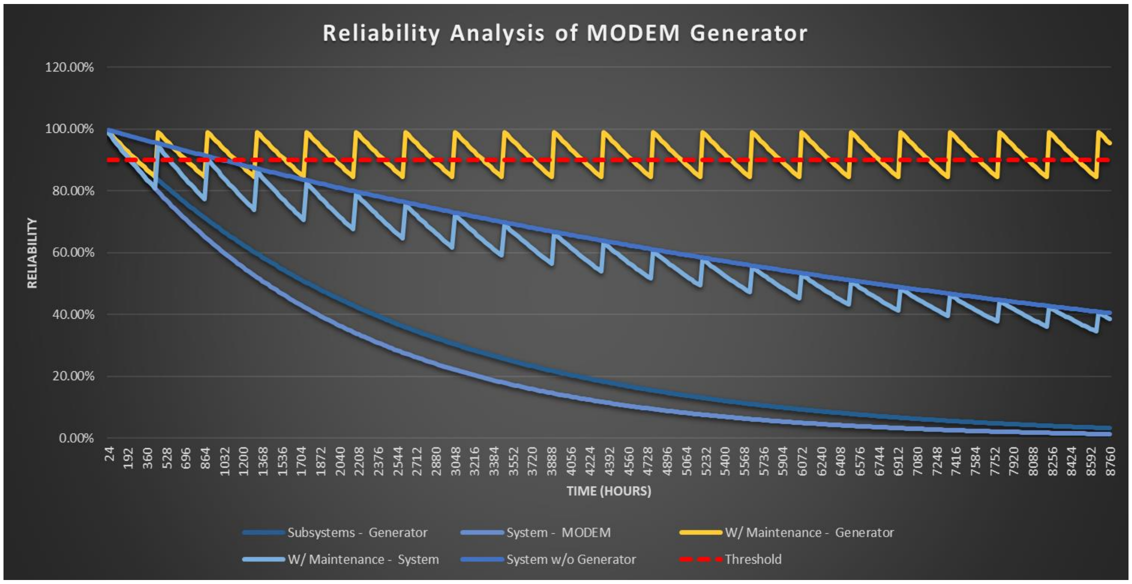


Figure 43. MODEM Reliability Assessment for Generator Maintenance

B. SYSTEM LIFE CYCLE

To aid in determining the financial feasibility of implementing the MODEM system, and with interest from our OCONUS Base Energy Manager stakeholder, the MODEM team performed a system LCCA. The MODEM team leveraged previous analyses and development by MAJ Daniel Varley and stakeholder feedback to determine the most accurate cost with the current information available. Using a performance analysis of the MODEM system in various use-cases, output data was pulled into an LCCA tool to determine the cost effectiveness.

1. Performance Analysis

The performance analysis of the MODEM system involved building off the work that MAJ Daniel Varley performed developing the MODEM model tool for evaluating the performance of the MODEM in specified use cases. The MODEM team evaluated the MODEM model tool, made necessary modifications to further our intended analyses, adjusted parameters for our use cases of interest, and tailored the output to support the LCCA.

a. MODEM Model Tool Background

The MODEM team utilized the MODEM model Excel tool developed by MAJ Varley to continue his research on MODEM implementation. The Excel analysis tool consist of inputs defining characteristics and efficiencies of the panels, batteries, and generator being used with the addition of global horizon irradiance (GHI) data for the intended operational environment. The Excel analysis tool utilizes this information to provide data on electricity output between the solar panels and generator against a normally distributed load based on typical usage. Further analyses within the Excel tool monitor BESS charge levels, load shed, and overall performance by looking at load supplied and generator usage. To enhance our analyses and support our cost effectiveness research, the MODEM team added additional analyses into the Excel tool that MAJ Varley developed.

b. MODEM Model Tool Modifications

To improve on the MODEM model Excel tool and aid further analysis, the MODEM team had to add additional analyses into the tool. The MODEM model modifications began with implementing a BESS charge level limitation so that the BESS did not exceed its limits and skew the results of the tests. In MAJ Varley’s analyses, the lack of charge restriction did not cause any error in the results of the tests he performed that only spanned a 14-day period. To expand on the tool capability, we increased the time span to encompass an entire year, which is when it was observed that the charge level could far exceed the capacity of the BESS—greater than 8 times the BESS limit when in use for longer periods of time. Figure 44 demonstrates the significant error in performance that can be observed by not properly accounting for equipment limitations.

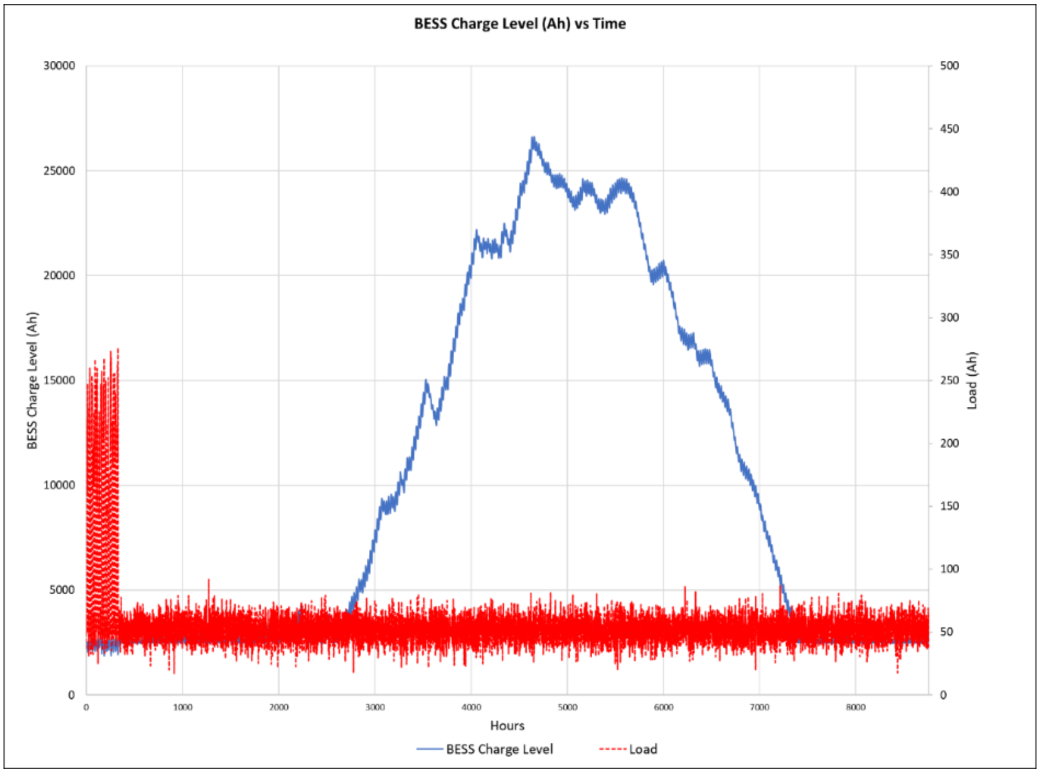


Figure 44. MODEM Model Performance Error

To analyze the performance of the MODEM system over an entire year, additional GHI data from the National Solar Radiation Database was gathered for the locations being analyzed. The data was populated within the MODEM model tool and the columns were extended to evaluate the larger dataset. Accounting for BESS limitations required adjusting the "Battery Charge After Load (Ah)" column equation to accurately calculate the charge in the BESS every half-hour. This was done by setting the BESS charge limit to 3000 Ah based on the current MODEM system configuration. The electricity generated beyond the 3000 Ah BESS charge limit was tracked in a separate column which the MODEM team decided would be electricity sold back to the grid. Selling the additional electricity that cannot be stored in the BESS back to the grid allows for increased cost effectiveness. To support the cost effectiveness research, the MODEM team also had to pull additional information from the MODEM model tool. Using simplistic formulas and analogies of the provided data, the MODEM team was able to capture the listed information to support further analyses:

Electricity:

- Total electrical energy generated (kWh & MWh)
- Electrical energy supplied by generator
- Percent of total electrical energy produced supplied by generator
- Total electricity sold to grid
- Money earned from selling electricity

Equipment:

- Number of gallons of diesel fuel used per year
- Number of oil changes required
- Number of tune-ups required
- Number of generator replacements required
- Number of times the BESS was cycled

Determining the amount of money earned from selling electricity required looking at net surplus compensation (NSC) rates for any surplus of electricity being sold back to the grid and the standard electricity rate for consumption. The generator maintenance was calculated based on median times for various upkeep functions depicted in Table 9.16 in *Renewable and Efficient Electric Power Systems* (Masters 2004, 580). To account for the batteries being cycled, the MODEM team tracked the amount of electrical energy being stored in comparison to the capacity. The number of times the BESS is cycled provided valuable information for our reliability analyses. Providing the additional information to calculate these factors and expand on the MODEM model tool proved to be very valuable in analyzing the cost effectiveness of the MODEM system.

c. MODEM Model Use Cases

To effectively evaluate the cost effectiveness of the MODEM system, the team decided to develop two use case scenarios which would depict possible system deployment situations that the team and stakeholders were interested in analyzing. By creating these use cases and performing an LCCA, the team attempted to gain a better understanding of the strengths and weaknesses of the MODEM system, what factors may be missing in the logical, functional, and physical architectures of the system model, and determine the overall cost effectiveness of the system as it is currently understood.

The first use case focused on using the MODEM system continuously in support of the installation microgrid at NPS in Monterey, California over the course of a full year. In this scenario, the MODEM system is constantly deployed to a 10 kW load on the base microgrid, only utilizing solar energy generated from the PV arrays. In this use case, the MODEM system is deployed at a designated location on the installation and connected directly to the installation microgrid. The power generated is power that the installation does not need to purchase from the utility provider, and, thus, any surplus of power is quantified as the money earned annually from selling electricity (State of California 2021) back to the utility provider.

The second use case was developed with the assistance of our OCONUS Base Energy Manager stakeholder and focused on a fictious Water Treatment Plant (WTP) facility at Naval Air Station (NAS) Sigonella in Italy, which is made up of 3 pump houses. In this scenario, one pump house (B3) pumps water from the source to the WTP while the other two pump houses (B1 & B2) pump the water through the WTP and distribute to the remainder of the installation. Pump Houses B1 and B2 have daily average loads of 500 kWh and are too large for MODEM to support. However, previous studies (Oriti and Piluso 2020) have been performed to design a static load specific microgrid for the larger pump houses. B3 has an average daily usage of 50 kWh which is supportable by the MODEM system. In our fictional scenario we assume that the water source is located remote of the installation. This use case focused on the MODEM system being deployed continuously through the whole year and providing power to B3 to ensure that the base was able to continue receiving water from the source. In the event of a power outage, it is assumed that the larger static microgrid can support the larger pump houses, but a MODEM unit will need to be deployed to power the smaller pump house.

d. MODEM Model Tool Output

Analyzing the Monterey and Sigonella use cases with the MODEM model tool provided a better understanding of the operation of the MODEM system. Comparing the two outputs gave insight into how the system performs based on different characteristics of the system and the load. Monterey and Sigonella both receive similar sun hours at an average of 4.811 and 4.664 hours. The similarities in the operational environment and the use of identical systems suggested any differences in operation are a result of load requirements. In Table 6, a comparison of the outputs from the Monterey and Sigonella use cases are provided.

A comparison of the MODEM model tool outputs between the Monterey and Sigonella use cases in Table 6 illustrates some drastic differences. The result of these differences between the two use cases is that the load for Sigonella was slightly less than three times that of Monterey. A less significant load resulted in less energy being generated and less demand on the generator, which is ideal because of the high usage and maintenance costs associated with using the generator. Additionally, less load demand allowed the Sigonella MODEM system to generate more electricity beyond its demand and sell electricity back to the grid. Worth noting is that in the Sigonella use case, electricity sold back to the grid is used on the installation where the MODEM unit would be installed. Using the additional electricity within the installation is cost avoidance at the standard electricity rate versus reimbursement received from the utility provider. For the Monterey use case, at this time we are assuming electricity sold back to the grid is sold back at the NSC rate (CA 2021), which provides significantly less profit than cost avoidance. Further cost analyses will be discussed in greater detail in the Life-Cycle Cost Analysis section on the cost effectiveness of the MODEM system within the boundaries of the Monterey and Sigonella use cases.

Table 6. MODEM Model Tool Output Comparison

MODEM Model Factors	Monterey	Sigonella
AVG Sun Hours (hrs)	4.811	4.664
Total Load Shed (Ah)	0	0
Load Shed/Load (%)	0.00%	0.00%
AVG Load/Day (kWh)	135.308	54.180
Total Energy Generated (kWh)	49,387.376	19,775.700
Total Energy Generated (MWh)	49.387	19.776
# of Times BESS Cycled per Year	686.002	274.658
GenSet Usage (hrs)	4,108.500	766.500
GenSet Usage (%)	47%	9%
Energy Supplied by Generator (kWh)	33,100	6,132
Percent of Total Energy Produced Supplied by Generator (%)	67.02%	31.01%
Diesel Fuel Usage per Year (Gal)	6,620.000	1,226.400
Oil Changes (#/yr)	9.194	1.703
Tune-ups (#/yr)	4.138	0.767
New unit purchase (#/yr)	0.690	0.128
Total Electricity Sold to Grid (Ah)	35,821.313	79,043.937
Total Electricity Sold to Grid (kWh)	1,719.423	3,794.109
Money Earned from Selling Electricity (USD)	$46.42	$1,067.55

2. Life-Cycle Cost Analysis

The LCCA of the MODEM system became a key focus after our OCONUS Base Energy Manager stakeholder expressed his input and interest in evaluating the financial viability of the project. While an LCCA was already intended to be a part of the team's analysis efforts, the stakeholder made suggestions that grew the effort and gave it a more specific focus. The stakeholder provided data, tools, and guidance that allowed the team to evaluate the financial feasibility of the MODEM unit in multiple use cases. The MODEM team was able to make recommendations in a similar manner to the stakeholder's methodology of evaluating new projects for NAS Sigonella. To best utilize the information provided by the stakeholder, the MODEM teams first focus in the LCCA was evaluating the LCCA tool that he provided.

a. Life-Cycle Cost Analysis Tool

Our OCONUS Base Energy Manager stakeholder provided many suggestions and needs when looking into the cost feasibility of the MODEM system. The stakeholder recommended calculating the savings to investment ratio (SIR) to determine if the system was financially wise to invest in and would be profitable over the systems life cycle. The stakeholder demonstrated the steps that he goes through and the parameters that he evaluates to determine the final SIR with the MODEM team. The MODEM team was also walked through the LCCA tool that the stakeholder uses for evaluating projects for NAS Sigonella. The stakeholder uses a government owned web-based tool that evaluates a vast amount of project related parameters to determine the SIR and guide decision making. For the MODEM project, the stakeholder provided the team with a more simplified Excel version of the LCCA tool that he uses. With the information that we have and the goal of our analyses, this LCCA tool provides enough capability and insight that we can make informed predications on the profitability of the MODEM system. To determine the parameters necessary to provide the most accurate SIR with the information available, we started by comparing the inputs of the web-based tool and the Excel version of the LCCA tool.

b. Life-Cycle Cost Analysis Tool Parameters

To identify the key parameters for the Excel-based LCCA tool the MODEM team compared the inputs for both the web-based and Excel version to analyze the differences and determine what was most important. The OCONUS Base Energy Manager stakeholder provided us with an export from the web-based version of the tool that included all entry fields. Many of the entry fields contained a lot of supporting information to provide context, but we did not require this level of detail for determining our SIR for the MODEM system. Our comparison of the two versions of the LCCA tool resulted in identifying the initial key parameters as well as unknowns in Table 7.

Table 7. LCCA Tool Parameter Identification

Category	Parameters
Output	SIR = Total Net Discounted Savings / (Total Funds Req'd - (Salvage Value + Rebate))
Investment Costs	Construction costs
	Supervision, Inspection and Overhead (SIOH) (% of construction costs)
	Design (% of construction costs)
Energy Savings	Electricity cost
	Distillate oil cost
	Annual electricity reduction (MWh)
	Annual distillate oil reduction (MBtu)
Non-Energy Savings	Capital cost avoidance
	Maintenance
Unknowns	Discount rate (%)
	Discounts I & II tab
	Tables tab

Table 7 list out the main parameters that the MODEM team identified for our analysis based on our comparison of two LCCA products and the OCONUS Base Energy Manager stakeholder's guidance. The first category listed is the output, which is the SIR value that provides the profitability of the project by evaluating the savings incurred by the cost of the system. For investment costs it is necessary to determine the construction costs, SIOH, and design costs. SIOH adds 4% of the overall construction cost and design adds 10% of the overall construction cost. For energy savings, the MODEM team determined that electricity and distillate oil prices in the area of the world where the MODEM would be deployed as well as the reduction in annual electricity and distillate oil by using the MODEM system would be necessary. For non-energy savings, it will be important to account for both capital cost avoidance and any maintenance related costs. Lastly, the Excel-based LCCA tool contained various discount rates and tabs with discount values that's purpose was left unclear at the time of receiving the tool. The lack of understanding of the information in the Unknowns category in Table 7 was the next phase of the MODEM teams LCCA research to determine whether the information being used in the tool was accurate and so that an SIR value could be evaluated with confidence.

c. Life-Cycle Cost Analysis Research

The MODEM team determined what parameters were unknown within the LCCA tool provided by the OCONUS Base Energy Manager stakeholder and began looking into the meaning of those parameters and how they were used in the calculations of the tool. When the team first received the LCCA tool there was data eluding to the possibility of the LCCA tool being 4 to 11 years old—adding to the uncertainty of the accuracy of the values being used. Early research into determining the unknowns was very much misguided and led to results that assisted with understanding the functionality of the LCCA, but ultimately were not used for our analyses. Research into the discount factor initially did not provide certainty whether 3.0% was accurate but seemed valid within a degree of error. With vague answers on discount factors, the research transitioned into looking into historical data for energy prices so that predictions could be made about the future energy rates. Historical data from January 1979 to June 2022 was analyzed through JMP Pro to make predictions using a logistic 4-parameter Rodbard curve to fit the dataset. This curve provided the best prediction but was not an ideal fit for the dataset, based on the R-squared value. The intention behind analyzing the prices of electricity and diesel, was to make future predictions of energy prices and comparing that to the uniform present value data being used in the Discount I tab. The MODEM team hoped that this comparison would provide a better understanding of the data within the Discount I tab of the LCCA tool and allude to the accuracy of the information.

To make sense of the modified uniform present value (UPV*) discount factors provided for the different census regions in the United States within the Discounts I tab of the LCCA tool, the MODEM team attempted making present value and future value calculations based on our predicted energy prices. There was a lack of understanding of UPV* and poor resources were utilized that misguided our method for verifying the provided values in the Discounts I tab. Similar values were not able to be replicated with the information we had, so the analyses were continued until we had the opportunity to discuss our sources of confusion with our OCONUS Base Energy Manager stakeholder. The MODEM team eventually met with the stakeholder in mid-September 2022 to discuss our multiple sources of confusion. The stakeholder cleared up a few misunderstandings and seemed to believe that the data within the LCCA tool that he provided may not be completely accurate but would at least provide enough value to make a semi-accurate conclusion from the results. The stakeholder also suggested looking into other available LCCA tools to make a better comparison of the data being used and methodology of how the SIR is calculated in the LCCA tool provided to us. The MODEM team dug further into LCCA research as the stakeholder suggested, with unfavorable results.

The research was then focused on determining accurate equipment costs. Prices for the batteries and panels had already been provided with MAJ Varley's research. The team had to look for the costs of the remaining components that MAJ Varley provided in his design, as well as the components we added for consideration in the MODEM design. The component research was an integrated effort with the O&S Planning; therefore, the cost of the components can be found in Table 5 in the Maintenance Analysis sub-section. For the LCCA, we wanted to account for associated acquisition cost such as shipping, processing fees, handling fees, and labor. The MODEM team discussed the acquisition of the generator and what percentage of cost on top of the purchase price would likely be incurred for acquisition related tasks during a phone conversation with a Task Manager at NSWC Crane. Through our discussion the task manager informed us that acquisitions for his division are normally performed through a contract vehicle. The acquisition costs associated with purchases through the contract would typically add an additional 20 to 40% of the purchase price to the total cost. The task manager also provided us with a Service Cost Center (SCC) calculator that his division uses to obtain Rough Order of Magnitude (ROM) estimates for purchases. The SCC calculator shows that there are different percentage rates to be added for contracting, supply, and purchasing as well as flat fees for shipping, material movement, and inventory. The SCC rates also differ based on the type of contract the material is purchased through (Large Contract/SAP/Seaport) (Task Manager at NSWC Crane, personal communication, October 4, 2022). In Table 8, an updated cost table has been provided accounting for the acquisition cost using a median percentage of 30%. In addition, it is worth noting that the generator used was exceptionally difficult to find a price for, which is why we are using information from an Ebay listing. By looking at the condition of the generator and hours of use, the MODEM team came to a consensus to use a purchase price of $20,000 for a new unit.

Table 8. MODEM Component Acquisition Costs Adjustments

Component	Cost per Item ($)	Cost per Item Accounting for Acquisition Costs ($)
Charge Bus	$3,250.00	$4,225.00
Charge Controller	$589.05	$765.77
Battery	$2,459.80	$3,197.74
DC/AC Inverter	$3,450.00	$4,485.00
Electrical Bus	$3,250.00	$4,225.00
Generator	$20,000.00	$26,000.00
PV Array	$365.00	$474.50
Combiner Box	$663.25	$862.23
TriCon	$3600.00	$4680.00

TriCon price is sourced from Alibaba (Alibaba n.d.).

After determining the total cost for the MODEM system components, the MODEM team investigated the potential savings from salvage prices. Due to time constraints, we limited calculating the salvage value for the Cummins generator only. The following method is what the MODEM team used to calculate the salvage cost of the generator based on information from HOMER Pro (HOMER 2020). The arithmetic detailed in equations 4, 5, and 6 are simplistic calculations to determine a rough estimation of the salvage value for the generator used for the MODEM system. Salvage value results for the generator using these equations are provided in Table 9, as well as definitions for the variables used.

$$R_{rep} = R_{comp} * INT\left(\frac{R_{proj}}{R_{comp}}\right) \qquad \text{(Equation 4)}$$

$$R_{rem} = R_{comp} - \left(R_{proj} - R_{rep}\right) \qquad \text{(Equation 5)}$$

$$S = C_{rep} * \frac{R_{rem}}{R_{comp}} \qquad \text{(Equation 6)}$$

Table 9. Diesel Generator Salvage Value Results

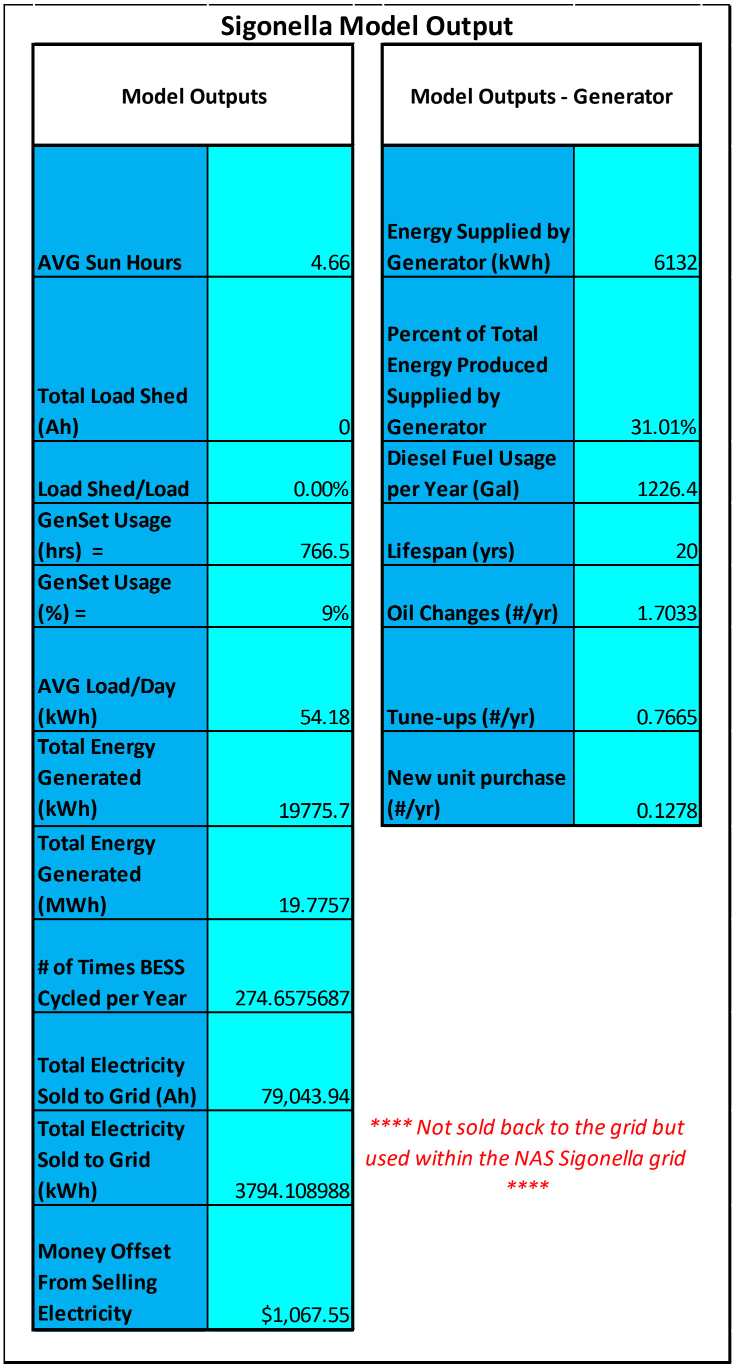
Variables	Definition	Value
C_{rep}	replacement cost (USD)	$20,000.00
R_{comp}	component lifetime (yrs)	30
R_{proj}	project lifetime (yrs)	20
R_{rep}	replacement cost duration (yrs)	0
R_{rem}	remaining life of the component at the end of the project lifetime (yrs)	10
S	salvage value (USD)	$6,666.67

The last piece of information that needed to be evaluated for the LCCA was the energy rates and availability of any tax credits or rebates for implementing a renewable energy system within the use case environments. Data sourced from the U.S. Energy Information Administration in June 2022 indicated a commercial electricity rate of 12.9 ₵/kWh (U.S. Energy Information Administration [EIA] 2022) and a diesel price of 5.77 USD/gal (EIA 2022). When looking at the Monterey based use case, the Clean Energy Tax Legislation in the Inflation Reduction Act (IRA) identifies the commercial solar investment tax credit (ITC) as providing a base 30% (Solar Energy Industries Association 2022), which is up from 26% before the IRA. Pending the construction of the MODEM system, there is potential to receive an additional 10% if 100% domestic iron or steel is used. This construction detail can be determined at a later stage of the realization of the MODEM system and the 30% ITC will be used for current cost analyses. Additionally, the production tax credit (PTC) based on the Clean Energy Tax Legislation is 2.7 US₵/kWh, with potential to receive an additional 0.3 US₵/kWh based on the same criteria discussed for the ITC (Solar Energy Industries Association 2022). The next use case focuses on operations in Sigonella, Italy, which required research to determine energy rates and available renewable energy incentives.

For Sigonella, Italy, prices for electricity and diesel were analyzed for October 2022. Based on data captured from Gestore Mercati Energetici, electricity rates were 289.39 Euros/MWh (Gestore Mercati Energetici 2022). To maintain unit consistency, the rate was converted to USD/MWh based on a conversion rate of 0.9723 USD/Euro (European Central Bank 2022). Using this conversion rate resulted in an electricity rate of 281.37 USD/MWh. Data used from Fuelo provided a diesel cost of 1.973 Euros/L, or 7.468 Euros/gal after converting to maintain consistent units (Fuelo 2022). Using the same USD/ Euro conversion rate previously used resulted in a diesel cost of 7.26 USD/gal for Sigonella, Italy. When looking at tax credits and rebates for the implementation of renewable energy sources in the Sigonella area, the MODEM team had difficulty finding information. Dentons report on Italian energy law indicated there were feed-in tariffs for PV solar generation beyond 20 kW (Dentons 2020), but these stipulations are not applicable using a 10 kW MODEM system. Worth noting is that the Dentons report is slightly outdated, so there very well could be cost incentives for implementing renewable energy sources that the MODEM team missed when conduction research. The team refrained from applying any tax credits or rebates in the LCCA for the Sigonella use case.

After determining all necessary data for the LCCA tool analysis, the MODEM team began populating all the information into the tool. This process began with pulling all the relevant output data captured in Table 6 from the MODEM model tool into the LCCA tool. Once the data was copied over, further analyses were performed on the generator maintenance actions to determine the number of oil changes, tune-ups, and generator replacements that would be required over the lifetime of MODEM operation.

Figure 46 shows the additional analyses for the Sigonella use case based on the MODEM model input data provided in Figure 45 to determine the number of oil changes, tune-ups, and generator replacements required over the lifetime of the MODEM system. For the generator maintenance actions, a cumulative number is provided based on the yearly MODEM model output data. For the oil change and tune-ups data, the cumulative real number is then dissected into a yearly integer. When looking at the generator replacement breakdown, the years in which replacement is necessary is highlighted based on when the real value increased to the next whole number. A similar process occurred to analyze the Monterey use case data, and the LCCA analysis data is provided in the Appendix. At this point, all information to determine the SIR value was provided for both use cases being evaluated.



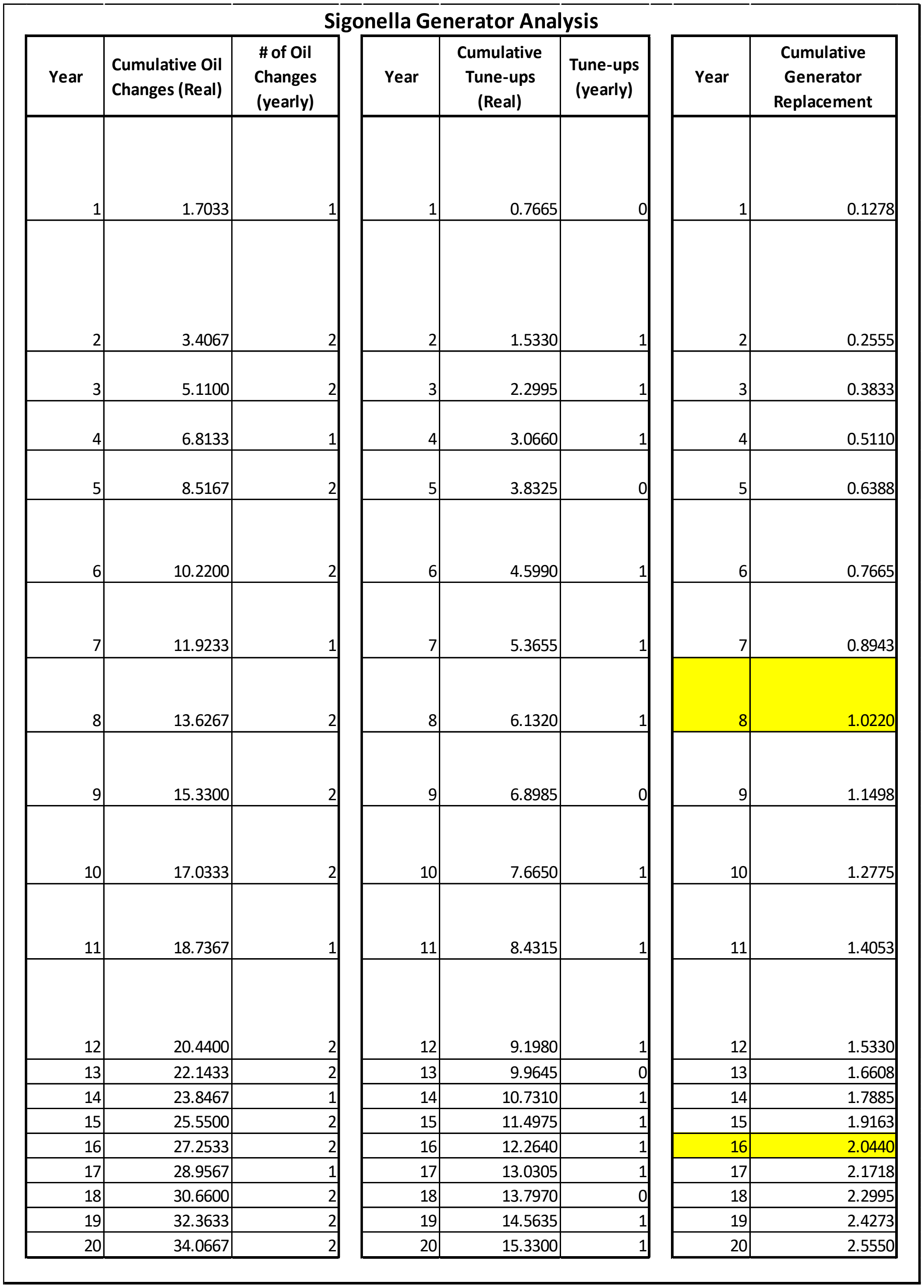
Sigonella Model Output

Model Outputs	
AVG Sun Hours	4.66
Total Load Shed (Ah)	0
Load Shed/Load	0.00%
GenSet Usage (hrs) =	766.5
GenSet Usage (%) =	9%
AVG Load/Day (kWh)	54.18
Total Energy Generated (kWh)	19775.7
Total Energy Generated (MWh)	19.7757
# of Times BESS Cycled per Year	274.6575687
Total Electricity Sold to Grid (Ah)	79,043.94
Total Electricity Sold to Grid (kWh)	3794.108988
Money Offset From Selling Electricity	$1,067.55

Model Outputs - Generator	
Energy Supplied by Generator (kWh)	6132
Percent of Total Energy Produced Supplied by Generator	31.01%
Diesel Fuel Usage per Year (Gal)	1226.4
Lifespan (yrs)	20
Oil Changes (#/yr)	1.7033
Tune-ups (#/yr)	0.7665
New unit purchase (#/yr)	0.1278

***** Not sold back to the grid but used within the NAS Sigonella grid *****

Figure 45. Sigonella LCCA Data Input from MODEM Model



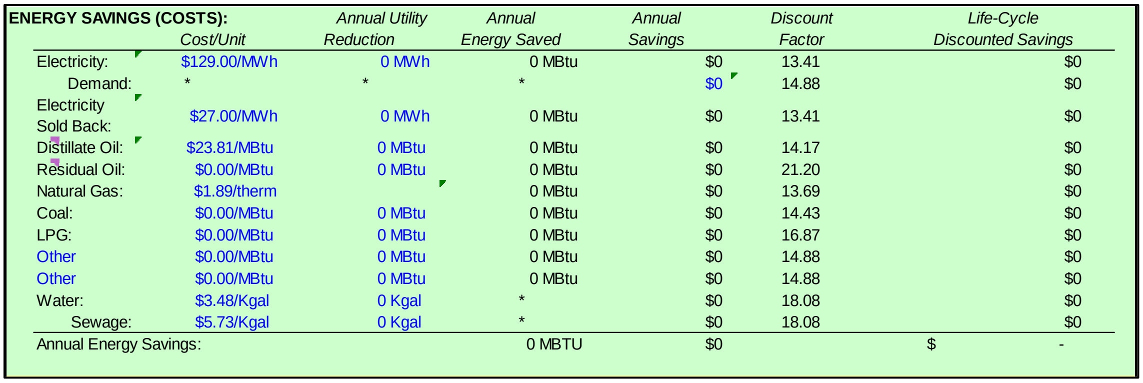
Sigonella Generator Analysis

Year	Cumulative Oil Changes (Real)	# of Oil Changes (yearly)	Year	Cumulative Tune-ups (Real)	Tune-ups (yearly)	Year	Cumulative Generator Replacement
1	1.7033	1	1	0.7665	0	1	0.1278
2	3.4067	2	2	1.5330	1	2	0.2555
3	5.1100	2	3	2.2995	1	3	0.3833
4	6.8133	1	4	3.0660	1	4	0.5110
5	8.5167	2	5	3.8325	0	5	0.6388
6	10.2200	2	6	4.5990	1	6	0.7665
7	11.9233	1	7	5.3655	1	7	0.8943
8	13.6267	2	8	6.1320	1	8	1.0220
9	15.3300	2	9	6.8985	0	9	1.1498
10	17.0333	2	10	7.6650	1	10	1.2775
11	18.7367	1	11	8.4315	1	11	1.4053
12	20.4400	2	12	9.1980	1	12	1.5330
13	22.1433	2	13	9.9645	0	13	1.6608
14	23.8467	1	14	10.7310	1	14	1.7885
15	25.5500	2	15	11.4975	1	15	1.9163
16	27.2533	2	16	12.2640	1	16	2.0440
17	28.9567	1	17	13.0305	1	17	2.1718
18	30.6600	2	18	13.7970	0	18	2.2995
19	32.3633	2	19	14.5635	1	19	2.4273
20	34.0667	2	20	15.3300	1	20	2.5550

Figure 46. Sigonella LCCA Generator Analysis Data

When all information was provided to determine the SIR value, the MODEM team began to evaluate the results and work on the write-up of the LCCA analyses. While attempting to gather additional supporting information for the write-up, the team discovered resources that definitively clarified the unknown LCCA information depicted in Table 7 in relation to the Monterey use case. Unfortunately, this discovery was too late into the capstone project to where it was not possible to fully evaluate the entirety of the information found. What was able to be updated was the discount rate, the UPV* values located in the Discounts I tab of the LCCA tool, and the team was able to verify the operations performed in the Discounts II tab. The team used the same data for the Sigonella use case because of time restrictions, acknowledging that there is a degree of error in the results.

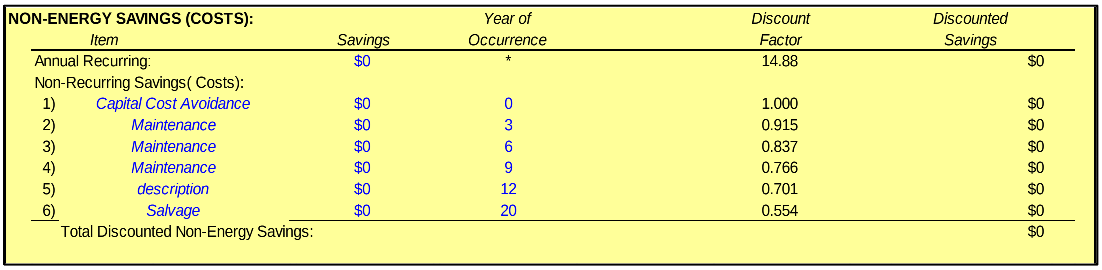
According to the Corporate Finance Institute, “a discount rate is the rate of return used to discount future cash flows back to their present value” (Corporate Finance Institute 2022). Additionally, the discount rate is determined by the DOE and is based on long-term Treasury bond rates that are averaged in the previous year (National Institute of Standards and Technology [NIST] 2022). The importance of the discount rate in the LCCA tool is that all of the calculations are leveraged off this value, therefore, being the greatest source of variance in our analyses. Based on sources from the DOE (Department of Energy 2021) and NIST (NIST 2022), the MODEM team finally verified that a discount rate of 3.0% is accurate and began looking at the Discounts I tab of the LCCA tool. The Discounts I tab has UPV* discount factors that account for the average increase of fuel prices 10, 15, and 20 years in the future. These discount factors are used within the Energy Savings section of the LCCA tool to accurately calculate the Life-Cycle Discounted Savings based on the economic life of the system. The Energy Savings section is provided in Figure 47 for reference and depicts the Discount Factors being pulled in from the Discounts I tab. After locating the 2022 LCCA discount factors put together by the NIST (NIST 2022), the MODEM team was finally able to update the values for the California census region.



ENERGY SAVINGS (COSTS):	Cost/Unit	Annual Utility Reduction	Annual Energy Saved	Annual Savings	Discount Factor	Life-Cycle Discounted Savings
Electricity:	$129.00/MWh	0 MWh	0 MBtu	$0	13.41	$0
Demand:	*	*	*	$0	14.88	$0
Electricity Sold Back:	$27.00/MWh	0 MWh	0 MBtu	$0	13.41	$0
Distillate Oil:	$23.81/MBtu	0 MBtu	0 MBtu	$0	14.17	$0
Residual Oil:	$0.00/MBtu	0 MBtu	0 MBtu	$0	21.20	$0
Natural Gas:	$1.89/therm		0 MBtu	$0	13.69	$0
Coal:	$0.00/MBtu	0 MBtu	0 MBtu	$0	14.43	$0
LPG:	$0.00/MBtu	0 MBtu	0 MBtu	$0	16.87	$0
Other	$0.00/MBtu	0 MBtu	0 MBtu	$0	14.88	$0
Other	$0.00/MBtu	0 MBtu	0 MBtu	$0	14.88	$0
Water:	$3.48/Kgal	0 Kgal	*	$0	18.08	$0
Sewage:	$5.73/Kgal	0 Kgal	*	$0	18.08	$0
Annual Energy Savings:			0 MBTU	$0		$ -

Figure 47. LCCA Tool Energy Savings Evaluation

In the Discounts II tab of the LCCA tool single present value (SPV) DOE discount factors are calculated based on the discount rate, as well as the simple payback calculations. The SPV DOE discount factors are used within the Non-Energy Savings section of the LCCA tool to accurately calculate the Discounted Savings based on the Year of Occurrence. The Non-Energy Savings section is provided in Figure 48 for reference and depicts the Discount Factors being pulled in from the Discounts II tab.



NON-ENERGY SAVINGS (COSTS): Item	Savings	Year of Occurrence	Discount Factor	Discounted Savings
Annual Recurring:	$0	*	14.88	$0
Non-Recurring Savings(Costs):				
1) Capital Cost Avoidance	$0	0	1.000	$0
2) Maintenance	$0	3	0.915	$0
3) Maintenance	$0	6	0.837	$0
4) Maintenance	$0	9	0.766	$0
5) description	$0	12	0.701	$0
6) Salvage	$0	20	0.554	$0
Total Discounted Non-Energy Savings:				$0

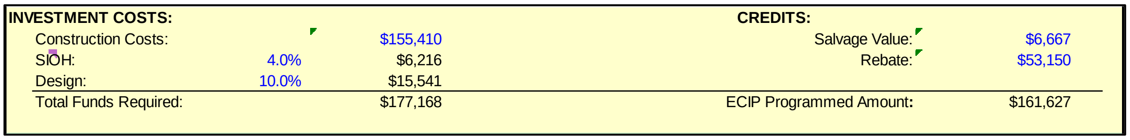
Figure 48. LCCA Tool Non-Energy Savings Evaluation

Reviewing the Table 3–1 in *NIST Handbook 135 2022 edition* verified that the single present value (SPV) factors in the Discounts II tab of the LCCA tool were being calculated accurately (NIST 2022). The *Energy Price Indices and Discount Factors for Life-Cycle Cost Analysis—2022* describes SPV as the following, "…factors for finding the present value of future non-fuel, non-annually recurring costs, such as repair and replacement costs and salvage values" (NIST 2022). These new sources of information allowed the MODEM team to update the LCCA tool UPV* data and verify the accuracy of SIR output.

d. Life-Cycle Cost Analysis Results

(1) Monterey LCCA Results

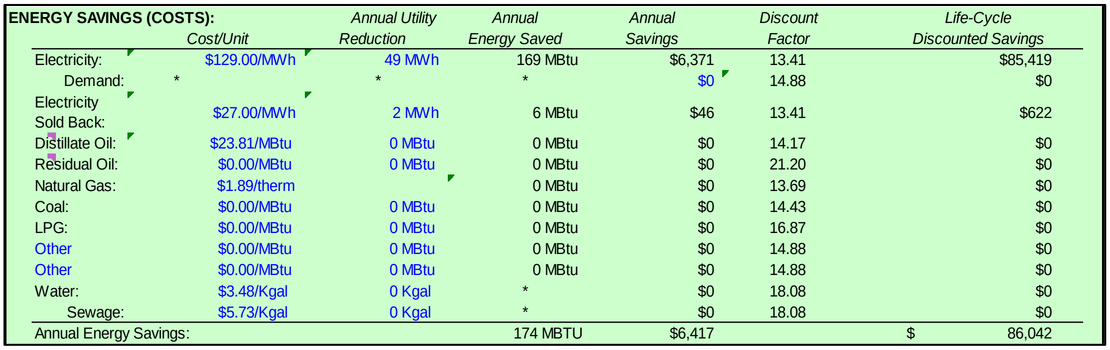
Once the Monterey and Sigonella use cases were analyzed in MAJ Varley's MODEM model, output data was analyzed in the OCONUS Base Energy Manager stakeholder's LCCA tool to determine the SIR. Looking at the Monterey use case, we first determined the Total Funds Required, provided in Figure 49.



INVESTMENT COSTS:			**CREDITS:**	
Construction Costs:		$155,410	Salvage Value:	$6,667
SIOH:	4.0%	$6,216	Rebate:	$53,150
Design:	10.0%	$15,541		
Total Funds Required:		$177,168	ECIP Programmed Amount:	$161,627

Figure 49. Monterey LCCA Tool Investment Costs Analysis

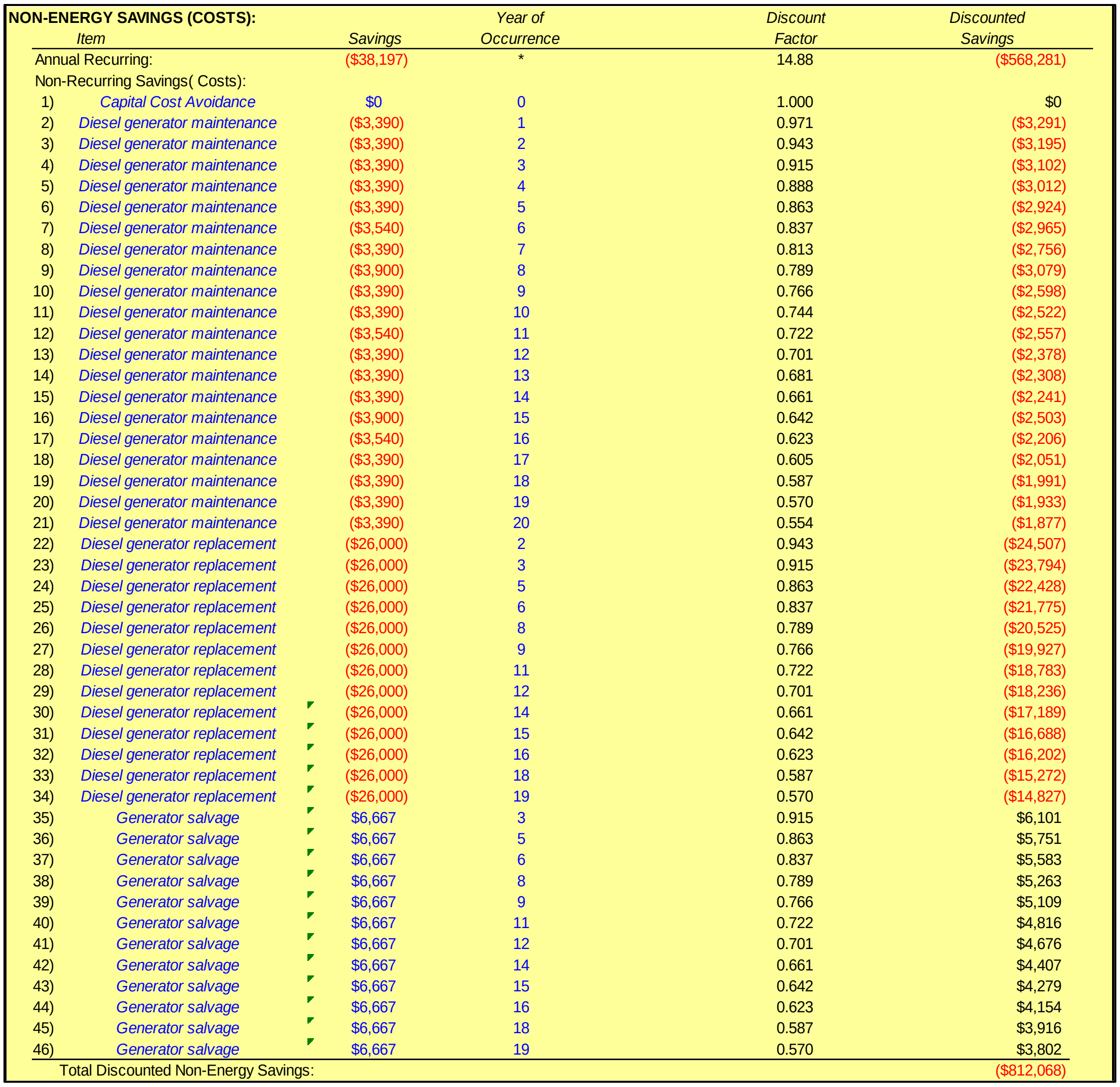
The adjusted component costs provided in Table 8 were summed together with the default SIOH and Design percentages applied to result in an overall investment cost of $177,168. The salvage value that accounts for the generator is shown as well as the 30% ITC rebate resulting in credits of $6,667 and $53,150 that help reduce the overall cost of the MODEM system. Next, the MODEM team analyzed the Energy Savings generated by the MODEM system in the continuous use case in Monterey. The results of the Energy Savings analysis are provided in Figure 50.



ENERGY SAVINGS (COSTS):	Cost/Unit	Annual Utility Reduction	Annual Energy Saved	Annual Savings	Discount Factor	Life-Cycle Discounted Savings
Electricity:	$129.00/MWh	49 MWh	169 MBtu	$6,371	13.41	$85,419
Demand:	*	*	*	$0	14.88	$0
Electricity Sold Back:	$27.00/MWh	2 MWh	6 MBtu	$46	13.41	$622
Distillate Oil:	$23.81/MBtu	0 MBtu	0 MBtu	$0	14.17	$0
Residual Oil:	$0.00/MBtu	0 MBtu	0 MBtu	$0	21.20	$0
Natural Gas:	$1.89/therm		0 MBtu	$0	13.69	$0
Coal:	$0.00/MBtu	0 MBtu	0 MBtu	$0	14.43	$0
LPG:	$0.00/MBtu	0 MBtu	0 MBtu	$0	16.87	$0
Other	$0.00/MBtu	0 MBtu	0 MBtu	$0	14.88	$0
Other	$0.00/MBtu	0 MBtu	0 MBtu	$0	14.88	$0
Water:	$3.48/Kgal	0 Kgal	*	$0	18.08	$0
Sewage:	$5.73/Kgal	0 Kgal	*	$0	18.08	$0
Annual Energy Savings:			174 MBTU	$6,417		$ 86,042

Figure 50. Monterey LCCA Tool Energy Savings Analysis

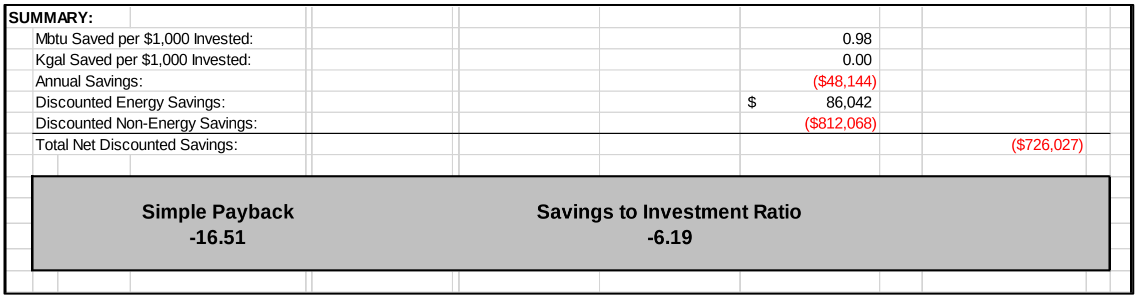
In Figure 50, the savings resulting from the MODEM performance is evaluated. The total utility reduction on a yearly basis resulted in 51 MWh that was supplied by the MODEM system which netted an annual savings of $6,371. Considering the lifespan of the MODEM system and using the associated Discount Factor resulted in a total Life-Cycle Discounted Savings of $86,042. The next analysis looked at Non-Energy Savings that include costs as well for usage and maintenance. The output from MAJ Varley's model on equipment usage was analyzed in the LCCA tool and the results are provided in Figure 51.



NON-ENERGY SAVINGS (COSTS): Item		Savings	Year of Occurrence	Discount Factor	Discounted Savings
Annual Recurring:		($38,197)	*	14.88	($568,281)
Non-Recurring Savings(Costs):					
1)	Capital Cost Avoidance	$0	0	1.000	$0
2)	Diesel generator maintenance	($3,390)	1	0.971	($3,291)
3)	Diesel generator maintenance	($3,390)	2	0.943	($3,195)
4)	Diesel generator maintenance	($3,390)	3	0.915	($3,102)
5)	Diesel generator maintenance	($3,390)	4	0.888	($3,012)
6)	Diesel generator maintenance	($3,390)	5	0.863	($2,924)
7)	Diesel generator maintenance	($3,540)	6	0.837	($2,965)
8)	Diesel generator maintenance	($3,390)	7	0.813	($2,756)
9)	Diesel generator maintenance	($3,900)	8	0.789	($3,079)
10)	Diesel generator maintenance	($3,390)	9	0.766	($2,598)
11)	Diesel generator maintenance	($3,390)	10	0.744	($2,522)
12)	Diesel generator maintenance	($3,540)	11	0.722	($2,557)
13)	Diesel generator maintenance	($3,390)	12	0.701	($2,378)
14)	Diesel generator maintenance	($3,390)	13	0.681	($2,308)
15)	Diesel generator maintenance	($3,390)	14	0.661	($2,241)
16)	Diesel generator maintenance	($3,900)	15	0.642	($2,503)
17)	Diesel generator maintenance	($3,540)	16	0.623	($2,206)
18)	Diesel generator maintenance	($3,390)	17	0.605	($2,051)
19)	Diesel generator maintenance	($3,390)	18	0.587	($1,991)
20)	Diesel generator maintenance	($3,390)	19	0.570	($1,933)
21)	Diesel generator maintenance	($3,390)	20	0.554	($1,877)
22)	Diesel generator replacement	($26,000)	2	0.943	($24,507)
23)	Diesel generator replacement	($26,000)	3	0.915	($23,794)
24)	Diesel generator replacement	($26,000)	5	0.863	($22,428)
25)	Diesel generator replacement	($26,000)	6	0.837	($21,775)
26)	Diesel generator replacement	($26,000)	8	0.789	($20,525)
27)	Diesel generator replacement	($26,000)	9	0.766	($19,927)
28)	Diesel generator replacement	($26,000)	11	0.722	($18,783)
29)	Diesel generator replacement	($26,000)	12	0.701	($18,236)
30)	Diesel generator replacement	($26,000)	14	0.661	($17,189)
31)	Diesel generator replacement	($26,000)	15	0.642	($16,688)
32)	Diesel generator replacement	($26,000)	16	0.623	($16,202)
33)	Diesel generator replacement	($26,000)	18	0.587	($15,272)
34)	Diesel generator replacement	($26,000)	19	0.570	($14,827)
35)	Generator salvage	$6,667	3	0.915	$6,101
36)	Generator salvage	$6,667	5	0.863	$5,751
37)	Generator salvage	$6,667	6	0.837	$5,583
38)	Generator salvage	$6,667	8	0.789	$5,263
39)	Generator salvage	$6,667	9	0.766	$5,109
40)	Generator salvage	$6,667	11	0.722	$4,816
41)	Generator salvage	$6,667	12	0.701	$4,676
42)	Generator salvage	$6,667	14	0.661	$4,407
43)	Generator salvage	$6,667	15	0.642	$4,279
44)	Generator salvage	$6,667	16	0.623	$4,154
45)	Generator salvage	$6,667	18	0.587	$3,916
46)	Generator salvage	$6,667	19	0.570	$3,802
Total Discounted Non-Energy Savings:					($812,068)

Figure 51. Monterey LCCA Tool Non-Energy Savings Analysis

At the top of the list displayed in Figure 51, we find an Annual Recurring listing. This accounts for any yearly savings or costs associated with running the MODEM system in the Monterey use case. The text is displayed in red, because there were $38,197 greater costs than savings for this use case, which solely accounts for diesel fuel used by the generator. Going further down the Non-Energy Savings item list we see a diesel generator maintenance listing that accounts for oil changes and tune-ups. The costs for generator maintenance were not constant, which is why it was not accounted for in the Annual Recurring listing. Additionally, the replacement of the generator is also accounted for in this list with the associated year it occurred to properly discount the cost. The last item worth noting was the salvage of the generator each year it was replaced. All of the listed savings and costs resulted in a Total Discounted Non-Energy Savings of –$812,068 over the life cycle of the MODEM system in the Monterey use case. The summary of the Monterey use case analysis is provided in Figure 52.



SUMMARY:		
Mbtu Saved per $1,000 Invested:	0.98	
Kgal Saved per $1,000 Invested:	0.00	
Annual Savings:	($48,144)	
Discounted Energy Savings:	$ 86,042	
Discounted Non-Energy Savings:	($812,068)	
Total Net Discounted Savings:		($726,027)

Simple Payback
-16.51

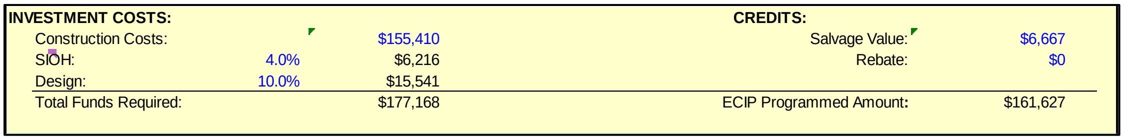
Savings to Investment Ratio
-6.19

Figure 52. Monterey LCCA Tool Results Summary

Accounting for the Annual Savings, Discounted Energy and Non-Energy Savings discussed previously, resulted in a Total Net Discounted Savings of –$726,027 over the life cycle of the MODEM system in the Monterey use case. Through these analyses, the MODEM team determined that the resulting SIR for the Monterey use case is –6.19. Since the SIR is less than 1.0, this indicates that the MODEM system being implemented in the Monterey use case is not profitable to the point of having a return greater than the investment cost. In this use case, the LCC for operations and maintenance surpasses the investment cost by a significant amount.

(2) Sigonella LCCA Results

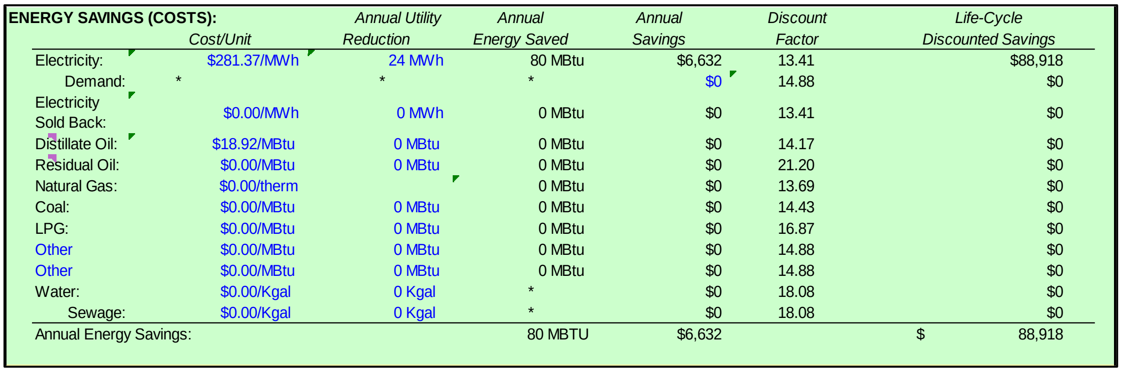
The Sigonella use cases was analyzed in MAJ Varley’s MODEM model, output data was analyzed in the OCONUS Base Energy Manager stakeholder’s LCCA tool to determine the SIR. Looking at the Sigonella use case, we first determined the Total Funds Required, provided in Figure 53.



INVESTMENT COSTS:			CREDITS:	
Construction Costs:		$155,410	Salvage Value:	$6,667
SIOH:	4.0%	$6,216	Rebate:	$0
Design:	10.0%	$15,541		
Total Funds Required:		$177,168	ECIP Programmed Amount:	$161,627

Figure 53. Sigonella LCCA Tool Investment Costs Analysis

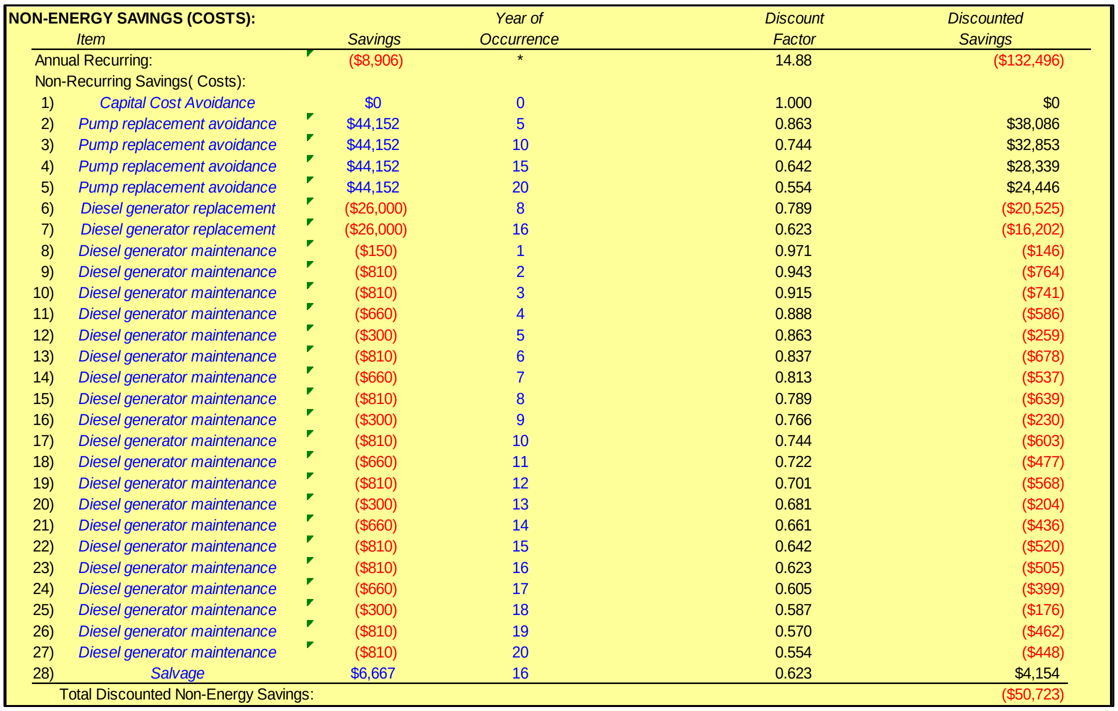
The adjusted component costs provided in Table 8 were summed together with the default SIOH and Design percentages applied to result in an overall investment cost of $177,168; the same as in the Monterey use case it is an identical system. The salvage value that accounts for the generator is shown as $6,667 and there is no rebate associated with the Sigonella use case since all rebate criteria found was for 20 kW, or greater, systems. Next, the MODEM team analyzed the Energy Savings generated by the MODEM system in the continuous use case in Sigonella. The results of the Energy Savings analysis are provided in Figure 54.



ENERGY SAVINGS (COSTS):	Cost/Unit	Annual Utility Reduction	Annual Energy Saved	Annual Savings	Discount Factor	Life-Cycle Discounted Savings
Electricity:	$281.37/MWh	24 MWh	80 MBtu	$6,632	13.41	$88,918
Demand:	*	*	*	$0	14.88	$0
Electricity Sold Back:	$0.00/MWh	0 MWh	0 MBtu	$0	13.41	$0
Distillate Oil:	$18.92/MBtu	0 MBtu	0 MBtu	$0	14.17	$0
Residual Oil:	$0.00/MBtu	0 MBtu	0 MBtu	$0	21.20	$0
Natural Gas:	$0.00/therm		0 MBtu	$0	13.69	$0
Coal:	$0.00/MBtu	0 MBtu	0 MBtu	$0	14.43	$0
LPG:	$0.00/MBtu	0 MBtu	0 MBtu	$0	16.87	$0
Other	$0.00/MBtu	0 MBtu	0 MBtu	$0	14.88	$0
Other	$0.00/MBtu	0 MBtu	0 MBtu	$0	14.88	$0
Water:	$0.00/Kgal	0 Kgal	*	$0	18.08	$0
Sewage:	$0.00/Kgal	0 Kgal	*	$0	18.08	$0
Annual Energy Savings:			80 MBTU	$6,632		$ 88,918

Figure 54. Sigonella LCCA Tool Energy Savings Analysis

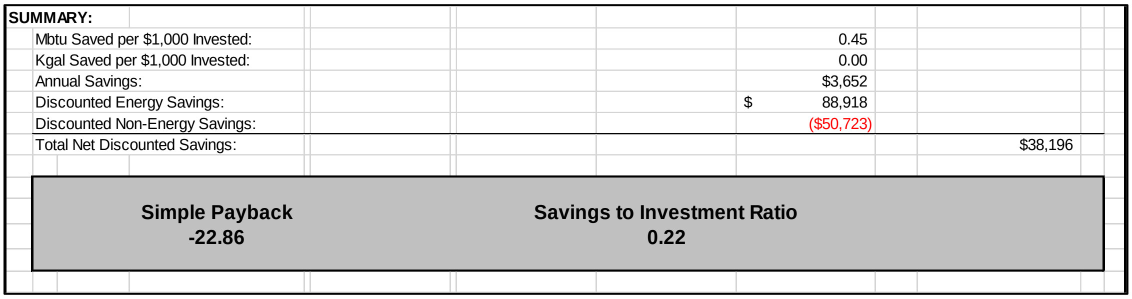
In Figure 54, the savings resulting from the MODEM performance is evaluated. The total utility reduction on a yearly basis resulted in 24 MWh that was supplied by the MODEM system which netted an annual savings of $6,632. Considering the lifespan of the MODEM system and using the associated Discount Factors resulted in a total Life-Cycle Discounted Savings of $88,918. The next analysis looked at Non-Energy Savings that include costs as well for usage and maintenance. The output from MAJ Varley's model on equipment usage was analyzed in the LCCA tool and the results are provided in Figure 55.



NON-ENERGY SAVINGS (COSTS):			*Year of*	*Discount*	*Discounted*
	Item	*Savings*	*Occurrence*	*Factor*	*Savings*
Annual Recurring:		($8,906)	*	14.88	($132,496)
Non-Recurring Savings(Costs):					
1)	*Capital Cost Avoidance*	$0	0	1.000	$0
2)	*Pump replacement avoidance*	$44,152	5	0.863	$38,086
3)	*Pump replacement avoidance*	$44,152	10	0.744	$32,853
4)	*Pump replacement avoidance*	$44,152	15	0.642	$28,339
5)	*Pump replacement avoidance*	$44,152	20	0.554	$24,446
6)	*Diesel generator replacement*	($26,000)	8	0.789	($20,525)
7)	*Diesel generator replacement*	($26,000)	16	0.623	($16,202)
8)	*Diesel generator maintenance*	($150)	1	0.971	($146)
9)	*Diesel generator maintenance*	($810)	2	0.943	($764)
10)	*Diesel generator maintenance*	($810)	3	0.915	($741)
11)	*Diesel generator maintenance*	($660)	4	0.888	($586)
12)	*Diesel generator maintenance*	($300)	5	0.863	($259)
13)	*Diesel generator maintenance*	($810)	6	0.837	($678)
14)	*Diesel generator maintenance*	($660)	7	0.813	($537)
15)	*Diesel generator maintenance*	($810)	8	0.789	($639)
16)	*Diesel generator maintenance*	($300)	9	0.766	($230)
17)	*Diesel generator maintenance*	($810)	10	0.744	($603)
18)	*Diesel generator maintenance*	($660)	11	0.722	($477)
19)	*Diesel generator maintenance*	($810)	12	0.701	($568)
20)	*Diesel generator maintenance*	($300)	13	0.681	($204)
21)	*Diesel generator maintenance*	($660)	14	0.661	($436)
22)	*Diesel generator maintenance*	($810)	15	0.642	($520)
23)	*Diesel generator maintenance*	($810)	16	0.623	($505)
24)	*Diesel generator maintenance*	($660)	17	0.605	($399)
25)	*Diesel generator maintenance*	($300)	18	0.587	($176)
26)	*Diesel generator maintenance*	($810)	19	0.570	($462)
27)	*Diesel generator maintenance*	($810)	20	0.554	($448)
28)	*Salvage*	$6,667	16	0.623	$4,154
Total Discounted Non-Energy Savings:					($50,723)

Figure 55. Sigonella LCCA Tool Non-Energy Savings Analysis

At the top of the list displayed in Figure 55, we find an Annual Recurring listing. This accounts for any yearly savings or costs associated with running the MODEM system in the Sigonella use case. The text is displayed in red, because there were $8,906 greater costs than savings for this use case, which solely accounts for diesel fuel used by the generator. Going further down the Non-Energy Savings item list we see pump replacement avoidance. This non-energy savings is a result of reducing power fluctuations by using the MODEM system and reducing the wear and tear on the water pumps in this use case. Utilizing information provided by the OCONUS Base Energy Manager stakeholder about the use case he described to the team, we used a pump motor that was comparable and adjusted the value to account for acquisition cost to arrive at a cost savings of $44,152 (Greenheck n.d.) every 5 years. The costs for generator maintenance were not constant, which is why it was not accounted for in the Annual Recurring listing. Additionally, the replacement of the generator is also accounted for in this list with the associated year it occurred to properly discount the cost. The last item worth noting was the salvage of the generator the year it was replaced. All of the listed savings and costs resulted in a Total Discounted Non-Energy Savings of –$50,723 over the life cycle of the MODEM system in the Sigonella use case. The summary of the Sigonella use case analysis is provided in Figure 56.



SUMMARY:		
Mbtu Saved per $1,000 Invested:	0.45	
Kgal Saved per $1,000 Invested:	0.00	
Annual Savings:	$3,652	
Discounted Energy Savings:	$ 88,918	
Discounted Non-Energy Savings:	($50,723)	
Total Net Discounted Savings:		$38,196

Simple Payback	**Savings to Investment Ratio**
-22.86	**0.22**

Figure 56. Sigonella LCCA Tool Results Summary

Accounting for the Annual Savings, Discounted Energy and Non-Energy Savings discussed previously, resulted in a Total Net Discounted Savings of $38,196 over the life cycle of the MODEM system in the Sigonella use case. Through these analyses, the MODEM team determined that the resulting SIR for the Sigonella use case is 0.22. Since the SIR is less than 1.0, this indicates that the MODEM system being implemented in the Sigonella use case is not profitable to the point of having a return greater than the investment cost.

THIS PAGE INTENTIONALLY LEFT BLANK

VI. RECOMMENDATIONS AND FUTURE WORK

A. SUMMARY

The MODEM team's work on this project was not exhaustive, and further research and analyses are recommended. While the MODEM system shows promise in increasing resiliency, there is still much work that needs to be performed to further refine the system. In this section the team identified areas for potential future projects to explore regarding the system model, interoperability, operations and sustainment, and system life cycle.

B. SYSTEM MODEL

For the system model the MODEM team recommends further refinement of the system model as the system design is matured, continued exploration of the implementation of multiple MODEM units to support larger critical loads, and expansion and implementation of value properties is recommended to aid in utilizing the system model for simulation. The MODEM team's goal for a system model was to review existing research to capture the MODEM system's high-level stakeholder needs and requirements, derive those requirements further to the subsystem and component level, and capture the system's logical, functional, and physical architectures as they are currently understood. The team was able to do this, but system modeling is an iterative process and future teams who utilize the MODEM team model should update the model as new information is gathered.

The MMA is also an area that could be further explored. The use of multiple MODEM units could add the capability for the system to support larger loads and open the possibility for new use cases. The current modeling for MMA is very high-level and further research would need to be done to better understand how to effectively integrate multiple MODEM units to support a single load. Further analysis of the MMA logical, functional, and physical architectures is necessary and would be a good starting point for future research. Additionally, stakeholder needs and system requirements specific to MMA would likely need to be developed to help define the additional capabilities needed for the implementation of MMA.

The MODEM team was able to incorporate value properties for the components of the MODEM system. Further expansion and implementation of these value properties could aid in using the system model for simulation of system processes. These simulations could prove to be beneficial in exploring the capabilities of the system and identifying potential strengths and weaknesses. Similarly, to other aspects of modeling, an iterative approach is necessary to further refine the model as new information is derived from existing sources or identified through new research.

C. INTEROPERABILITY

For interoperability the MODEM team recommends future projects expand upon the Interface Control Document (ICD) produced in this project, and research the necessary interfaces for the subsystems and components. As stated in Chapter V Section A, the preliminary interoperability analysis conducted by the MODEM team is intended to act as a foundation to build upon in future efforts prior to implementation of the MODEM design or integration with identified critical loads. This section outlines recommendations on the next steps necessary to be completed as future work to fully define both external system interfaces and internal interfaces to ensure interoperability between the MODEM design and the intended end user from each of the defined use cases.

The ICD produced as a result of the MODEM team’s integration planning activities documents within the system model all critical interfaces identified throughout the functional, logical, and physical definition phases of this project. The overarching intent of the ICD is to document and manage the interfaces between systems, subsystems, or components to ensure successful integration and interoperability. Critical aspects of the ICD include capturing and allocating interface requirements as well as documenting interface definitions which outline key characteristics of interfaces themselves and the interactions that they enable.

Through research regarding various methodologies for interface assessment with respect to identifying integration issues and evaluating interoperability of systems, the MODEM team identified a process proposed in “Interface Management for a NASA Flight Project using Model-Based Systems Engineering” (Vipavetz, Shull, and Infeld 2016) that is recommended as a starting guide for follow-on interoperability analyses. The process outlines concise steps for an interface management methodology utilizing Model-Based Systems Engineering (MBSE) that will allow the work captured in the MODEM team's MSOSA model to be utilized and expanded upon. Vipavet's paper proposes:

- Identify: Perform interface analysis via MBSE diagrams utilizing the ICWG. Identify interface boundaries using system architecture and Concept of Operations (ConOps).
- Capture: Capture interface requirements in model and/or a requirements management tool (e.g., CORE®). Assign attributes, including Requirement Owners. Place under configuration control.
- Define: Develop interface design solutions and document in Interface Control Document (ICDs) or identify documents for pre-existing interfaces. Assign attributes, including agreements. Place under configuration control.
- Allocate: Flow interface requirements down to the architecture level at which the hardware or software on each side will first be integrated during the realization process.
- Verify: Define interface verification activities and success criteria. Conduct verification activities. Place results under configuration control.
- Comply: Requirement Owners review and analyze results for compliance and approval, write verification compliance reports.
- Integrate: Interconnect SOIs at their interface(s) (bring the two sides together) and validate (checkout) the integrated SOIs in the installed, operational environment, Repeat steps five to seven until project system is complete. (Vipavetz, Shull, and Infeld 2016, 3)

D. OPERATIONS & SUSTAINMENT

1. Reliability Analysis

For the reliability analysis the MODEM team recommends further analysis of the optimization of the generator for all use cases. The reliability analysis performed by the MODEM team should serve as a framework for initial reliability assessments should the MODEM program be funded and executed. The reliability-based values provided were derived from readily available data that likely does not directly represent the COTS hardware that would ultimately be chosen as a final product. We propose that the calculations and assessments performed be redone after COTS items have been identified. Again, these COTS items could have different predicted values from those identified and utilized by the team and companies would be more open to sharing their reliability data if a government program were to show interest and attempt to utilize their product within a system solution.

The logic behind our assessment would still hold true in that the program would identify areas of concern and attempt to mitigate. In the case of our analysis, the generator was the primary cause of concern and we attempted to mitigate this through maintenance practices. Were a program going through the acquisition cycle, they could identify alternative generators, attempt to alter the design to improve the overall reliability, adjust the generators utilization through additional hardware, or many other options. The overall goal of the preliminary analysis is to identify a theoretical baseline and attempt to design the system for reliability.

Additionally, the current system configuration is optimized solely for functional performance and does not include reliability. The majority of MAJ Varley’s work was to identify if a combination of COTS items could provide the power necessary for the MODEM to be a viable energy resiliency solution (Varley, Van Bossuyt, and Pollman 2022). To this end, he was concerned only with the power and other related functional values that came from his identified system. Due to limitations of the tool MAJ Varley created, our team was limited in our ability to alter and assess changes to this original design. We recommend that the system configuration be assessed and designed with redundancy in mind. The current system RBD has all components and subsystems in series when the final design would greatly benefit from some level of parallel components. Namely, the PV arrays and batteries could be designed to have redundancy by adding additional assets. Figure 57 shows an example of how the PV arrays could be arranged within the system RBD to include redundancy. The current number of panels, and batteries, could be increased and arranged such that they have an n:n-x have-need relationship. Calculations could be done such that the optimal number of panels is identified. Doing so would increase the overall system reliability along with increasing the systems output.

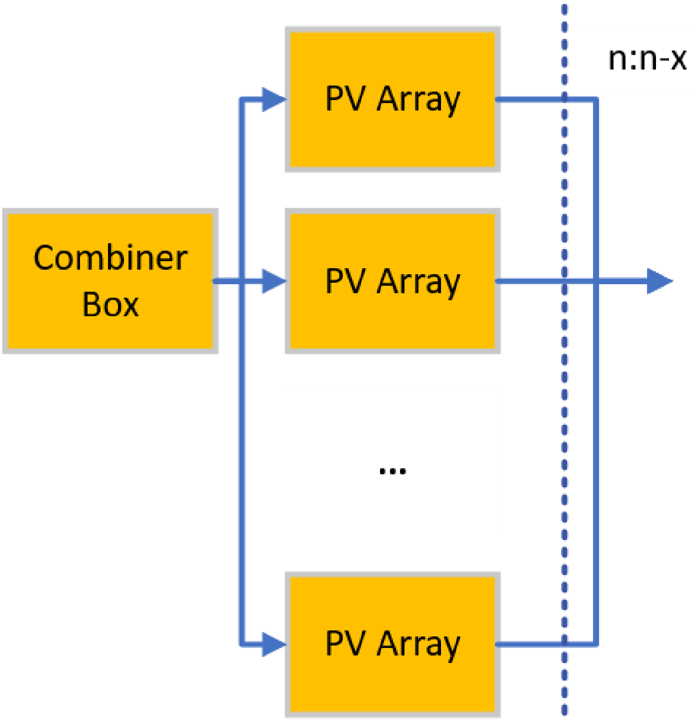


Figure 57. PV Array Panel Redundancy Example

Finally, it is very likely that the generator would still end up being the primary area of concern from a reliability perspective for the overall MODEM system. This is especially true in the continuous use case scenario. Even for the service interruption use case scenario, the utilization rate of the generator is relatively high at 65%. The primary function of the generator is to keep the batteries at sufficient charge and to add additional power in cases where the PV Arrays cannot generate enough. Further analysis is recommended for both use cases to optimize the utilization of the generator. Doing so would allow the program to more accurately gauge the generator, and overall system, reliability over the specified mission timeframes and adjust the design accordingly.

2. Maintenance Analysis

Like the reliability analysis, the maintenance analysis performed by the team should be further refined and optimized should the MODEM program be funded and fielded. There are many additional assessments that can and should be performed to fully and effectively support a system. The initial assessment and results here are the early estimates towards what is known as a Level of Repair Analysis (LORA). In essence, a LORA aims to determine the level of repair an item undergoes when maintenance is necessary. Beyond just determining if a part should be replaced, repaired, or discarded, the LORA also looks at where the maintenance should be done (organizational, intermediate, or depot) and the infrastructure necessary to perform the maintenance. While a full LORA analysis using sophisticated software and modeling is typically only necessary for complex systems with hundreds of parts, a simple system such as MODEM will still greatly benefit from some level of analysis. Like the reliability analysis, the team recommends further research and assessment once specific items are identified. Cost, supply chain, and maintenance practices can vary greatly even across similar functional items.

Another important process within the product support function is the identification and placement of spares necessary for items determined replaceable. Alluded to in the initial maintenance analysis, spares are critical for performing most types of maintenance regardless of the specific strategy identified—something must replace a removed or failed item to return the system to working order. Pre-positioning spares in optimal quantities ensures the systems overall MLDT requirements are achievable. While there are many methods and tools of determining this, the team recommends using the OPUS Suite of tools from Systecon. OPUS, and the other tools within the suite, are specifically aimed at modeling and simulation so that programs can answer questions related to product support. OPUS specifically, looks at the system and relevant data, such as failure rates, to determine how often spares will be needed and then accounts for any infrastructure that exists to determine how many spares should be placed where to maximize Ao at cost. Additionally, the SIMLOX tool within the suite, allows the program to take the identified sparing strategy and simulate various mission sets to see if the solution is truly achievable. For example, a sparing strategy for the service interruption use case could be identified using OPUS, and SIMLOX could then utilize this strategy to determine the impact to various metrics of the system including up time and various forms of downtime. While there are other factors to consider to the mission, this type of analysis can be very insightful to the product support group of the program.

E. SYSTEM LIFE CYCLE

1. Performance Analysis Recommendations

Additional performance analyses are recommended to optimize the output of the PV arrays, minimize generator usage, and more accurately define the behavior of the generator. Additionally, the MODEM team recommends that more detailed load profiles be used in future analyses to provide a better understanding of the system's performance for the intended use case.

The reasoning behind the performance analysis of the MODEM system was to evaluate the key output parameters within specific uses cases and then to drive the LCCA with the performance results. In the evaluation of the Monterey and Sigonella use cases, the MODEM team was able to analyze the behavior of the MODEM system and how it changed depending on the different input factors. Through various performance analyses, the team was able to make informed recommendations on both the MODEM system configuration, as well as the MODEM model tool.

After analyzing how the MODEM system performs in the Monterey and Sigonella use cases, it was clear that there were a few limiting factors in the system. When analyzing the Monterey use case performance, the results indicated very heavy usage of the generator to maintain load requirements and keeping the BESS charged to approximately 80% of its total capacity. Around 67% of all electricity produced from the MODEM was generated by the generator, which is not the intention behind the design of the system. The generator is intended to be a back-up to the PV array and only support electricity generation as need and in a limited capacity ideally. As a result of the high generator usage, it would be the MODEM team’s recommendation to conduct further performance analyses to determine the ideal configuration of PV panels, batteries, and generator to maximize output from the PV array. Maximizing the electricity generated from the PV array so that the generator is used infrequently would greatly reduce generator maintenance and downtime to perform maintenance. Additionally, reducing the reliance on the generator would increase the SIR and make the MODEM system more financially feasible. The stipulation of this recommendation is that it is heavily based on the use case and what the load requirements are. In relation to the MODEM model tool, there are a few recommendations that the MODEM team determined would improve analyses going forward and assist with development of the MODEM system.

The load characteristics are a key factor in the analysis that greatly effects the performance of the MODEM system. The Monterey use case does not have a very realistic load profile to accurately evaluate the MODEM system over the course of a year. A normal distribution is used to account for the minor changes in load from day-to-day. To analyze the performance of the MODEM system more accurately it would be the MODEM team’s recommendation to perform a detailed analysis, or capture, of the intended use cases load requirements for a period of a month and then interpolate that data for a performance analysis encompassing a year. This would greatly improve the accuracy of the performance analysis, as well as the results of the LCCA. It is understood that the load profile of the intended use case may not be readily available and could be troublesome to capture if required. With this difficulty in mind, the MODEM team would recommend only performing this for use cases likely for implementation or utilizing historical data of similar loads if possible. In addition to updating data used within the performance analysis, the generator maintenance periods could be improved as well. The MODEM team recommends that generator maintenance actions be researched in relation to the specific generator that will be used for operations and utilize any available historical data to provide more accurate maintenance periods. Providing more accurate maintenance data for the generator could potentially provide significant improvements on the LCC of running the

MODEM system. In addition to improving the generator maintenance cycles, the analysis of the MODEM system could also be improved to simulate a more realistic performance by accounting for maintenance downtime. As the design evolves and is close to finalized, it would be a recommendation to try to incorporate this data into the performance analysis. Lastly, the MODEM team would recommend adjusting the algorithm that the generator follows to determine whether it is running or not running. Currently, the generator will either run for a full 30-minute period, or not, depending on whether the PV array is keeping up with the BESS charge level cutoff of ~80%. It would be advantageous to develop a more efficient algorithm for determining runtime to minimize usage, maintenance, and reduce operation cost of the generator. Ultimately, the generator only needs to run for as long as required and this would greatly improve the results in the LCCA. Many of the performance analysis recommendations also tie into the LCCA recommendations.

2. Life-Cycle Cost Analysis Recommendations

The MODEM team recommends that future projects further define the intended use cases, research potential non-energy savings, and perform a deeper market research for the identified COTS equipment for the MODEM system. The goal of the LCCA was to determine the SIR of the MODEM system to determine if the system was financially effective in relation to the specific use cases it was analyzed for. Through the MODEM teams analyses, we were able to make recommendations on the use cases and the LCCA tool.

When evaluating the Sigonella use case it was difficult to find relatable information, especially tax incentives and rebates for implementing renewable energy solutions. It is the MODEM team’s recommendation that further research be conducted to determine what initiatives are available to assist in the development and implementation of a MODEM system in the Sigonella area, and any additional use case areas that have yet to be analyzed. All cost incentives for technologies such as the MODEM system will assist with improving the SIR and the chances of the MODEM system being funded and developed. Another use case factor that the MODEM team insists on evaluating is the value added by the resilience the MODEM system provides. The SIR values were low for both use cases evaluated, but if the resilience factor could be properly analyzed, or provided a dollar amount in relation to savings, this would assist in determining the usefulness and cost effectiveness of the MODEM system. Another recommendation of the MODEM team in relation to the use cases, is trying to gather greater detailed information about the usage of the MODEM system in the intended environment to assist with accurately determining all the non-energy savings. Currently, the non-energy savings are light for both use cases and as a result, indicate low SIRs. The light detail in our non-energy savings lists is a result of having minimal detail on the analyzed use cases, their loads, and the expected effects of the MODEM system when installed on the intended grid. The MODEM team also recommends reaching out to more vendors for the MODEM equipment intended for the design to gather accurate cost estimates. Most of the information used in the LCCA is accurate, but the TriCon container and generator prices were based on less reputable sources because of lack of available data and options. This will continue to be important going forward with development as more components are selected for the MODEM design. In relation to cost, the MODEM team also suggest further determining salvage prices for the equipment being used and potentially find more accurate methods of evaluating those prices. Contacting a salvage dealer that deals with the type of components that make up the MODEM system would be valuable, as well as looking for historical data on salvage prices. Beyond the use case details, the MODEM team also had recommendations on the LCCA tool.

Recommendations for the LCCA tool itself would be to further evaluate readily available LCCA tools. It was mentioned that the MODEM team discovered multiple valuable resources late in the project, and as a result, were not able to evaluate all the information. Some of this information were a few very detailed LCCA tools that performed similarly to the LCCA tool analyzed in this project. Without the knowledge of or familiarity with these tools, the MODEM team decided to invest a large amount of time into the LCCA tool provided to us to understand it and update it. More valuable analyses with greater detail could be provided by using or leveraging other available LCCA tools.

F. RISK

MODEM is on the path to being a design that can be fully implemented and interoperated at any Navy facility. Despite the progress made, there are some inherent considerations that need to be accounted for; the generated risks do a good job of capturing technical, cost, and design considerations. From a cost perspective, our LCCA needs to be further assessed through different tools, however it is critical that we consider that this project needs to be able to provide a strong return on investment. As a result, this is being tracked as a risk to assess the likelihood of this occurring and the consequences associated with this possibility. Ultimately if the severity can't be decreased this whole project will need to be analyzed for the effect and impacts of the risk.

From a technical and design perspective, MODEM must be safe and interoperable to be used and executed to meet its mission's purpose. The technical risk does an effective job of capturing the need for MODEM to abide by the safety standards that all Navy facilities use. The standard is critical in ensuring the safety of personnel as well as the execution of its technology. If MODEM does not meet P-604 the system will not be installed at the facility, hence its probability being unlikely but the seriousness of the risk being high. For the design risks, the current design was assessed to be a 48V system, categorizing it as a low voltage system. Components from MODEM that are being tracked to being a risk are the generators, batteries, and the modules. Out of the all the risks, the modules have the lowest effect in severity and using engineering knowledge it can be assumed that the preventative maintenance for the modules will help prevent the mismatched risk and not affect the array output.

On the other hand, the generator and battery risks are denoted as more severe. One of the generator risks can also be decreased in severity with preventative maintenance procedures. This generator risk needs the maintainers to have procedures in place for an outage so that the reclosing procedure does not prolong the outage. The last two risks deal with the environment that MODEM operates in. The battery needs to have proper ventilation to prevent high temperatures from affecting the purpose of this part or in a more severe scenario, cause the battery to explode. The generator also needs to have adequate ventilation to be able to supply the power MODEM will need to achieve its purpose. The battery and generator also drive a lot of our reliability recommendations, for this reason it is recommended that either MODEM is in a facility that has a quality heating, ventilation, and air conditioning system, or that the COTS chosen for the final design have ventilation or overheating preventative components. These risks were developed to take effective considerations of the current design to decrease the likelihood of the event and to ensure that the consequences do not affect the mission of the system.

VII. CONCLUSION

A. RESEARCH QUESTIONS

At the onset of the project the MODEM team set out to answer a set of initial research questions. Though some of the overall project goals shifted through interaction with stakeholders and the availability of information the MODEM team was able to gain insight on aspects of each question. While concrete answers were not gained for each question, the MODEM team was able to provide a deeper understanding of the system based on the research and analyses initiated by these questions. This conclusion section revisits the research questions and provides answers to them according to the MODEM team's understanding.

"Can mobile microgrids (one size fits all) effectively meet an average 10kw critical load while reducing the reliance on diesel fuel for power generation?" (Varley, Van Bossuyt, and Pollman 2022, 2) "What are the trade-offs between a mobile microgrid and a single load specific microgrid (e.g., resilience, time, cost, over or under utilization, load shedding)?" (Varley, Van Bossuyt, and Pollman 2022, 2)

The MODEM system as it is currently designed can support a 10 kW critical load through hybrid energy generation. However, the reduction of diesel fuel reliance is heavily dependent on the location and use case for the MODEM system.

The MODEM team did not conduct a trade-off analysis on mobile microgrids and static load specific microgrids, but some generalizations can be made based upon the results of the team's analyses. Because the MODEM system has a requirement to be easily transported by fitting in a single TriCon, it limits the system's ability to utilize solar energy to power the critical load. A load specific microgrid could be designed to be able to support the load completely on renewable energy sources depending on availability of space for the PV arrays. The performance analysis of the analyzed use cases showed that the MODEM system can support the identified loads with no load shedding which increases resilience. The MODEM team did not compare the MODEM LCCA to any analyses for a load specific microgrid to identify differences in cost.

When evaluating the performance of the MODEM system, the team focused their analyses on two continuous use cases based on the OCONUS Base Energy Manager stakeholder’s guidance. The stakeholder explained to the team how it would not be cost effective to only utilize the MODEM system in service interruption use case. The team made the determination to focus the performance analysis and LCCA of the MODEM system on two continuous use cases for NPS in the Monterey, California area and another continuous use case in the NAS Sigonella, Italy area. Using MAJ Daniel Varley’s MODEM model tool and modifying it for our specific use cases and capturing additional data to feed into the LCCA tool provided the team with valuable information. For both continuous use cases, neither resulted in load shed and both generated electricity beyond the BESS capacity causing the MODEM system to sell electricity beyond their microgrid. From a performance standpoint, the MODEM system is very capable in satisfying load demands at operating as the design intended. With further research and development to refine the performance of the MODEM system, the results will be very desirable. The results of the MODEM performance analysis were then evaluated in the LCCA.

When, if at all, is utilizing a solar-powered microgrid financially advantageous in comparison to using a diesel fueled generator? When does return on investment (ROI) yield cost savings? What is the LCC of a MODEM unit?

When evaluating the LCC of the MODEM system, the team focused their analyses on the two continuous use cases evaluated for the performance analysis. The Monterey use case resulted in an SIR of -6.19, indicating that the MODEM system would never recoup the investment and O&S costs during its life cycle. Based solely on the SIR, the Monterey use case is far from cost effective, and it would not be a feasible implementation of the MODEM system. The Sigonella use case resulted in an SIR of 0.22, indicating that the MODEM system would not recoup the investment and O&S costs during its life cycle. The Sigonella use case is not profitable, but it significantly outperforms the MODEM in the Monterey use case in terms of cost effectiveness. Ultimately, neither LCCA indicated a feasible implementation of the MODEM system in the Monterey or Sigonella use case when basing determination solely on SIR. Potentially, with more thorough analyses of the load requirements, non-energy savings, and improvements of MODEM performance could result in a positive SIR.

What objective/threshold power levels are necessary for most DOD critical loads?

The MODEM team did not pursue research on critical loads outside of the proposed 10kw average load. However, the team did gain insight on what types of loads could potentially be supported with the current system design. The power generated by the MODEM system is sufficient to support a variety of use cases, such as a small office building or pump house, but could not be expected to fully support loads greater than 10kw without load shedding.

What long-term supportability requirements exist for MODEM units?

The MODEM team's reliability and maintenance analyses identified that the sustainment of the MODEM units is heavily driven by the reliability of certain subsystems. These are primarily the diesel generator and electrical bus systems. The generator has the lowest overall reliability of any component within the system and the primary method of keeping it maintained has been identified as time-based preventative maintenance, though much of this is driven by the amount the generator is utilized. The electrical bus systems are only a concern with one of the two use cases identified (continuous). Overall, the system will need to be adequately assessed for long-term sparing and maintenance practices of low reliability parts, along with the rest of the system. Analyses of alternatives and design for reliability could help to offset some of the reliability concerns, which would, in turn, impact the supportability. Additionally, alternatives should be evaluated based on cost as this has large impacts as well. Optimization between reliability and cost ultimately optimizes the long-term sustainment of the system. It is also recommended that the program monitor obsolescence early and throughout the system life cycle.

Are MODEM units feasible to provide forward deployment power capabilities for LSCO?

The MODEM team's analyses ultimately were not focused on LSCO but based upon the results of the performance analysis for the remote pump house it seems likely that MODEM units could be used to provide LSCO with a source of hybrid power generation to support loads within the designed power output. The transportability of the system should allow it to be deployed using ground or air assets to reach LSCO locations. However, further investigation and research would need to be conducted to verify the performance of the system to support LSCO critical loads and the time required to fully set up and tear down the MODEM system.

B. SUMMARY

There is an ever-increasing push across the DOD to increase energy resiliency of DCEI. Improving the resilience of these DCEI is critical in the execution of our nation's national defense strategy and ensuring success (EAC 2022). Ongoing research into hybrid microgrids by numerous groups and organizations shows promise in addressing many of the concerns related to DOD energy infrastructure resiliency. Based on prior work by MAJ Varley, the MODEM team aimed to assess the interoperability and viability of the MODEM system as a potential solution (Varley, Van Bossuyt, and Pollman 2022). Specifically, the team aimed to assess the interoperability of the system and identified components both between each other and with the infrastructure they would be supplying power to, perform initial reliability and maintainability analyses to assess performance and support feasibility, and to provide initial LCC assessment for both acquisition and support considerations. By creating a SysML model of the system and related data, the team developed a baseline that could potentially serve future work on this specific effort and similar areas of interest. This model also aided in the various analyses by capturing the values necessary for calculations along with the results of these analyses in a centralized location which can be utilized for additional future assessments.

The team focused O&S assessments on two uses cases with varying CONOPs—a continuous use case that was identified through discussions with stakeholders and an service interruption use case that was the focus of MAJ Varley's work (Varley, Van Bossuyt, and Pollman 2022). From an O&S assessment perspective, the continuous use case is not feasible while the service interruption use case is feasible. The continuous use case fails due in large to the system utilization pushing the hardware beyond their originally intended use. The team has identified areas of concern and made recommendations to bolster the overall system design so that the continuous use case is potentially more feasible.

The MODEM team conducted the system performance and LCC analyses based heavily on feedback from project stakeholders. These analyses focused on two continuous use cases—NPS Monterey and NAS Sigonella. The system performance analysis found that the MODEM system was able to support the loads in the identified use cases. However, the team concluded that the current design of the MODEM system does not provide a viable SIR for the analyzed use cases based upon the LCCA.

The SysML model created by the MODEM team effectively captures the MODEM mission context, use cases, stakeholder needs, MOEs, MOPs, and system, subsystem, and component requirements. Additionally, the model provides a baseline of the MODEM functional, logical, and physical architectures as they are currently understood with traceability between model elements through the systems engineering process baselines. The system model serves as a starting point for future projects so that researchers can quickly gain familiarity with the system and its requirements.

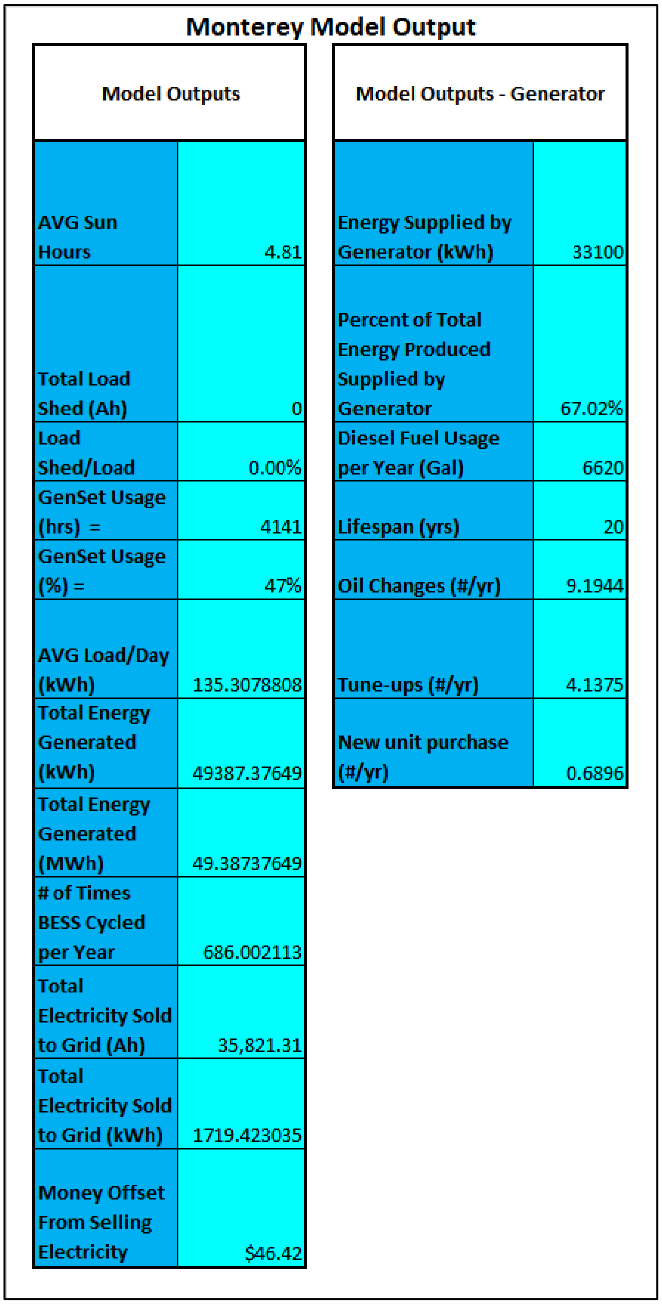
Overall, the MODEM system shows considerable promise as a potential solution to improving and maintaining resilience of DOD energy infrastructure across multiple CONOPs. However, further analysis and refinement of the system is imperative to more accurately make a determination.

THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX. LIFE-CYCLE COST ANALYSIS

This appendix contains supporting information for the LCCA of the MODEM system that was not presented in the body of the report. The details in this appendix were developed while the MODEM team was populating the necessary information from the MODEM model tool into the LCCA tool.

The Monterey use case MODEM model data that was further analyzed in the LCCA tool to determine the number of generator maintenance actions that occurred over the life cycle of the MODEM system is provided in Figure 58 and Figure 59. Figure 58 is the MODEM model data that was pulled into the LCCA tool and Figure 59 is the additional generator maintenance analyses that the MODEM team performed within the LCCA tool.

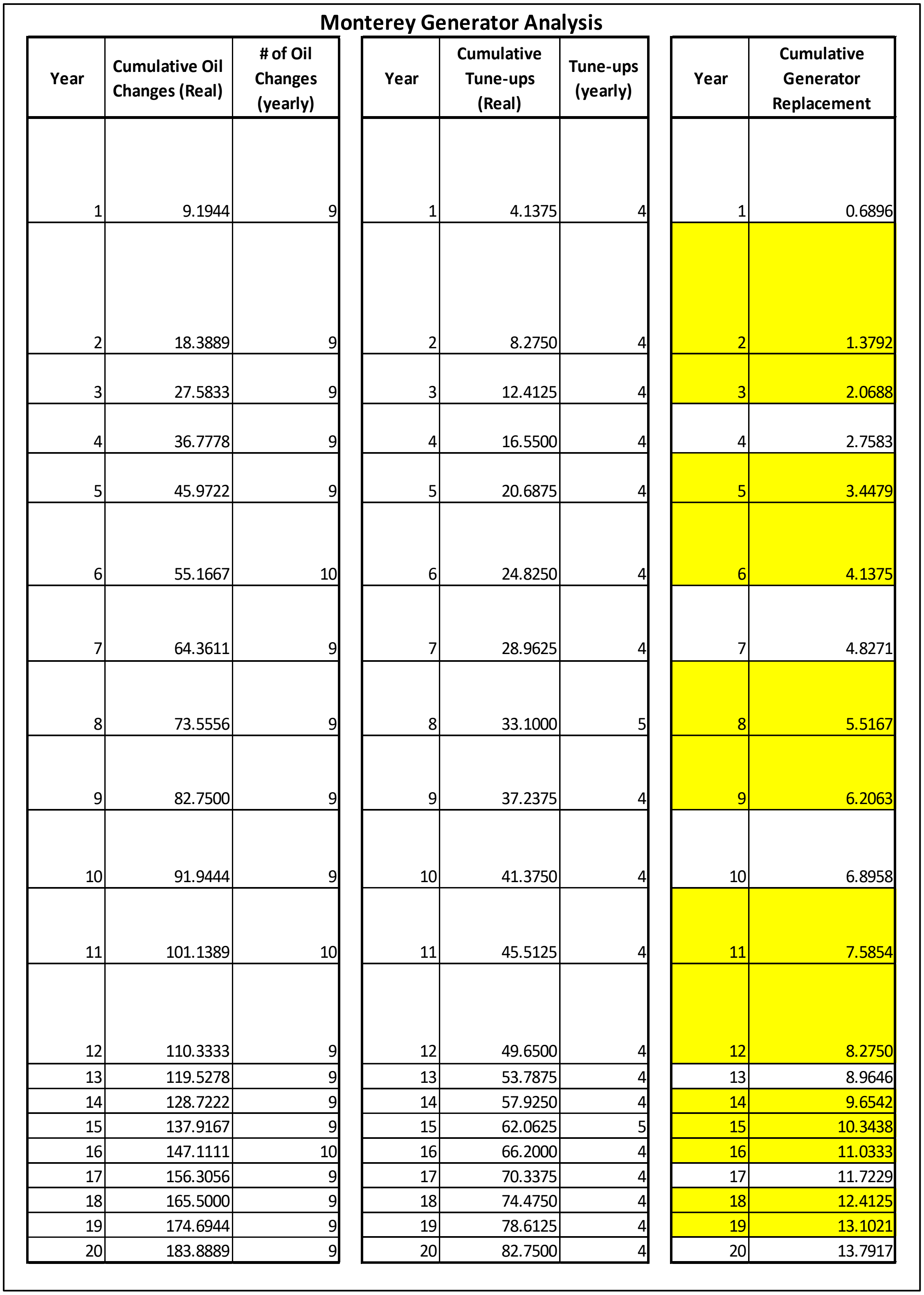


Monterey Model Output

Model Outputs	
AVG Sun Hours	4.81
Total Load Shed (Ah)	0
Load Shed/Load	0.00%
GenSet Usage (hrs) =	4141
GenSet Usage (%) =	47%
AVG Load/Day (kWh)	135.3078808
Total Energy Generated (kWh)	49387.37649
Total Energy Generated (MWh)	49.38737649
# of Times BESS Cycled per Year	686.002113
Total Electricity Sold to Grid (Ah)	35,821.31
Total Electricity Sold to Grid (kWh)	1719.423035
Money Offset From Selling Electricity	$46.42

Model Outputs - Generator	
Energy Supplied by Generator (kWh)	33100
Percent of Total Energy Produced Supplied by Generator	67.02%
Diesel Fuel Usage per Year (Gal)	6620
Lifespan (yrs)	20
Oil Changes (#/yr)	9.1944
Tune-ups (#/yr)	4.1375
New unit purchase (#/yr)	0.6896

Figure 58. Monterey LCCA Data Input from MODEM Model



Monterey Generator Analysis

Year	Cumulative Oil Changes (Real)	# of Oil Changes (yearly)	Year	Cumulative Tune-ups (Real)	Tune-ups (yearly)	Year	Cumulative Generator Replacement
1	9.1944	9	1	4.1375	4	1	0.6896
2	18.3889	9	2	8.2750	4	2	1.3792
3	27.5833	9	3	12.4125	4	3	2.0688
4	36.7778	9	4	16.5500	4	4	2.7583
5	45.9722	9	5	20.6875	4	5	3.4479
6	55.1667	10	6	24.8250	4	6	4.1375
7	64.3611	9	7	28.9625	4	7	4.8271
8	73.5556	9	8	33.1000	5	8	5.5167
9	82.7500	9	9	37.2375	4	9	6.2063
10	91.9444	9	10	41.3750	4	10	6.8958
11	101.1389	10	11	45.5125	4	11	7.5854
12	110.3333	9	12	49.6500	4	12	8.2750
13	119.5278	9	13	53.7875	4	13	8.9646
14	128.7222	9	14	57.9250	4	14	9.6542
15	137.9167	9	15	62.0625	5	15	10.3438
16	147.1111	10	16	66.2000	4	16	11.0333
17	156.3056	9	17	70.3375	4	17	11.7229
18	165.5000	9	18	74.4750	4	18	12.4125
19	174.6944	9	19	78.6125	4	19	13.1021
20	183.8889	9	20	82.7500	4	20	13.7917

Figure 59. Monterey LCCA Generator Analysis Data

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF REFERENCES

Alfano, Dan. 2011. *Solar Inverter Reliability.* Annapolis, MD Power System Designs. https://www.powersystemsdesign.com/articles/solar-inverter-reliability/22/5873.

Alibaba. n.d. “Military Tricon for sale to U.S. Army 8ft x 6ft Shipping Container.” Accessed September 24, 2022. https://www.alibaba.com/product-detail/US-Army-use-Military-Tricon-Shipping_60542908166.html.

Anuat, Edward, Douglas L. Van Bossuyt, and Anthony Pollman. 2022. “Energy Resilience Impact of Supply Chain Network Disruption to Military Microgrids.” *Infrastructures* 7 (1) (December): 4. https://doi.org/10.3390/infrastructures7010004.

Baschel, Stefan, Elena Koubli, Jyotirmoy Roy, and Ralph Gottschalg. 2018. “Impact of Component Reliability on Large Scale Photovoltaic Systems’ Performance.” *Energies* 11 (6) (June): 1579. https://www.mdpi.com/1996-1073/11/6/1579.

Collins, Elmer, Michael Dvorack, Jeff Mahn, Michael Mundt, and Michael Quintana. 2009. “Reliability and Availability Analysis of a Fielded Photovoltaic System.” In *2009 34th IEEE Photovoltaic Specialists Conference (PVSC)* 002316-002321. https://energy.sandia.gov/wp-content/gallery/uploads/093004c.pdf.

Corporate Finance Institute. 2022. “Discount Rate.” February 6, 2022. https://corporatefinanceinstitute.com/resources/knowledge/finance/discount-rate/.

Electricity Advisory Committee. 2022. *Strengthening the Resilience of Defense Critical Electric Infrastructure*. Washington, DC: Department of Energy. https://www.energy.gov/sites/default/files/2022-03/EAC%20Recommendations%20-%20Strengthening%20DCEI%20Resilience%20-%20Final_508.pdf.

European Central Bank. 2022. “Euro Foreign Exchange Reference Rates.” October 28, 2022. https://www.ecb.europa.eu/stats/policy_and_exchange_rates/euro_reference_exchange_rates/html/eurofxref-graph-usd.en.html.

Fuelo. 2022. “Diesel.” October 28, 2022. https://it.fuelo.net/fuel/type/diesel?lang=en.

Gerken, K, and Welsh, D. 1997. *A Pulse-Width Modulated, High Reliability Charge Controller for Small Photovoltaic Systems.* Report Numbers SAND-97-0329, ON: DE97004744, TRN: 97:002419. Albuquerque, NM: RAND https://www.osti.gov/servlets/purl/459871.

Gestore Mercati Energetici. 2022. “Results of the Electricity Market.” October 31, 2022. https://mercatoelettrico.org/en/Default.aspx.

Giachetti, Ronald E., Christopher J. Peterson, Douglas L. Van Bossuyt, and Gary W. Parker. 2020. “Systems Engineering Issues in Microgrids for Military Installations.” Paper presented at the 30th Annual Incose International Symposium, Cape Town, South Africa.

Greenheck. n.d. “Motor, ABB Motors & Mechanical Inc, 40HP, 1500 RPM, 380/400/415V, 50Hz, 3Ph, Product # 312630VK.” Accessed October 30, 2022. https://www.greenheck.com/shop/parts/motors-bases-and-drives/motors/312630vk.

HOMER. 2021. HOMER Pro, version 3.15. Boulder, CO. Accessed October 14, 2022. https://www.homerenergy.com/products/pro/docs/latest/salvage_value.html.

International Council on Systems Engineering (INCOSE). 2015. *Systems Engineering Handbook*. 4th ed. San Diego, CA.

International Organization for Standardization (ISO). 2015. *Systems and Software Engineering—System Life Cycle Processes*. ISO/IEC/IEEE 15288. Geneva, Switzerland. https://www.iso.org/standard/63711.html.

Kasunic, Mark. 2001. *Measuring Systems Interoperability*. McLean, VA: Booze Allen Hamilton. https://apps.dtic.mil/sti/pdfs/ADA400176.pdf.

Masters, Gilbert. 2004. “*Photovoltaic Systems*.” In *Renewable and Efficient Electric Power Systems*.544–622. Hoboken, NJ: John Wiley and Sons.

Marqusee, Jeffrey, and Jenket II, Donald. 2020. “Reliability of Emergency and Standby Diesel Generators: Impact on Energy Resiliency Solutions.” *Applied Energy* 268 (15) (June): 1–20. https://doi.org/10.1016/j.apenergy.2020.114918.

Narducci, Riccardo and Carsten Steinhauer. 2020. “Italy: The 2019–2020 Incentives Regime for Renewable Energy Plants.” Dentons. December 18, 2020. https://www.dentons.com/en/insights/alerts/2020/december/17/fer1-decree-2019-2020-incentives-regime-for-renewable-energy-plants.

National Institute of Standards and Technology. 2021. *NIST Framework and Roadmap for Smart Grid Interoperability Standards*. NIST Special Publication 1108r4 Release 4.0. Gaithersburg, MD. https://doi.org/10.6028/NIST.SP.1108r4.

National Institute of Standards and Technology. 2022. *Energy Price Indices and Discount Factors for Life-Cycle Cost Analysis—2022*. NISTIR 85–3273-37 update 1. Gaithersburg, MD. https://doi.org/10.6028/NIST.IR.85-3273-37-upd1.

National Renewable Energy Laboratory (NREL). 2017. “Research at NREL Find Fewer Failures of PV Panels and Different Degradation Modes in Systems Installed after 2000.” April 10, 2017. https://www.nrel.gov/news/program/2017/failures-pv-panels-degradation.html.

Naval Facilities Engineering Command. 2019. *P-604 Electrical Safe Acts for Employees (E- Safe)*. Washington, DC: NAVFAC. https://www.wbdg.org/FFC/NAVFAC/PPUBB/P-604.pdf.

Oriti, Giovanna and Antonino Piluso. 2020. “Microgrid with PV and Batteries to increase the Resilience of the Water Treatment Plant in NAS Sigonella.” Unpublished manuscript, June 16, 2020.

Rodriguez-Diaz, Enrique, Chen Fang, Juan C. Vasquez, Josep M. Guerrero, Rolando Burgos, and Dushan Boroyevich. 2016. “Voltage-Level Selection of Future Two-Level LVdc Distribution Grids.” *IEEE Electrification Magazine*, May 30, 2016. https://ieeexplore-ieee-org.libproxy.nps.edu/document/7480936.

Solar Energy Industries Association. 2022. “Inflation Reduction Act: Solar Energy and Energy Storage Provisions Summary.” https://www.seia.org/sites/default/files/2022-08/Inflation%20Reduction%20Act%20Summary%20PDF%20FINAL.pdf.

State of California. 2021. “Net Energy Metering.” Accessed September 3, 2022. https://www.cpuc.ca.gov/industries-and-topics/electrical-energy/demand-side-management/net-energy-metering.

U.S. Department of Defense. 2021. *Major Capability Acquisition*. DOD Instruction 5000.85. Washington, DC: Department of Defense. https://www.esd.whs.mil/Portals/54/Documents/DD/issuances/dodi/500085p.pdf.

U.S. Department of Defense. 2018. *Manual for the Operation of the Joint Capabilities Integration and Development System*. Washington, DC: Department of Defense. https://www.acq.osd.mil/asda/jrac/docs/2018-JCIDS.pdf.

U.S. Department of Defense. 2014. *Risk Management Guide for Defense Acquisition Programs*. Washington, DC: Department of Defense. https://acqnotes.com/wp-content/uploads/2014/09/DOD-Risk-Mgt-Guide-v7-interim-Dec2014.pdf.

U.S. Department of Defense. 2018. *Operational Risk Management*. OPNAVINST 3500.39D. Washington, DC: Department of Defense. https://nps.edu/documents/111291366/0/3500.39D+OPERATIONAL+RISK+MANAGEMENT.pdf/dc34052e-7aba-e283-deb8-b614e4c6e7c0?t=1634767245161.

U.S. Department of Energy. 2021. “2021 Discount Rates.” https://www.energy.gov/sites/default/files/2021-04/2021discountrates.pdf.

U.S. Energy Information Administration (under section “2. Energy Prices: U.S. Electricity: Prices to Ultimate Customers: Commercial Sector”; accessed October 12, 2022). https://www.eia.gov/outlooks/steo/data/browser/#/?v=8&f=M&s=&start=202206&end=202312&id=&maptype=0&ctype=linechart&linechart=WTIPUUS.

U.S. Environmental Protection Agency. 2022. “Electricity Storage.” November 1, 2022. https://www.epa.gov/energy/electricity-storage.

Varley, Daniel W., Douglas L. Van Bossuyt, and Anthony Pollman. 2022. “Feasibility Analysis of a Mobile Microgrid Design to Support DOD Energy Resilience Goals.” *Systems* 10 (3) (June): 74. https://doi.org/10.3390/systems10030074.

Varley, Daniel. 2022. “Mobile Microgrid Concept to Improve Installation Energy Resilience.” *SURGE Energy Academic Group Quarterly Newsletter*. Summer 2022. https://nps.edu/documents/106660594/136674728/EAG-Surge-2022-Q3-vFinal.pdf/a8236698-3c2f-c685-333b-2b5fd7586372?t=1657743399070.

Vipavetz, Kevin, Thomas A. Shull, Samantha Infeld, and Jim Price. 2016. “Interface Management for a NASA Flight Project using Model-Based Systems Engineering (MBSE).” In *26th Annual INCOSE International Symposium* 1–15. https://ntrs.nasa.gov/api/citations/20160010336/downloads/20160010336.pdf.

INITIAL DISTRIBUTION LIST

1. Defense Technical Information Center
   Ft. Belvoir, Virginia

2. Dudley Knox Library
   Naval Postgraduate School
   Monterey, California