NPS-CE-24-024

ACQUISITION RESEARCH PROGRAM
SPONSORED REPORT SERIES

Marine Corps Expeditionary Power: Cost Effective Analysis of Power Generation/Storage to Offset Constrained Logistics

March 2024

Maj Joshua A. Gray, USMC

Thesis Advisors: Dr. Daniel A. Nussbaum
Dr. Robert F. Mortlock, Professor

Department of Defense Management

Naval Postgraduate School

The research presented in this report was supported by the Acquisition Research Program of the Department of Defense Management at the Naval Postgraduate School.

To request defense acquisition research, to become a research sponsor, or to print additional copies of reports, please contact the Acquisition Research Program (ARP) via email, arp@nps.edu or at 831-656-3793.

ABSTRACT

This thesis provides a preliminary cost and operational effectiveness analysis of alternative power generation and storage capabilities needed to advance the Marine Corps Expeditionary Power and reduce fuel reliance during constrained combat operations at the tactical level. This work compares the current fuel efficiency of 60-kilowatt generators to three emerging energy alternatives: power storage, hydroelectric buoys, and solar photovoltaic technology. This effort uses quantitative analysis to determine each capability's life-cycle cost while using qualitative assessments to determine each system's overall measure of effectiveness. The qualitative operational effectiveness is assessed across three criteria identified within the Marine Corps concept of employment: (1) operational persistence, (2) mobility, and (3) survivability. The intent of this study is to guide decision-making for future energy systems at the tactical level. The outcome shows that energy storage is the most effective alternative energy method for offsetting fuel consumption based on the established objective hierarchy, with a measure of overall effectiveness (MOE) score of .7996. Both solar power and hydroelectric buoys are less effective alternatives based on the established objective hierarchy, with MOE scores of .6251 and .2322 respectively. Energy storage, however, is more costly to implement than the current 60-kilowatt generator method of employment, requiring decision-makers to trade off costs.

THIS PAGE INTENTIONALLY LEFT BLANK

ACKNOWLEDGMENTS

I would like to thank my advisors for their support and feedback throughout the thesis process. Whether though insights, criticism, or valuable guidance, you were critical to my research. Your commitment to excellence and your passion to provide greater capability to the warfighter inspires all of us more than you can imagine. For your passion and dedication, I am better. Thank you.

Special thanks are also extended to Army Lieutenant Colonel Thomas Beyerl and Marine Corps Gunnery Sergeant Zoyla Bocksnickrabanales for their indispensable subject-matter expertise. Their willingness to engage in countless discussions has significantly enhanced my work. Your experience and perspectives have not only enriched this thesis, but have also contributed greatly to my personal growth as a researcher.

Finally, my heartfelt love and appreciation goes to my wife, Tabatha, and our two daughters, Mailie and Emma. I cannot thank you enough for your unwavering support and your sacrifices throughout my career. Your love, understanding, and patience continue to provide one of my greatest sources of strength. Your encouragement during challenging times and your belief in my abilities provide motivation that allows me to persevere. Girls, sincerely, thank you. I love you.

THIS PAGE INTENTIONALLY LEFT BLANK

NPS-CE-24-024

ACQUISITION RESEARCH PROGRAM
SPONSORED REPORT SERIES

Marine Corps Expeditionary Power: Cost Effective Analysis of Power Generation/Storage to Offset Constrained Logistics

March 2024

Maj Joshua A. Gray, USMC

Thesis Advisors: Dr. Daniel A. Nussbaum
Dr. Robert F. Mortlock, Professor

Department of Defense Management

Naval Postgraduate School

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

I. INTRODUCTION 1
  A. PROBLEM STATEMENT 1
  B. RESEARCH QUESTIONS 3
  C. SCOPE AND METHODOLOGY 5
  D. BENEFITS OF THIS THESIS 6
  E. ORGANIZATION OF THE STUDY 6
  F. THESIS LIMITATIONS AND SHORTFALLS 6

II. BACKGROUND AND LITERATURE REVIEW 9
  A. BACKGROUND 9
  B. LITERATURE REVIEW 10
  C. LITERATURE REVIEW TAKEAWAYS 13

III. ENERGY ALTERNATIVES AND MEASURES OF EFFECTIVENESS (METHODOLOGY AND ANALYSIS) 17
  A. DATA 17
  B. METHODOLOGY 18
    1. Objectives Hierarchy 18
    2. Assigning Individual Attribute Values 20
    3. Direct Assessment for Importance Weights 28
  C. ASSESSING ALTERNATE ENERGY AND INDIVIDUAL ATTRIBUTES 29
    1. Assessing Fuel Powered Generators 30
    2. Assessing Solar Power Generation (without Power Storage) 34
    3. Assessing Power Storage in Concert with Generators 39
    4. Assessing Hydroelectric Buoys in Concert with Generators 43
  D. MOE SCORE AND COST-EFFECTIVE SOLUTION 47

IV. PROGRAM COST ANALYSIS 49
  A. DATA 49
    1. Calendar Year Dollars and Inflation 49
    2. Time Covered for Estimates 50
    3. Updated Fuel Costs 50
    4. Methodology 50

B. PROGRAM ESTIMATES 51
  1. 60-kW Generator Cost Analysis 51
  2. Solar Power Cost Analysis 55
  3. Energy Storage Cost Analysis 59
  4. Hydroelectric Buoy Costs Analysis 63
C. OVERALL PROGRAM COSTS 66
D. COST-EFFECTIVENESS RESULTS 67

V. CONCLUSIONS AND RECOMMENDATIONS 69
A. CONCLUSION 69
B. FUTURE RESEARCH 70

LIST OF REFERENCES 73

LIST OF FIGURES

Figure 1. Example Hierarchy Tree. Source: Wall and Mackenzie (2015). 19

Figure 2. Alternative Power Measures of Effectiveness. Adapted from Marine Corps Concept of Employment (2024). 19

Figure 3. Assigned Importance Weights. Adapted from Marine Corps Concept of Employment (2024). 29

Figure 4. Technical Manual 11300-15/1. Source: U.S. Marine Corps (2023). 31

Figure 5. Photovoltaic Potential (Philippines, Indonesia, and Japan). Source: SolarGIS (2024). 35

Figure 6. HGT20K Hybrid Generator during Exercise STEADFAST LEDA 2021. Source: IDE Intracom Defense (2023). 40

Figure 7. Different Energy Conversion Principles. Source: Hansen et al. (2013). 44

Figure 8. AquabuOY Wave Energy Converter. Source: University of Strathclyde (2024). 45

Figure 9. Contracted Generator Price List. Source: Department of the Army, working document (2023). 52

Figure 10. Program Affordability Estimates. Source: Department of the Army (2014). 53

Figure 11. Online Solar Calculator Quote for 12-kW Solar System. Source: Inverter Supply (2024). 57

Figure 12. Cycle Life to 80% Capacity Loss. Source: Saft America (2023). 62

Figure 13. AquabyOY 20-year LCCE. Source: University of Strathclyde (2023). 64

Figure 14. All Programs 17-year (1,280 Operational Hours)................................... 67

Figure 15. All Programs 17-year (3,600 Operational Hours)................................... 68

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF TABLES

Table 1. Incremental Values for Fuel Efficiency 21

Table 2. Individual Attribute Values for System Fuel Efficiency 21

Table 3. Incremental Values of Technical Readiness Levels 22

Table 4. Individual Attribute Values for TRL 22

Table 5. Marine Corps Transport Vehicle (Equipment) 23

Table 6. Incremental Values for Capable Transport Vehicles 23

Table 7. Individual Attribute Values for Transport Capabilities 24

Table 8. Incremental Values for Displacement/Emplacement Times 25

Table 9. Individual Attribute Values for Displacement/Emplacement Times 25

Table 10. Incremental Values for Combat Footprint 26

Table 11. Individual Attribute Values for Combat Footprint 27

Table 12. Individual Attribute Values for MTBF 27

Table 13. Individual Attribute Values for MTTR 28

Table 14. Generator Individual Attribute Scores 34

Table 15. Solar Power Individual Attribute Scores 39

Table 16. Energy Storage Individual Attribute Scores 43

Table 17. Power Storage Individual Attribute Scores 47

Table 18. Capability Measures of Effectiveness 48

Table 19. 60-kW Generator 17-year LCCE 55

Table 20. 12-kW Solar System 17-year LCCE 59

Table 21. Energy Storage 17-year LCCE 63

Table 22. Hydroelectric Buoy 17-year LCCE 66

Table 23. 17-year LCCE for all Programs (1,280 / 3,600 Operational Hours) 66

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF ACRONYMS AND ABBREVIATIONS

A2AD	anti-access aerial denial assets
AMMPS	Advanced Medium Mobile Power Sources
AO	area of operation
BTU	British thermal units
CA	certification authority
CBA	cost-benefit analysis
CDD	capability development document
CEA	cost-effectiveness analysis
CER	cost-effectiveness ratio
COC	command operations center
COE	concept of employment
CPD	capability production document
CY	calendar year
DOD	Department of Defense
DOTMLPF-P	doctrine, organization, training, materiel (non-development), leadership/education, personnel, facilities, or policy
EAB	expeditionary advanced base
EABO	expeditionary advanced basing operations
ETP	Energy Technology Perspective
FBCF	fully burdened cost of fuel
FoMPS	Family of Mobile Power Systems
FY	fiscal year
GREENS	Ground Renewable Expeditionary Energy System

IB	industrial base
IEA	International Energy Agency
INDOPACOM	Indo-Pacific Command
KPP	key performance parameter
LCCE	life-cycle cost estimate
MAGTF	Marine Air Ground Task Force
MARCORSYSCOM	Marine Corps Systems Command
MLR	Marine Littoral Regiment
MOE	measures of effectiveness
MTBF	mean time between failures
MTTR	mean time to repair
NATO	North Atlantic Treaty Organization
NAVSEA	Naval Sea Commands
OE	operational energy
PV	photovoltaic
QUADCON	quadruple containers
RFI	request for information
SIF	stand-in force
SYSCOM	systems Command
TPS	tactical power systems
TRL	technical readiness level
WECs	wave energy converters

I. INTRODUCTION

This thesis provides a preliminary cost and operational effectiveness analysis of alternative power generation and storage capabilities to advance the Marine Corps' Expeditionary Power and improve fuel use during constrained combat operations. First, this work measures the effectiveness and efficiency of the Marine Corps' 60-kilowatt (kW) generator for the creation of power. Additionally, this thesis compares three alternative power generation technologies (power storage solutions, hydroelectric power capabilities, as well as solar power generation) to determine which, if any, provide a more cost-effective method. This cost effectiveness analysis incorporates both qualitative and quantitative approaches to provide a more comprehensive understanding of the value and impact of each power storage and generation approach specific to the Marine Corps' assigned roles and responsibilities to the Joint Force.

A. PROBLEM STATEMENT

As the U.S. Department of Defense (DOD) encounters some of its biggest external changes in decades, every Service is evaluating their roles and responsibilities to the Joint Force to effectively operate in a resource constrained operational environment against peer competitors. The Marine Corps, specifically, is undergoing potentially the largest strategic shift in its history to provide the Joint Force with forward reconnaissance to enable fires against peer adversaries. From the highest level of the National Defense Strategy down to the Service level of the Marines Corps power concept of employment, the DOD holistically identifies a need to become a more agile expeditionary force, capable of operating in resource constrained environments. Future campaigns and operational environments will challenge the Marine Corps ability to amass large surpluses of equipment and supplies as experienced by the U.S. military's campaigns in Iraq and Afghanistan over the past two decades. To better support the Joint Force with forward reconnaissance and fires, the Marine Corps will have to remain light and extremely mobile. China and Russia's improvements in intelligence collection capabilities and long-range precision guided munitions completely change the dynamics of future conflict that will place strains on logistics and supply lines, requiring the Marine Corps to operate forward with minimal resources for potentially long periods of time. Fuel and energy will likely pose a significant issue in keeping the Joint Force's reconnaissance force operational. The Marine Corps needs to better understand all methods of energy development, storage, and sustainment and determine the most cost-effective method of operating in a severely restrained environment.

Current strategic, DOD, and Marine Corps guidance highlight future warfare challenges, often paying specific attention to operational energy (OE). Operational energy, as defined by the Office of the Assistant Secretary of Defense for Sustainment, is "the energy required for training, moving, and sustaining military forces and weapons platforms for military operations" (Office of the Assistant Secretary of Defense for Sustainment, n.d., para. 2). When addressing future requirements, the Office of the Assistant Secretary of Defense for Sustainment states that the DOD needs to "improve future combat effectiveness and capability by thoroughly integrating energy supportability into capability development and investing in innovation tailored to an enhanced ability to operate in contested environments" (n.d., para. 4). Carpenter et al. (n.d.) from the Naval Postgraduate School write in *Operational Energy—Essential Knowledge for Military Officers* that OE is far more than just getting fuel to where it is needed, rather than "OE decisions will be more complex and will require an immediate understanding of the battlespace before maneuvering and expending OE" (para 3). As the modern battlespace demands greater energy requirements and adversarial threats are assessed to impact fuel and logistics flow, each military organization is challenged with understanding its fuel/energy requirements, knowing considering all options for energy development/storage, and identifying effective methods to sustain combat roles.

Unfortunately, the knowledge gaps within operational energy are numerous. Like Carpenter et al. state, "Many of the future weapon systems will evolve from petroleum motors to hybrids, and then to fully electrical/alternate fuel engines that are charged from wireless support systems" (para. 6). The Marine Corps' Family of Mobile Power Systems Concept of Operations (FoMPS) reflects that, "growth in the Marine Air Ground Task Force (MAGTF) since 2001 include a 250% increase in radios, 300% increase in computers, and the introduction of new types of systems (e.g., counter-IED jammers, persistent surveillance, position location/reporting and situational awareness, etc.)" (2024, p. 3). Everything from intelligence collection to the size of command operations centers to weapons systems, the military requires greater energy consumption. The first of many knowledge gaps simply lies in understanding current energy requirements and how those continue to grow. The next shortfall in information is the knowing what current and emerging technologies will help offset fuel/energy logistics and which are appropriate at various levels of conflict. Finally, there is the cost-effective part of the discussion. While there may be several ways by which the Marine Corps can offset fuel/energy requirements, not all of them are relevant in terms of operational effectiveness and suitability. These methods or capabilities may prove too costly or may not be survivable for combat operations.

This study seeks to identify and evaluate various methods the Marine Corps may use to offset its current fuel use and energy consumption to suggest the best or most cost-effective OE methods during combat operations in a resource constrained conflict with a peer adversary. The Marine Corps' role and responsibilities in support of the U.S. Navy and the greater Joint Force is somewhat unique when considering the OE. The Marine Corps and its warfighting organizations will find themselves well inside an adversary's weapons engagement zone. Survivability requires deception and considerable mobility. Marine Corps units will likely have to sustain themselves for long periods of time, potentially with limited logistical support from the Joint Force. This research executes three things. Firstly, it uses Marine Corps formations and equipment to estimate current fuel/ energy consumption. Secondly, it identifies new and emerging technologies that support offsetting these current requirements. Thirdly, it concludes by providing a cost-effectiveness analysis on fuel/energy consumption methods. These findings will help guide Marine Corps decision makers on immediate and long-term goals to meet future OE needs.

B. RESEARCH QUESTIONS

This paper seeks to answer two questions. First, it looks at current or emerging energy production or storage technologies capable of offsetting fueled current energy use to allow the Marine Corps to sustain combat operations more effectively in a contested environment. The second question focuses on how cost-effective each method or technology is for Marine Corp implementation as a long-term solution.

1. Primary Research Question: Which emerging energy technology is more efficient at offsetting current fueled power generation at the tactical edge?

Current and future external challenges for the Marine Corps require more substantial changes to how it operates in a resource constrained environment. The U.S. military peer adversaries as well as the political landscape necessitate the Marine Corps be more responsible in both mindset, acquisitions, and training to improve current energy use. Tactical power, while not quite as driven by the political environment, does require the Marine Corps to explore alternative fuel sources to minimize the reliance of fuel in future campaigns. As various organizations lobby for funding in support of research and development within the alternative energy sector, not every alternative energy solution is created equal in terms meeting the Marine Corps requirements. Given the Marine Corps expeditionary nature, new systems need to be persistent, survivable, and mobile. Large structures and permanent locations that may work for the Army and the Air Force may not be suitable for the Marine Corps. Should logistics lines of communication and support get severed, the Marine Corps may not be able to rely on Navy resupply for fuel or parts. A future OE necessitates that energy production and storage capabilities be both maintainable and highly mobile, capable of moving using Marine Corps assets.

2. Secondary Research Question: Does the costs of emerging technologies make them a viable expeditionary energy source?

After the research applies qualitative measures of effectiveness (MOE) for each technology, it compares those to the system cost. This cost-effectiveness analysis (CEA) provides a systematic approach to evaluate the benefits of each technology relative to its costs. The outcome aids with two key things. First, it creates a starting point by which further sensitivity analysis can be accomplished at higher levels and determine which MOE is most critical to future systems. Next, the research should aid decision-makers to choose options that maximize energy capabilities while minimizing expenditures, ensuring resources are used efficiently.

C. SCOPE AND METHODOLOGY

This study is dedicated to evaluating current and emerging energy technologies across various industries: power storage, solar generation, hydroelectric power generation (buoys). By analyzing the overall capability of alternative energy sources, the Marine Corps may better identify and invest in technologies that align with the mission of providing a light, agile reconnaissance force.

The methodology is structured into three primary phases: data collection and effectiveness evaluation, cost analysis, and results. Data is gathered from military development documents, commercial manufacturers, and previous research studies. This data provides a comprehensive understanding of each capability currently available or in development, their effectiveness as defined by DOD and Marine Corps guidance, and associated costs.

The first phase focuses on evaluating the effectiveness of each power capability. Effectiveness is measured in terms of the Marine Corps Family of Mobile Power Systems Concept of Employment, identifying the need for persistence, mobility, and survivability. This phase involves synthesizing capability data to assess how well each power capability meets the specific needs of a tactical unit such as a Marine Littoral Regiment (MLR). The outcome of this phase is an overall effectiveness score for each power capability, which, when considered alongside the cost analysis, provides a comprehensive cost-effectiveness analysis.

The cost analysis phase employs a constant dollar analysis to estimate each system’s procurement and operations and sustainment costs. The objective is to develop a clear picture of the cost of ownership for each power capability over its expected operational lifespan. Cost models are standardized to ensure comparability across different types of power capabilities.

Finally, this thesis concludes with a graphical depiction of the cost-effectiveness ratios for each system to aid future decisions. This work also provides recommendations for future research.

D. BENEFITS OF THIS THESIS

As aforementioned, this study provides a systematic approach to evaluate the benefits of three different energy storage/generation technologies relative to their costs. The outcome of this study creates a foundation for further sensitivity analysis to assign system MOEs most critical to the Marine Corps' needs. The research should also aid decision-makers in choosing options or request funding for systems that are suitable (not shiny), while minimizing costs and ensuring resources are used efficiently.

E. ORGANIZATION OF THE STUDY

Chapter I identifies the focus a purpose of the thesis as well as the primary and secondary research questions.

Chapter II provides the reader with additional background drivers. This chapter also reviews various literature of emerging technologies as well as military interest and potential application for those technologies.

Chapter III defines the measures of effectiveness for each alternative power source and assigns qualitative effectiveness scores to determine suitability.

Chapter IV analyzes the estimated life-cycle cost of each alternative power solution.

Chapter V presents the conclusions and recommendations of the thesis and highlights future sensitivity analysis and research.

F. THESIS LIMITATIONS AND SHORTFALLS

The alternative power capabilities do not yet have DOD development documentation, requiring data to be drawn from commercial sources or other academic work. Metrics supporting mean time between failures (MTBF) and mean time to repair (MTTR) pose issues when collecting from the commercial market, requiring some assumptions to be made. Hydroelectric buoys are still in the research and development stages. While technology has made considerable progress over the last decade, supporting data again proved challenging. The U.S. Marine Corps also operates generators ranging from 2 kW to 60-kW at the MLR-level. This thesis focuses on the 60-kW generator as it supports the largest combat footprint within the MLR and the largest load capacity. Future research may extend to other power generation capabilities. Technologies, such as micro-nuclear and hydrogen power, are great considerations for expanding this research.

THIS PAGE INTENTIONALLY LEFT BLANK

II. BACKGROUND AND LITERATURE REVIEW

This chapter provides background information on the current problem and review current literature regarding the way forward. Reviewed literature includes national and military strategic guidance, compares efforts from various DOD organizations, identifies energy production/storage technologies, and compares new/emerging methods. The follow-on chapter weighs each of the emerging technologies qualitatively to assign values for each capability's MOE. As there are many ways performance can be estimated, the research method assigns each capability's measure of effectiveness scores in terms of being survivable, sustainable, and mobile. The final chapter provides the results, draws a conclusion, and provides recommendations for future decisions.

A. BACKGROUND

The past 20 years of sustained combat operations in Iraq, Afghanistan, and limited-scale operations in Syria forwarded the Marine Corps with an ability to stage equipment and resupply without consequence. Manpower, parts, weapons, and fuel arrived to support the Marine Corps' combat operations with minimal concern that the adversary could shut those supply lines off. The overall fuel requirements needed to support military operations have grown steadily since World War II. Every new piece of equipment in the inventory requires power generation. Gorsich and Boehman (2020) note, "In 2008 alone, approximately 68 million gallons of fuel were supplied per month to support U.S. military operations in Iraq and Afghanistan" (para. 3). Sustaining operations requires tremendous fuel and energy, and it can be expected that future campaigns will require far more than the last.

The external environment impacting the Marine Corps has changed considerably since the United States exited Afghanistan. The area of operations over the last two decades focused heavily on counterterrorism with a far more inferior adversary in terms of intelligence collection and fighting capabilities. There was little in the way of stifling forces, fuel, or equipment flow. Since the U.S. withdrawal from Afghanistan, there has been great refocus on pacing adversaries like China and Russia, and for the first time since the cold war, the U.S. military has peer adversaries rather the "near peer" threats it was long accustomed to. Extended anti-access aerial denial assets (A2AD), greater intelligence collection capabilities, and long-range precision guided munitions offer adversaries unique abilities to hold U.S. bases and stations as well Air Force and Navy assets at great risks within the Indo-Pacific area of operation (AO). China's continued growth in both size and capability severely limits U.S. maneuver efforts, considerably altering successful campaigns with the Indo-Pacific AO. This means the United States and its coalition partners no longer hold the same superiority and ability to forward stage and sustain operations logistically against a peer adversary like China.

B. LITERATURE REVIEW

The literature review focuses on the military's evolving OE needs and strategies to enhance energy usage efficiency. With the DOD being the largest energy consumer in the United States, a concerted effort is underway across all Service branches and government organizations to reduce energy dependency and mitigate logistical vulnerabilities essential for deterrence and the execution of large-scale operations. This section aims to synthesize research findings pertinent to the Marine Corps' specific mission and requirements, addressing the broader energy and logistics challenges while spotlighting ongoing research in power generation and storage.

The United State Marine Corps Expeditionary Energy Strategy and Implementation Plan documents the significant increases in fuel and energy consumption, attributed to heavier equipment, expanded computer use, and a greater number of communication devices. Since the Vietnam conflict, "fuel consumption per military member has surged by 175%, with an average annual increase of about 2.6% over the last 40 years" (Marine Corps Expeditionary Energy Status Section, 2011, p. 10). This escalation necessitates innovative measures to better measure, monitor, and ultimately reduce energy usage.

Sprague's thesis at the Naval Postgraduate School emphasizes the economic and human costs of fuel and energy provision to military forces, particularly highlighting the dangers and financial burdens of resupply missions. Sprague's (2015) thesis reveals that fuel deliveries during the U.S. conflicts in Iraq and Afghanistan were linked to significant costs and casualties, with "an estimated $1.4 billion in costs and 33 resupply convoy casualties per year at the peak of these conflicts" (p. 8). Sprague's analysis underscores the inefficiency of diesel generators, which, despite their widespread use, consume a disproportionate amount of the total expeditionary electricity, spotlighting the urgent need for more efficient energy solutions (2015, p. 22).

The DOD's Defense Science Board (2016) report on Energy Systems for Forward/Remote Operating Bases critiques the current energy strategies, noting the inadequacy of alternative energy sources like wind, solar, and tidal power in meeting the demands of forward operating bases and expeditionary forces (p. 6). The report calls for more aggressive efforts in acquiring energy-efficient innovations and exploring new power generation forms to alleviate the logistical strain of liquid fuels (Defense Science Board, 2016, p. 24).

Title 10 U.S. Code 2911 and subsequent discussions on building energy resiliency introduce "the concept of energy security and resilience as critical components of the military's energy procurement strategy" (2024, para b). Emphasizing the importance of on-site generation resources, the legislation and associated briefs from the U.S. Army Communications–Electronics Research, Development and Engineering Center lay the groundwork for a comprehensive approach to energy production, storage, control/distribution, and management. This holistic view extends to the identification of gaps in knowledge and application of new technologies, highlighting the need for greater innovation and efficiency in energy use across the military spectrum.

Collectively, the literature underlines a unified drive towards reducing energy reliance through enhanced efficiency, innovative technologies, and a strategic reevaluation of energy usage practices. The focus extends from high-level strategic directives down to specific technological solutions, indicating a comprehensive approach to addressing the energy challenges faced by the Marine Corps and the broader DOD in sustaining future operations.

There are several ways by which energy can be produced, but not all of them are feasible or suitable when supporting combat operations. Some methods also prove very costly to create infrastructure and convert power. The DOD's Defense Science Board published a report in 2016 on Energy Systems for Forward/Remote Operating Bases, noting "alternative energy sources, such as wind, tidal, solar, and other sources, were unlikely to comprehensively meet current or future energy demands for forward operating bases, remote operating bases, and expeditionary forces" (p. 6). This report highlights several shortfalls with the DOD's current approaches to being more energy efficient and quelling its fuel use, particularly at tactical level. They conclude that although military units are working to be more energy efficient, current practices are falling well short, and military organizations are still burning more liquid fuel to meet operational needs. The Defense Science Board's recommendations were numerous, stating the DOD should seek more aggressive acquisitions for energy efficient innovation. The DOD needs to explore new forms of power generation to meet growing power needs and to scale back the logistical strain of liquid fuels. The study also finds that commanders at all levels need to be more aware of energy use and methods to curb it.

A cost-effectiveness analysis offers a sound method of assessing a program's effectiveness and suitability when challenges exist with monetizing a system's benefits. There are several examples of Naval Postgraduate School theses executing a cost-effectiveness analysis to compare programs. Paul Moreau (2022) provides an exemplary cost-effectiveness analysis which compares unmanned aerial platforms used for intelligence, surveillance, and reconnaissance. In Moreau's cost-effectiveness analysis, a program is operationally effective by having speed, being more durable, and having increased maneuverability. Since each of these qualities present challenge with assigning a monetary value, his cost-effectiveness analysis uses qualitative analysis to create an apples-to-apples comparison of each system. The quantitative cost analysis is much easier to discern. Moreau concludes the study by providing a conclusion on each program's qualitative effectiveness score compared to the program costs. Moreau's analysis enables decision-makers to identify the more effective and more costly program to decide if increased capability is worth an increase in program costs.

There are several cost-effectiveness analyses available detailing the impacts of incorporating renewable energy methods at a state or national level to meet strategic goals.

However, there are very few cost-effectiveness analyses conducted about alternative energy at a tactical level. Of the one or two cost-effectiveness analyses found during this research focuses energy policies on permanent military installations. This research qualitatively and quantitatively assesses an overall cost-effectiveness of various energy technologies applied to a Marine Littoral Regiment. This work is unique, because it provides a method by which decision-makers can continue to assess future technologies and acquire those system's that best align with the Marine Corps unique mission to the Joint Force in conflict with peer adversaries.

The Army's Capability Production Document (CPD) for tactical electric power points to low-cost generators as a stopgap solution for medium power needs, acknowledging the strides made in fuel consumption and efficiency but also recognizing the significant energy potential lost through inefficiencies, particularly in diesel generator use. This is further elaborated in the Diesel Generator Fuel Consumption Guide, which illustrates the pressing need for advancements in energy efficiency beyond incremental improvements, noting that approximately 65% of energy potential is lost through exhaust alone (*Journal of Cleaner Production*, 2019, p 785) and current diesel generators use approximately 0.4 litres of fuel for every kWh produced, equating to an efficiency ratio of 25% ("Diesel Generator Fuel Consumption Guide," June 2023, para 4).

C. LITERATURE REVIEW TAKEAWAYS

Guidance from the strategic level down to the tactical edge realizes the importance of curbing reliance on liquid fuels to support logistics in future campaigns. The external environment has also changed considerably since the U.S. military's exit from Afghanistan. Internally, U.S. social and political drivers are mandating the DOD be more responsible and more efficient with fuel consumption. Externally, growing peer adversaries, namely China and Russia, have an ability to locate and target logistics far more accurately than the DOD is accustomed to from previous campaigns. All these considerations emphasize a need for every Service and DOD organization to offset its fuel consumption. The Marine Corps arguably has a larger reason for consideration. Given the Marine Corps' roles and responsibilities in support of the Joint Force's mission against peer adversaries, Marine forces will likely find themselves self-supporting operations within island chains for extended periods of time. Limited logistics have the potential to render the Marine Corps combat ineffective.

Perhaps some issues with the current guidance result from the messaging and attention the guidance receives. Strategic and military guidance needs to separate U.S. internal and external drivers when addressing future fuel consumption and energy needs. As military organizations primarily focus on waging and winning wars, the message cannot stem primarily from social and political drivers. The once established "Greening Marines" campaign is a key example of this. Warfighting organizations have far less interest in curbing fuel consumption when they believe it is socially or politically driven. The Greening Marines movement had great intentions but had limited impacts to improving fuel efficiency and becoming more persistent in a resource constrained environment.

Marines and leadership at all levels require a tremendous understanding of the vast amount of fuel that is used to wage combat. They further need to understand what supply lines look like when moving that amount of fuel into an operational area. Finally, a new mindset needs to be developed focusing on the fact that fuel may stop flowing altogether in a fight with stronger, more capable aggressors. The first step is to significantly change how Marine Corps units and its leadership monitors current fuel consumption. All strategic guidance has mandated this improvement for several years, but there seems to be little in the way of accomplishing this. Units can only start to realize greater effectiveness and efficiency if they understand the baseline from which they are starting.

The Marine Corps largely has three ways by which it continues to address its fuel consumption issue. First, much like the example of the "Greening Marines," the Marine Corps can adjust its doctrine, organization, training, materiel (non-development), leadership/education, personnel, facilities, or policy (DOTMLPF-P). Like the results provided by the Defense Science Board, however, these changes seem to be falling short. The next option the Marine Corps has is to invest heavily in key bases and stations to improve its ability to move fuel and equipment more easily and efficiently throughout an area of operations. The issue with this method is that it is expensive and targetable. If an aggressor targets those installations, the Marine Corps may find itself again in a situation where fuel and equipment supply lines are severed. Finally, and the method in which this thesis focuses, the Marine Corps can look for more unique technologies that allow its forces to offset fuel consumption. Of the many technologies to consider, this work compares current fueled generation, power storage capabilities, solar power, and hydroelectric buoys to determine which of these technologies are most cost effective at the tactical edge, predominantly focusing on a Marine Littoral Regiment (MLR).

THIS PAGE INTENTIONALLY LEFT BLANK

III. ENERGY ALTERNATIVES AND MEASURES OF EFFECTIVENESS (METHODOLOGY AND ANALYSIS)

This chapter defines and applies the CEA methodology to evaluate each alternative power's operational capability. Given there is no current capability development document (CDD) for the new technologies, this chapter assesses each technology based on guidance within the Marine Corps concept of employment for the Family of Mobile Power Systems (FoMPS) and the *Tentative Manuel for Expeditionary Advanced Base Operation* (2nd Edition). Both documents place considerable emphasis on an agile force, noting that systems must "effectively sustain distributed units to increase their mobility, operational persistence, and survivability at a reduced signature" (COE, 2024, p. 20). These three attributes guide this chapter's MOE development. The conclusion of this chapter provides an overall effectiveness rating for each program that can be paired with each alternative's cost to provide a cost-effectiveness ratio (CER) to be used for decision-making of future tactical power systems.

The three technologies compared in this work include the addition of solar power, energy storage, and hydroelectric buoys (wave energy converters) to identify which of these technologies are most effective at the least costs to offset fuel used in power generation. Solar power is assessed by applying a 12-kilowatt system to generators used to apply tactical power. This work proposes an energy storage system capable of approximately 52-kilowatt hours used with generators to identify tactical impacts and increased fuel efficiency. Finally, this thesis looks at the feasibility of adding wave energy converters, specifically point-absorber buoys, to determine the technology's ability to reduce fuel consumption in a tactical environment. Each of these technologies are compared to the current method of employment of the 60-kilowatt generator used to support combat operations at the regimental level.

A. DATA

The data used in this chapter is predominantly equipment specification data gathered through commercial sources. Some, limited data, can be found via DOD sources relating to military installation solar power. A greater portion of information surrounding power storage capabilities comes from military experts in the field conducting power storage research and concepts of employment.

B. METHODOLOGY

Both cost-benefit analysis (CBA) and cost-effectiveness analysis are tools used in decision-making processes, often applied in economics, healthcare, and policymaking. CBA quantifies both costs and benefits in monetary terms, thereby facilitating decisions where outcomes can be valued financially, making it apt for business and economic policy decisions focused on financial optimization (Boardman et al., 2017). In contrast, a CEA is often preferred when there are considerable challenges in applying monetary values to the program's outcome. Examples may include health improvements or educational achievements of a policy. A CEA is more suited for this study because the benefits being measured (mobility, operational persistence, and survivability) cannot easily be valued in dollars.

1. Objectives Hierarchy

The execution of a CEA comprises several key steps. It begins with a clear definition of the objective and the specific outcomes to be measured (Siegel et al., 1996). The tree method is often used as a graphical depiction to help visualize the programs objective hierarchy. Figure 1 offers a generic hierarchy tree. Wall and Mackenzie's (2015) work *Multiple Objective Decision-Making* notes the hierarchy method to CEA "takes us from the top level down to the lowest level where measurement is obvious" (p. 5).

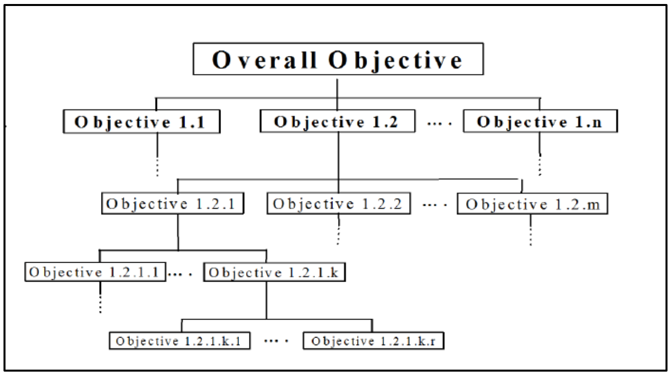


Figure 1. Example Hierarchy Tree. Source: Wall and Mackenzie (2015).

As alternative energy sources are evaluated using a hierarchy, the overall objective is an alternative that is operationally effective, but the whole of the CEA determines the level to which the alternative is effective and at what cost. The Marine Corps Family of Mobile Power Systems concept of employment establishes the system needs to be mobile, persistent, and survivable. Therefore, for the execution of this study's CEA the top portion of the hierarchal tree includes those three objectives within the second level. Building out sub-objectives allows the CEA to further define what is meant by the terms persistent or mobile. The effort requires that each sub-objective is defined further until a measurable metric can be identified that supports the primary objective. Sub-objects can be widely debated and offer considerable room for sensitivity analysis. For this CEA, the hierarchy tree follows the objectives outlined in Figure 2.

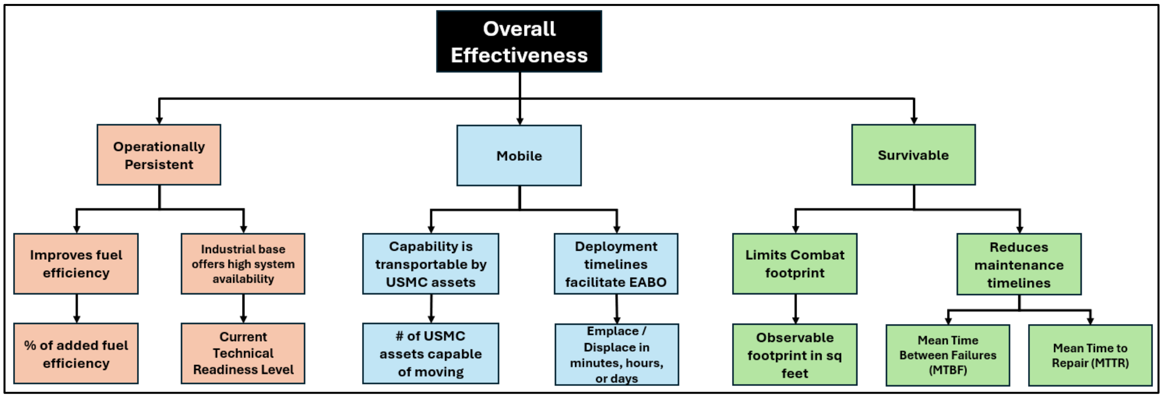


Figure 2. Alternative Power Measures of Effectiveness. Adapted from Marine Corps Concept of Employment (2024).

The sub-objectives offer an ability to assess each power alternative's overall effectiveness. As Wall and Mackenzie (2015) highlight, the study must also "develop a way to convert all these disparate measures to a common unit of measure" (p. 8). The common unit of measure gives leadership and decision makers an apples-to-apples comparison of all alternatives. Executing this part of the MOE analysis is a bottom-up process whereby the first step is assigning individual attribute values to the attributes in the lowest row in the hierarchy tree. The second and third steps determine the level to which each of those individual attributes are important to the system's overall effectiveness.

2. Assigning Individual Attribute Values

This CEA uses natural measures to determine the effectiveness measures. Natural measures, as defined by Wall and Mackenzie (2015), are "those that can be easily counted or physically measured" (p. 7). Individual attribute values between 0–1 are added to the bottom level to "provide a scaling function to convert the natural units of measurement into units of value" (Wall & Mackenzie, 2015, p. 8). Creating a value function can be done using several different methods. Since each power alternative should either seek to maximize or minimize the attributes at the lowest level, the methods used in this study uses a cumulative value function to assign individual attribute values. Consider the "percentage of added fuel efficiency" attribute for determining if the alternative is operationally persistent. Each 10% increase in efficiency increases the incremental increase by a value of 1. The following cumulative value functions are applied to assign all individual attribute values along the bottom of the hierarchy table.

a. Percentage of Added Fuel Efficiency

As previously mentioned as an example, for every 10% increase the alternative provides in fuel efficiency, it increases the incremental value assigned to that measurement. Incremental values for fuel efficiency follow the increases outlined in Table 1.

Table 1. Incremental Values for Fuel Efficiency

Fuel Efficiency	Incremental Value
10%–20%	0
20%–30%	1
30%–40%	2
40%–50%	3
50%–60%	4
60%–70%	6
70%–80%	7
80%–90%	8
90%–100%	9

Next, using the incremental values assigned in Table 1, a cumulative value function can be created by summing all incremental values.

$$Sum: 0 + 1 + 2 + 3 + 4 + 6 + 7 + 8 + 9 = 35$$

Table 2. Individual Attribute Values for System Fuel Efficiency

Fuel Efficiency	Cumulative Value	Attribute Value
10%–20%	0	0/40 = 0
20%–30%	1 +0 = 1	1/40 = .03
30%–40%	2 +1 = 3	3/40 = .08
40%–50%	3 + 3 = 6	6/40 = .15
50%–60%	4 + 6 = 10	10/40 = .25
60%–70%	6 + 10 = 16	16/40 = .40
70%–80%	7 + 16 = 23	23/40 = .58
80%–90%	8 +23 = 31	31/40 = .78
90%–100%	9 + 31 = 40	40/40 = 1

As an example, if the alternative storage or power system's increases fuel efficiency to approximately 25%, that system is assigned an individual attribute of [.03].

b. Technical Readiness Level

The technical readiness level (TRL) indicates a strong industrial base (IB) capable of sustaining each power alternative and its requisite equipment. The stronger the IB, the more flexibility a program has, making it more sustainable and persistent. For the TRL considerations, any TRL level three or below is not sufficient to sustain the program. The rest of the incremental values are assigned as defined in Table 3.

Table 3. Incremental Values of Technical Readiness Levels

Technical Readiness Level (TRL)	Incremental Value
Between 1–3	0
4	3
5	4
6	6
7	7
8	8
9	9

The sum of the incremental values creates the cumulative value function for assigning this metric.

Sum: $0 + 3 + 4 + 6 + 7 + 8 + 9 = 37$

Table 4. Individual Attribute Values for TRL

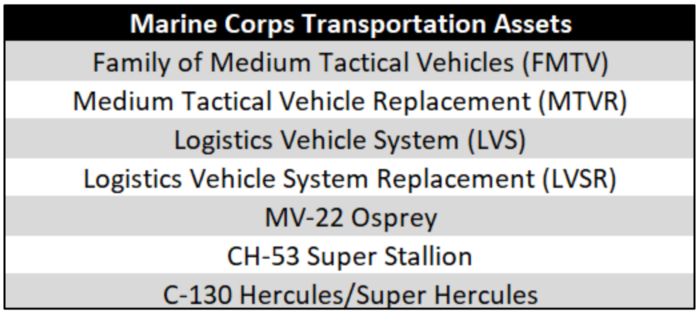
Technical Readiness Level (TRL)	Incremental Value	Attribute Value
Between 1–3	0	0/37 = 0
4	3 + 0 = 3	3/37 = .08
5	4 + 3 = 7	7/37 = .19
6	6 + 7 = 13	13/37 = .35
7	7 + 13 = 20	20/37 = .54
8	8 + 20 = 28	28/37 = .76
9	9 + 28 = 37	37/37 = 1

As an example, given TRL-7, the alternative storage or power system is awarded an individual attribute of [.54].

c. Number of Marine Corps Assets Capable of Moving the System

This individual attribute value considers the amount of flexibility a commander has within the operational area. While this individual attribute leaves room for discussion, this study uses the total number of Marine Corps land and air transport assets capable of moving the power alternative capability throughout the AO. The Marine Corps has seven transport vehicles and aircraft (listed in Table 5) available to move equipment. Again, the total number of available transport vehicles relies solely on Marine Corps assets to capture internal support to mobility.

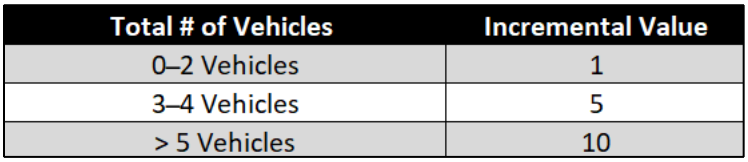
Table 5. Marine Corps Transport Vehicle (Equipment)



Marine Corps Transportation Assets
Family of Medium Tactical Vehicles (FMTV)
Medium Tactical Vehicle Replacement (MTVR)
Logistics Vehicle System (LVS)
Logistics Vehicle System Replacement (LVSR)
MV-22 Osprey
CH-53 Super Stallion
C-130 Hercules/Super Hercules

Using the total number of transport assets provides an ability to create a cumulative value function. A cumulative value function is created in the same manner as before. Incremental values for transportation assets are assigned in Table 6.

Table 6. Incremental Values for Capable Transport Vehicles



Total # of Vehicles	Incremental Value
0–2 Vehicles	1
3–4 Vehicles	5
> 5 Vehicles	10

Next, using the incremental values assigned in Table 6, a cumulative value function is created by summing all incremental values.

$$Sum: 1 + 5 + 10 = 16$$

Using the total incremental value of 16 from the above equation, Table 7 creates individual attribute values for the number of vehicles capable of moving each alternative power source by dividing the cumulative value for each displacement/emplacement block of time by the cumulative value of 16.

Table 7. Individual Attribute Values for Transport Capabilities

Total # of Vehicles	Cumulative Value	Attribute Value
0–2 Vehicles	1	1/16 = .06
3–4 Vehicles	5 + 1 = 6	6/16 = .38
> 5 Vehicles	10 + 6 = 16	16/16 = 1

As an example, if one of the power alternatives can only be transported (due to size or any other limitations) by four Marine Corps assets, it receives an individual attribute value of [.38].

d. *Equipment Emplacement and Displacement Timelines*

Another significant part of mobility stems from the amount of time it takes for a unit to emplace and displace equipment. Expeditionary forces will likely need to displace often to slow or confuse an adversary’s targeting calculus. Dreadfully slow displacement and emplacement timelines hamper the MLR’s ability to move and reestablish effective positions quickly. Delays in equipment setup and breakdown times strain a commander’s ability to properly plan for mutually supporting positions, ensuring at least one element is operational and integrated with the Joint Force. Assigning the individual attribute values for equipment emplacement and displacement times follows the same cumulative function approach as used with vehicle transport considerations. The incremental values assigned to displacement/emplacement timelines follows Table 8.

Table 8. Incremental Values for Displacement/Emplacement Times

Displacement/Emplacement	Incremental Value
> 16 Hours	0
14–16 Hours	1
12–14 Hours	2
10–12 Hours	3
8–10 Hours	5
6–8 Hours	7
4–6 Hours	8
0–4 Hours	9

Next, using the incremental values assigned in Table 8, a cumulative value function is created in the same manner that it was calculated for the previous attributes.

Sum: 0 + 1 + 2 + 3 + 5 +7 + 8 + 9 = 35

As shown in Table 9, individual attribute values are created for each displacement and emplacement time block by dividing the cumulative value for each block of time by the overall cumulative value of 35.

Table 9. Individual Attribute Values for Displacement/Emplacement Times

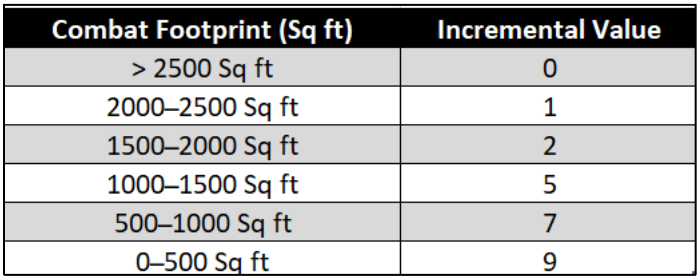
Displacement/Emplacement	Cumulative Value	Attribute Value
> 16 Hours	0	0/35 = 0
14–16 Hours	1 + 0 = 1	1/35 = .03
12–14 Hours	2 + 1 = 3	3/35 = .09
10–12 Hours	3 + 3 = 6	6/35 = .17
8–10 Hours	5 + 6 = 11	11/35 = .31
6–8 Hours	7 + 11 = 18	18/35 = .51
4–6 Hours	8 + 18 = 26	26/35 = .74
0–4 Hours	9 + 26 = 35	35/35 = 1

Here, assume an estimated emplacement and displacement timeline is approximately 14 hours to set up and hours to pack for the next movement. An average of those two times is taken for an average displacement and emplacement time of 11.5 hours. Therefore, that energy alternative receives a [.17] value for the individual attribute.

e. Capability Increases Combat Footprint

It is important to understand how a system or capability's combat footprint may make the MLR more observable and targetable within the battlespace. The Marine Corps continues all efforts to conceal unit positions or create deception to limit an adversary's ability to locate and target friendly assets. Measuring this individual attribute considers how much the capability increases a unit's footprint once the system is placed and operationally effective. Using the same methodology for operational combat footprint, the incremental value is assigned by an increase in square footage the asset needs to be functionally operational, increasing every additional 500 square feet. Incremental value assignments follow in accordance with Table 10. The individual attribute values are calculated and represented in Table 11.

Table 10. Incremental Values for Combat Footprint



Combat Footprint (Sq ft)	Incremental Value
> 2500 Sq ft	0
2000–2500 Sq ft	1
1500–2000 Sq ft	2
1000–1500 Sq ft	5
500–1000 Sq ft	7
0–500 Sq ft	9

After conducting the cumulative value functions in the same manner as the previous examples, individual attributes for the system's combat footprint are annotated in Table 11.

Table 11. Individual Attribute Values for Combat Footprint

Combat Footprint (Sq ft)	Cumulative Value	Attribute Value
> 2500 Sq ft	0	0/24 = 0
2000–2500 Sq ft	1 + 0 = 1	1/24 = .04
1500–2000 Sq ft	2 + 1 = 3	3/24 = .13
1000–1500 Sq ft	5 + 3 = 8	8/24 = .33
500–1000 Sq ft	7 + 8 = 15	15/24 = .63
0–500 Sq ft	9 + 15 =24	24/24 = 1

In this example, assuming additional equipment increases the MLR’s current footprint by 600 square feet (in addition to the current generation requirement), the individual attribute score is [.63].

f. Equipment Maintenance Considerations

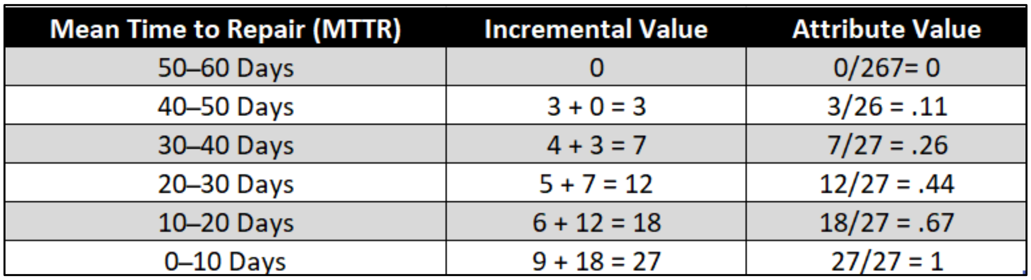
Finally, the last evaluation for each power alternative is the level of anticipated maintenance required to keep the system operating. To assign the final two attribute values, the study applies data collected for each alternative’s MTBF and MTTR to better understand the system’s overall reliability. MTBF is defined as “a maintenance metric that measures the standard amount of time between expected equipment failures for an asset performing under normal operational usage” (Eisner, 2022). MTTR is the total time it takes to repair a failed system, including all times to determine there is a failure, diagnose the issue, and fix it. To assign the individual attribute values for MTBF, this study uses the same cumulative value function approach measured over three-month periods (see Table 12). MTTR values are assigned based on number of days passed until the system can recover.

Table 12. Individual Attribute Values for MTBF

Mean Time Between Failures	Cumulative Value	Attribute Value
0–3 Months	0	0/26 = 0
3–6 Months	3 + 0 = 3	3/26 = .12
6–9 Months	6 + 3 = 9	9/26 = .35
9–12 Months	8 + 9 = 15	15/26 = .58
12–15 Months	9 + 15 = 26	26/26 = 1

Attribute values for the equipment's MTTR follow in accordance with the individual attribute values listed in Table 13. It is worth noting that MTTR days are reflective of commercial data and not representative of a resupply of parts in a combat environment.

Table 13. Individual Attribute Values for MTTR



Mean Time to Repair (MTTR)	Incremental Value	Attribute Value
50–60 Days	0	0/267= 0
40–50 Days	3 + 0 = 3	3/26 = .11
30–40 Days	4 + 3 = 7	7/27 = .26
20–30 Days	5 + 7 = 12	12/27 = .44
10–20 Days	6 + 12 = 18	18/27 = .67
0–10 Days	9 + 18 = 27	27/27 = 1

Providing examples for both metrics, if an asset has a MTBF roughly ten months, the individual attribute value for that asset is [.58]. Likewise, should the asset have a MTTR of 23 days, it receives an individual attribute mark of [.44].

3. Direct Assessment for Importance Weights

The second and third steps of the CEA are to assign importance weights to first the sub-objectives and finally the primary objectives. If there are a limited number of effectiveness measures, "the most obvious way to gain the information required is to directly ask the decision maker" (Wall & Mackenzie, 2015, p. 12). Since there was no direct access to the decision maker for the purpose of this study, two primary considerations from the concept of employment and the *Tentative Manual for Expeditionary Advanced Base Operations* are used to assign importance weights for the objectives and sub-objectives. First, when balancing the perceived importance required to execute Expeditionary Advanced Basing Operations (EABO), Marine forces must first remain operationally persistent to provide the greater Joint Force with battlespace awareness. Secondly, Marine units need to be light, agile, and mobile. This portion of the MOE evaluation typically offers the greatest source of debate and lends itself well to future sensitivity analysis. Therefore, the importance weights for this study are assigned in Figure 3.

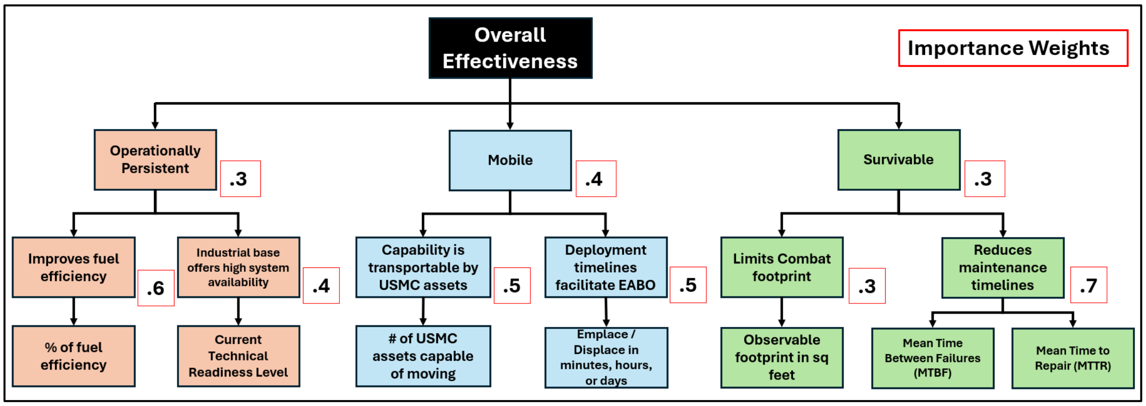


Figure 3. Assigned Importance Weights. Adapted from Marine Corps Concept of Employment (2024).

C. ASSESSING ALTERNATE ENERGY AND INDIVIDUAL ATTRIBUTES

The analysis in this report is based on the power requirements of a MLR operating forward and composed of approximately 2,500 Marines. The MLR serves as the Joint Force's "stand-in force (SIF) for maritime reconnaissance and Counter-reconnaissance" (DON, 2023, p. 11). The MLR conducts operations using company reinforced size units (comprised of 100–300 Marines), or EABs. Each EAB is tasked with either fires, sensing or collecting, and logistics. Because the MLR focuses efforts to maintain light, agile capabilities, the largest footprint, in terms of power requirements, is the MLR Command Operations Center (COC). This analysis assumes the MLR is operating within the Indo-Pacific Area of Operations (INDOPACOM) to provide the basis for each alternative's expected output based on environmental conditions, specifically for solar and hydroelectric power.

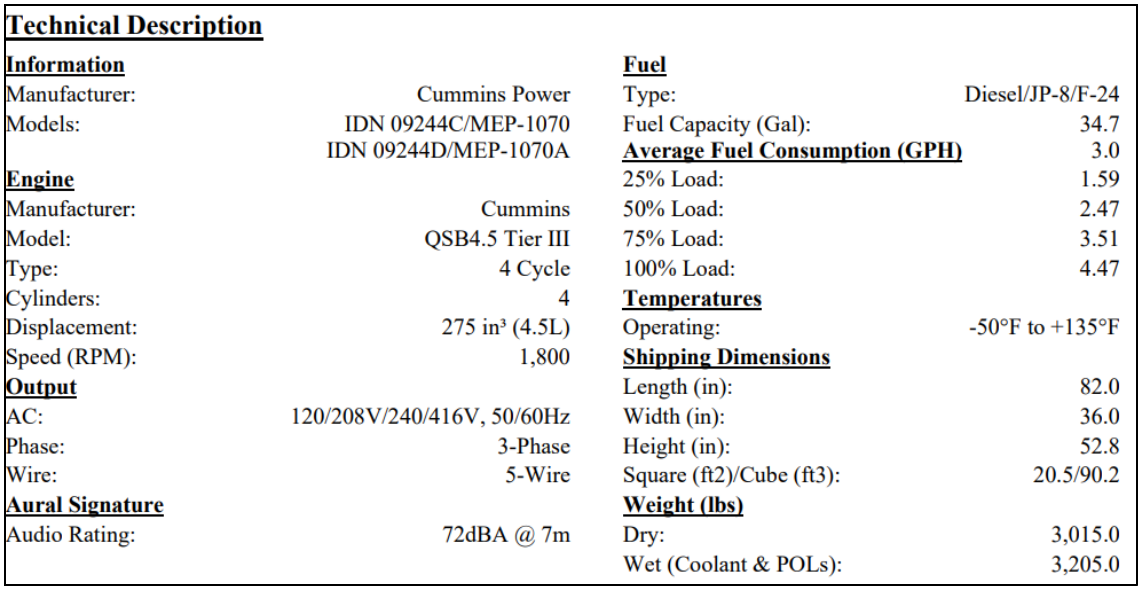
While all three of the researched alternate energy measures may have specific benefits, this portion of the chapter measures each technology's data required to assess the individual attribute values defined in the above methodology. Applying the MOE includes current generator use to provide a comparative foundation for all other alternative measures. This section concludes with an overall effectiveness rating for each power alternative to best compare all three systems against the defined objectives.

1. Assessing Fuel Powered Generators

According to Technical Manual 11300-15/1, the Marine Corps currently has 10 generators within its inventory ranging from 2 kilowatts (kW) to 60 kW. It is most common that six of the 10 generators are standard at a regimental level. At the time of this writing, units within the MLR are working to refine future power requirements. It is important to note within this work moving forward: since load rates and fuel efficiency vary considerably between all generators 2 kW and 60 kW, this study focuses on the MLR COC requirements. The COC, as the largest MLR element, offers the largest personnel footprint, the heaviest load capacity requirement, and uses two of the 60-kW generators to meet mission objectives. It is of considerable importance to note that power requirements across MLR units vary considerably. Therefore, future research should expand across all available generators to best ensure maximum fuel efficiency at all tactical levels.

a. Current Generator Fuel Efficiency

Considering the MLR COC's load requirements and generator use to meet operational requirements, working documents detailing MLR COC's load plan notes several considerations. The average kilowatt hours (kWh) required for COC operations is approximately 50 kW, with periodic surges just over 52 kW. The standard operating procedure for all power supply units is to run two 60-kW generators to provide redundancy in the case of a generator failure. The MLR typically splits the load requirements between the two generators, each operating at approximately 40% load capacity. Figure 4 reflects the technical manual's 60-kW fuel consumption at various loads.



Technical Description			
Information		**Fuel**	
Manufacturer:	Cummins Power	Type:	Diesel/JP-8/F-24
Models:	IDN 09244C/MEP-1070 IDN 09244D/MEP-1070A	Fuel Capacity (Gal):	34.7
		Average Fuel Consumption (GPH)	3.0
Engine		25% Load:	1.59
Manufacturer:	Cummins	50% Load:	2.47
Model:	QSB4.5 Tier III	75% Load:	3.51
Type:	4 Cycle	100% Load:	4.47
Cylinders:	4	**Temperatures**	
Displacement:	275 in^3 (4.5L)	Operating:	-50°F to +135°F
Speed (RPM):	1,800	**Shipping Dimensions**	
Output		Length (in):	82.0
AC:	120/208V/240/416V, 50/60Hz	Width (in):	36.0
Phase:	3-Phase	Height (in):	52.8
Wire:	5-Wire	Square (ft2)/Cube (ft3):	20.5/90.2
Aural Signature		**Weight (lbs)**	
Audio Rating:	72dBA @ 7m	Dry:	3,015.0
		Wet (Coolant & POLs):	3,205.0

Figure 4. Technical Manual 11300-15/1. Source: U.S. Marine Corps (2023).

At approximately 40% load capacity for each generator, the technical manual presents an average fuel consumption of about 2.3 gallons of fuel per hour for each generator. This means the two generators consume more than 110.4 gallons of fuel per day. Using the efficiency equation provides an estimated fuel efficiency of about 26.7% for each generator, giving the 60-kW generator's assigned individual attribute value for fuel efficiency a [.03] (refer to Table 2).

$$\text{Efficiency} = [\text{Energy Output (kWh)} / \text{Energy Input (kWh)}] \times 100\%$$

b. *Current Technical Readiness Level*

Much easier to discern is the current TRL of fueled generators. At the time of the Army's CPD in 2014, the assessed TRL was a TRL-8, meaning "the system is completed and qualified through test and demonstration" (Carter, 2022, para 9). The 60-kW generator technology has been fielded for over two decades and tested extensively in all environments through military operations, making the capability a TRL-9. Given the high TRL of current fuel-generating equipment, the assigned individual attribute value is [1] as referenced in Table 4.

c. *Marine Corps Assets Capable of Transporting the System*

The dimensions of the 60-kW generator support the individual attribute values for both vehicle and aircraft transport as well as total footprint when being employed. The Marine Corps' technical manual 11300-15/1 (2023) provides shipping dimensions for the generator with a length of 82 inches, a width of 36 inches, a height of 52.8 inches, and the total square footage of 20.5 (fig. 6–11). Then manual also provides both dry weight and wet weight at 3,015 pounds and 3,205 pounds respectively. Given these dimensions and weight, all equipment transportation vehicles and aircraft can move the 60-kW generator throughout the AO. Therefore, the individual attribute value assigned to this sub-objective is [1] (reference Table 7).

d. *Generator Emplacement and Displacement Timelines*

Perhaps one of the biggest positives for the diesel generator is the emplacement and displacement timelines. The generator is trailered, so Marines typically train to placing the system and starting power flow in just minutes. The complete emplacement of tentage to complete the COC takes longer, but the generators power equipment while the position is being refined. The same holds true for displacing the generators. They are often left generating power until a position teardown is almost complete, taking only minutes to connect to a truck and prepare for movement. For this reason, the 60-kW generator is given a [1] for the individual attribute of movement timelines (Table 9).

e. *Observable footprint within the AO*

As previously mentioned in the transportation metric, the technical manual denotes the total square footprint of one generator is 20.5 square feet. Since the MLR COC employs two generators, the total square footprint is 41 square feet. While the MLR and all EABs have become experts at concealing their generators, we still include this metric to give equal comparisons to all alternative power capabilities. The individual attribute for total combat footprint for the two generators is [1] as referenced in Table 11.

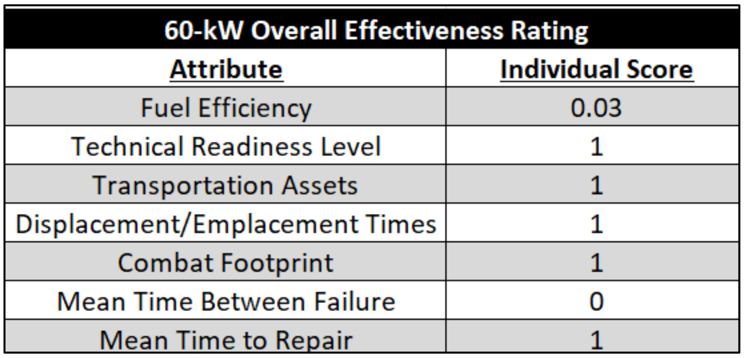
f. Mean Time Between Failure and Mean Time to Repair

Although the key performance parameters (KPP) within the Army's CPD outline thresholds and objectives for reliability and maintainability, it does not as easily paint the picture for how often generators experience failure during operations. Marqusee, Ericson, and Jenket's work *Emergency Diesel Generator Reliability and Installation Energy Security* conducts an in-depth study into MTTF and MTTR for various generators. The datasets used in Marqusee et al. (2020) comes from "over 200 sites in the United States and Canada. The sites include military facilities, hospitals, and universities" (p. 11). Within their dataset, two key facts are noted. First, a large majority of the generator data collected is from generators below 200 kW. The second key fact is their study found, "data contains no statistically significant evidence that the generator's make, model, or size (10 kW–2,000 kW) has any significant impact on reliability" (Marqusee et al., 2020, p. 13). Although the development document has a lower objective for MTBF, Marquess et al.'s (2020) study concludes that well-maintained generators within the 10 kW–2,000 kW range have an average MTBF of 1,662 hours or approximately 69 days (p. 13). The Army's CPD (2014) also provides that with dedicated mechanics MTTR should not exceed two hours in field conditions (p. 11). Given the MTBF results in Marqusee et al.'s study and the MTTR outlined in the CPD, the individual attribute values for the 60-kW generator is [0] and [1] (Tables 12 and 13).

g. Generator Overall Effectiveness Score

All assignments to the individual attribute scores for the 60-kW generator are represented in Table 14.

Table 14. Generator Individual Attribute Scores



60-kW Overall Effectiveness Rating	
Attribute	**Individual Score**
Fuel Efficiency	0.03
Technical Readiness Level	1
Transportation Assets	1
Displacement/Emplacement Times	1
Combat Footprint	1
Mean Time Between Failure	0
Mean Time to Repair	1

2. Assessing Solar Power Generation (without Power Storage)

Assessing the overall effectiveness of solar power is limited to commercial data requiring a few assumptions to be made with individual attribute scores. At the time of this writing, there were no discovered military units training on rapid displacement or emplacement of solar capabilities at a magnitude compared in this work. Therefore, rough estimations are used to determine individual attribute values for transportation dimensions as well as setup and breakdown timelines and the system's transportation dimensions. Also, very few datasets discuss reliability specific to MTBF and MTTR. Most simply discuss the reliability and life of the panels.

The *SolarGIS* website provides peek sunlight hours for portions of the INDOPACOM, primarily pulling reports for the Philippines, Indonesia, and Japan (Figure 5). The averages for Japan and Indonesia tend to be slightly lower, while the Philippines offers an average between 4.5 and 5 peek sunlight hours per day. Although these areas average up to five peak sunlight hours, this study applies an even 6-hour daily duration, assuming enough sunlight on either side of the peak hours to produce the full capability of the proposed solar power system.

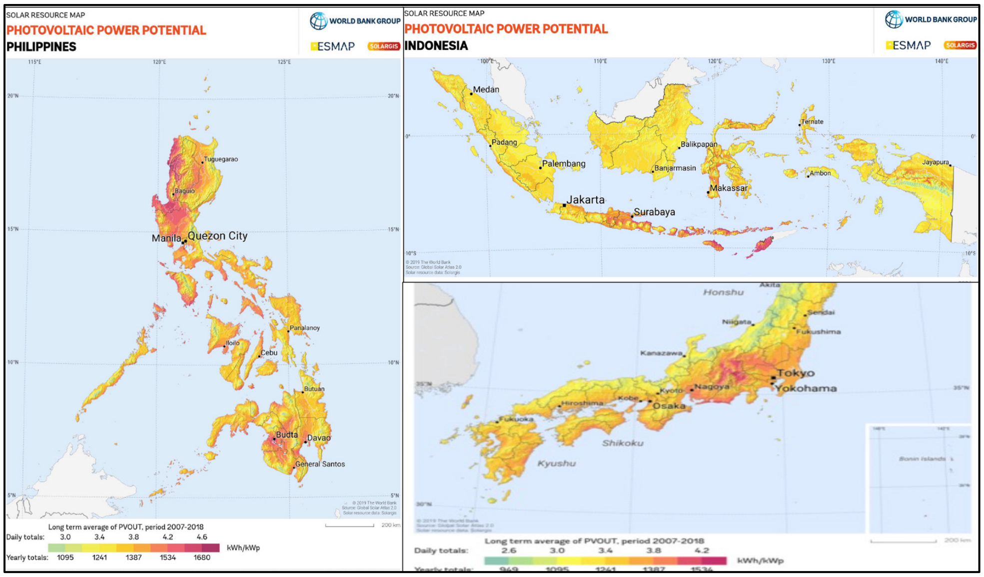


Figure 5. Photovoltaic Potential (Philippines, Indonesia, and Japan). Source: SolarGIS (2024).

As previously indicated, the average energy load for the MLR COC is 50 kW and a 52-kW surge. Estimations can consider providing a solar power system up to and including the full 52-kW load; however, calculations approximate the combat footprint of a system that size is almost 3,400 square feet. Therefore, this study assesses a 12-kW capability to improve efficiency and help minimize footprint. The overall size and output capability for future systems can be debated and used in further sensitivity analysis. It should also be noted that, even with a solar power system capable of supporting the full power load (52 kW), one generator must continue running to serve as a system failure backup.

a. Solar Power Increased Fuel Efficiency

There are a couple ways by which the improved fuel efficiency of adding a solar power capability can be calculated. The first and easiest method is to recognize that the two 60-kW generators are operating close to their 50% load capacity. Mathematically, at 50% load capacity the generator produces 30 kW. If the generator consumes 2.47 gallons per hour (Figure 4), dividing the 30 kWh of production by 2.47 gallons highlights that it produces just over 12 kWh per gallon of gas. Using a 12-kW solar capability at the 6-hour planning factor, provides 12 kW per hour that a generator no longer needs to produce. Using this calculation, assuming the sunlight facilities the power for any given day, a 12-kW solar system saves approximately six gallons of fuel over a 24-hour period.

The second way of calculating is in terms of the system's fuel efficiency. Sciencing's How to Calculate the Efficiency of an Electrical Generator provides equations by which a generator's efficiency is calculated. This article notes, "the efficiency of the generator can be calculated as the ratio of the energy output to the energy content of the fuel used" (Sciencing, 2017).

$$\text{Efficiency} = [\text{Energy Output (kWh)}/\ \text{Energy Input (kWh)}] \times 100\%$$

Using this equation to calculate the fuel efficiency of a generator at a 50% load capacity results in approximately 30.3% fuel efficiency. Now, consider the 12-kW solar power system is connected to the grid. The solar power takes that 12-kW off the bottom line, leaving the generator to account for the rest. Sciencing (2017) gives the following equation to calculate energy input using a British thermal units (BTU) conversion of 1 kWh = 3,412 BTU.

$$137{,}000\ \text{BTU/gallon} \times 2.47\ \text{gallons} = 338{,}390\ \text{BTU}$$

$$338{,}390\ \text{BTU} \div 3{,}412\ \text{BTU/kWh} = 99.17\ \text{kWh}$$

Simplifying this a bit, assume the load now requires 42 kW of power, and the peak sunlight hours allow the 12-kW solar system to supply the initial 12 kW of needed power. The generator, running at 50% load capacity, supplies the other 30 kW at the previously calculated 30.3% efficiency. Again, using the above equation, the system is now providing the same energy input as before with a 12-kW increase in energy output. For six hours of the day, the system's energy efficiency jumps to approximately 42.35%. The shortfall in this approach is failing to account for the other 18 hours of the day. When averaged over the 24-hour period, fuel efficiency of the system reaches about 31%. Given these considerations, adding a 12-kW solar capability (without additional power storage) is awarded a [.08] for an individual attribute score assessing increased fuel efficiency (refer to Table 2).

b. Solar Power's Technical Readiness Level

This research did not find any military specific documents supporting the current TRL classification of photovoltaic (PV) technology. However, *ETP Clean Energy Technology Guide,* an interactive commercial database, places this technology at a TRL-9, stating the technology is "in commercial operation in relevant environments, Integration needed at scale" (International Energy Agency, 2023). Although IEA's assessment largely refers to rigid PV panels, flexible PV panels are widely available within the commercial space. Therefore, the individual attribute value for solar will retain the TRL-9 score, assigning the individual attribute value of [1] as referenced in Table 4.

c. Marine Corps Assets Capable of Transporting the System

Again, the assumption for this section is that MLR and other expeditionary forces require flexible solar panels to limit the damage of transporting, assembly, and disassembly. At the time of this writing, the largest one-piece flexible solar panel identified within the commercial market was a 330 watt (w) solar panel. A 12-kW system with 330-w solar panels requires 38 solar panels. Each 330-w solar panel measures 41.5 inches wide, 71.8 inches long, and .8 inches thick (Xantrex, 2023). Referencing the Marine Corps Unit Embarkation Handbook, the overall system packed for transportation exceeds the limits of a Palletized container. A solar system capable of this output likely requires at least two quadruple containers (QUADCON) when factoring in protective packing measures, cables, and inverters. Given a rough assessment of a PV system's containerized footprint, five total USMC transportation assets can move a full system. Therefore, the individual attribute value for transportation is [.38] (see Table 7).

d. Solar Power Emplacement and Displacement Timelines

The assessment for emplacement and displacement has no verifiable metric to support it, requiring major assumptions to be made. At the time of this writing, neither U.S. Army nor Marine Corps units were identified as training on expeditious setup of flexible solar panels, at least to this magnitude. UEC Electronics (2024) both publishes and provides a video of setting up the 1000-w Ground Renewable Expeditionary Energy System (GREENS) in 20 minutes (para. 1). GREENS has prefabricated angular stands on which that system's solar panels can be placed, expediting setup. Supposing a ground force commander decides the tactical situation is such that all flexible solar panels can be positioned, it is likely that flexible panels will be placed atop tents or vehicles. Otherwise, tactical positions must be built to place the solar panels. Factoring the proposed flexible panels are placed at the same pace as the GREENS panels, a full 12-kW system takes more than 240 minutes to complete. Without a prefabricated installation method, emplacement and displacement is estimated to take 30–40% longer, placing the estimated time between four and six hours. Therefore, an individual attribute value for emplacement and displacement timelines is assessed as [.74] for this attribute (Table 9).

e. Solar Power Observable Footprint Within the AO

This section requires the least amount of explanation. Solar panels capable of providing the full load of the MLR COC require a massive footprint. As previously mentioned, solar power is extremely scalable, so the commander may employ solar panels as the tactical situation dictates. Calculating the system's combat footprint into square footage, with each panel measuring 41.5" x 71.8," that is approximately 766 square feet. A 305 tent is roughly 18 feet by 25 feet. If flexible panels are placed on one side of the 305 tent to maximize sun exposure, it takes approximately seven tents to place all panels. Due to the footprint of the system's panels, the individual attribute value for observable footprint is [.63] (reference Table 11).

f. Mean Time Between Failure and Mean Time to Repair

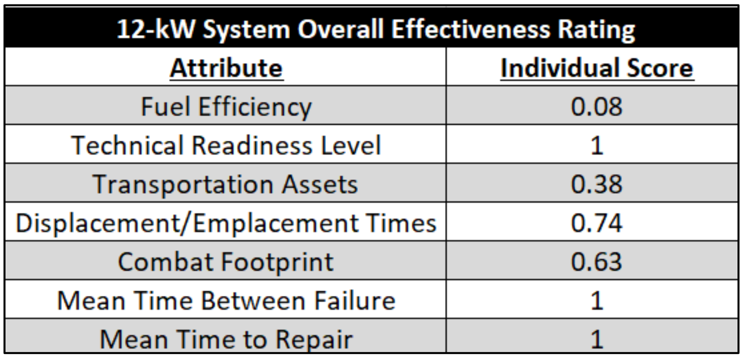
Although data is limited to these metrics and collected typically from large industry solar grids, most commercial sources boast impressive numbers for both solar power's MTBF and MTTF. Several sources agree that due to the nature of the system it is difficult to calculate reliability rates. Almost all sources note PV panel degradation is minuscule. A National Renewable Energy Laboratory study states that solar panels sold and installed after 2000 "exhibited a median failure rate of 5 panels out of 10,000 annually" (2017, para.

3). One study did note that inverters tend to have a shorter MTBF, noting that “75% of the failures were due to inverters, with a MTBF of 1.65 year” (Cheng et al., 2019). Although inverter technology has likely improved since Maish’s work, applying this MTBF still exceeds the threshold for this individual attribute. Therefore, MTBF is assessed as a [1] (referencing Table 12). It is also worth noting that due to a solar system’s simplicity, comprised of the PV panels, inverters, wires, and a control module, they are capable of self-assessment. Given this knowledge and the fact that most reputable solar companies offer extensive warranties for the life of the system, the individual attribute value for MTTR is also a [1] in accordance with Table 13.

g. *Solar Power Overall Effectiveness Score*

All assignments to the individual attribute scores for the 60-kW generator are represented in Table 15.

Table 15. Solar Power Individual Attribute Scores



12-kW System Overall Effectiveness Rating	
Attribute	**Individual Score**
Fuel Efficiency	0.08
Technical Readiness Level	1
Transportation Assets	0.38
Displacement/Emplacement Times	0.74
Combat Footprint	0.63
Mean Time Between Failure	1
Mean Time to Repair	1

3. Assessing Power Storage in Concert with Generators

Adding power storage to diesel generators to create a hybrid capability has numerous advantages which improve the system’s fuel consumption and over energy efficiency. Of note, battery storage improves the system’s load balancing and load smoothing during operations, redirects otherwise lost energy into power storage for later use, and potentially allows for a downsizing of generators required to meet load demands.

Load smoothing, as defined by Rocha, Maia, and Filho (2022), is when "systems store energy during off-peak hours, releasing it for usage during high consumption periods" (p. 1). Rocha et al. (2022) also highlights that load smoothing "has been the preferred approach to smooth the electricity load curve of consumers from different sectors around the world" (p. 2).

Many of the individual attributes for power storage get similar assignments to the ones assigned for the 60-kW generators. Hybrid systems are like-sized to a generator, capable of being trailered, and do not require excessive time to emplace or displace. The assignments for power storage's individual attributes are presented as follows.

Figure 6. HGT20K Hybrid Generator during Exercise STEADFAST LEDA 2021. Source: IDE Intracom Defense (2023).

a. Power Storage Increased Fuel Efficiency

It is hard to precisely identify the increase in fuel consumption and energy efficiency of adding power storage to a system without knowing or simulating hourly load demands. There are, however, several sources present developmental testing data of these systems. Much of this data presents considerable increases in efficiency and fuel consumption to a 60-kW generation system. Trevizan et al.'s (2021) research states, "generators typically operate more efficiently close to their rated power output" (p. 58).

Using the efficiency equation provided by Sciencing.com "Efficiency = [Energy Output (kWh)/ Energy Input (kWh)] × 100%" to again calculate the efficiency of the 60-kW, shows the generator witnesses an increase in fuel efficiency from 23.5% to 33.5% as it nears full capacity (1996, para 6). Another key consideration is that using a power storage capability prevents the requirement of running a second backup generator. Since the batteries and inverter are a feasible backup, the hybrid portion of the system can hold power to allow the second generator to start.

More interestingly, the load balancing of the system has multiple positives to both system efficiency and longevity. Keeping batteries in peak condition requires they are not overcharged or completely expelled for long periods, essentially "minimize the amount of time the battery spends at either 100% or 0% charge" (Erickson, 2020). Load balancing allows the system to maximize the load on the generator while passing power requirements to the batteries for optimal use. This is essentially the "talking guns" of power generation, whereby the generator covers the life and wellbeing of the batteries, and the batteries return the favor. IDE Intracom Defense portrays data collected from the pictured system during a NATO exercise. The data presents the system's ability to load balance where the system transitioned the load between the two, using 51% generator power and 49% power storage (silent power). While IDE's data presents periods where the hybrid system ran at 91% efficiency, mathematically the MLR 60-kW generator nears 70% efficiency while running at its current load requirements. This is calculated by estimating a 3.74 gallons per hour at approximately an 81% load. If load balancing places only 50% of the work on the generator, this means the system potentially delivers 52 kW while only burning 1.87 gallons per hour. Using the efficiency equation puts the system at approximately 70% energy efficiency.

Perhaps even more important is the amount of fuel that can be saved. As previously calculated, the current two generator setup consumes approximately 110.4 gallons per day. Assuming the hybrid system runs at the calculated 70% efficiency, without the second generator requirement, means it consumes approximately 44.9 gallons over the same 24-hour period. This is a savings of approximately 65.5 gallons per day. Given the possibility of seeing a fuel efficiency upwards of 70%, the individual attribute for this is [.58] (reference Table 2).

b. Technical Readiness Level of Power Storage

Again, this research did not find any military specific documents supporting the current TRL classification of power storage. ETP, the commercial source used for solar power places power storage capabilities at a TRL-9, stating the technology requires "integration needed at scale" (IEA, 2023). Unlike the adjustment made to solar power's TRL, due to flexible PV requirements, the batteries and inverters required for this capability are already being used by the military. Therefore, the recommendation is keeping the technology rating with focus on integration, making the individual attribute value a [1] as referenced by Table 4.

c. Marine Corps Assets Capable of Transporting the System

Many of the researched commercial power storage capabilities are similar in size to the 60-kW generator. Systems are also being developed to support developmental and operational testing. These systems can be trailered to offer easier transportation throughout the operational environment while minimizing the system's overall size and weight. This offers ground force commanders greater flexibility to move the system by land or air. The current assessment is this attribute receives a [1] but may require change as system designs are finalized (reference Table 7).

d. Power Storage Emplacement and Displacement Timelines

Like the 60-kW generator, power storage capabilities can be implemented in a matter of minutes to support energy flow. This assigns an individual attribute value of [1] (reference Table 9).

e. Power Storage Observable Footprint Within the AO

This metric is again like transportation and emplacement considerations. The pictured system shows dimensions comparable to that of the 60-kW generator. Therefore, footprint receives a [1] for the individual attribute (reference Table 11).

f. Power Storage Mean Time Between Failure and Mean Time to Repair

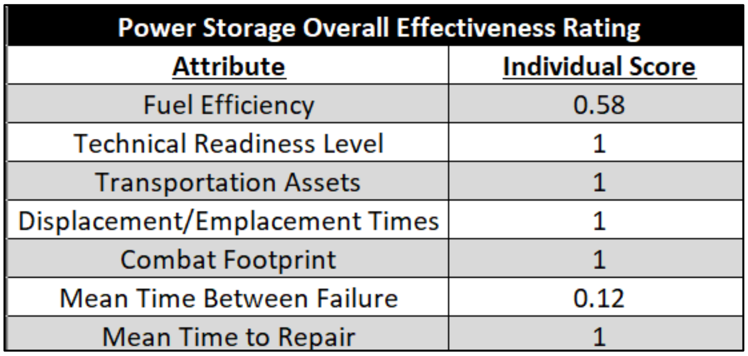
Public Works and Government Services Canada's published *Request for Information* (RFI) details data for both MTBF and MTTR of the hybrid system (figure 6). System designs specify a minimum MTBF of 3000 hours (Public Works and Government Services Canada, 2023). Although the document does not give a specific number for MTTR, the RFI does specify an overall availability of 98%. Using the overall availability and the given MTBF, the MTTR is calculated using the following equation. The MTTR is approximately 61 hours. Given these metrics, the individual assignments for MTBF and MTTR are [.12] and [1] respectively (reference Tables 12 and 13).

$$Ao = MTBF / (MTBF + MTTR)$$

g. Power Storage Overall Effectiveness Score

All assignments to the individual attribute scores for power storage are represented in Table 16.

Table 16. Energy Storage Individual Attribute Scores



Power Storage Overall Effectiveness Rating	
Attribute	**Individual Score**
Fuel Efficiency	0.58
Technical Readiness Level	1
Transportation Assets	1
Displacement/Emplacement Times	1
Combat Footprint	1
Mean Time Between Failure	0.12
Mean Time to Repair	1

4. Assessing Hydroelectric Buoys in Concert with Generators

This research finds the application of hydroelectric power capabilities interesting as the Marine Corps focuses on littoral combat operations and both the Marine Corps and the Navy explore sea basing opportunities. Using the power of the ocean, also known as wave energy converters (WECs), represents numerous approaches to harnessing energy from ocean waves. A few examples of WECs include point absorbers, attenuators, and overtopping devices.

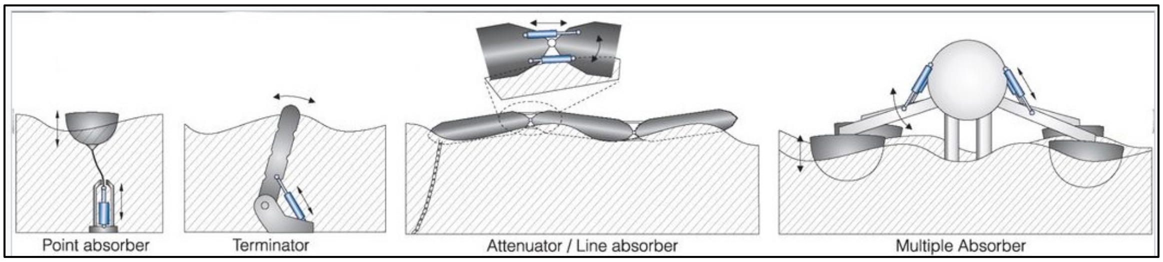


Figure 7. Different Energy Conversion Principles. Source: Hansen et al. (2013).

This technology is an area of active research and development, aiming to provide a sustainable and clean source of power. Given the size and complexity of these WEC devices, this study assesses that a point absorber buoy is currently the WEC technology most capable of supporting tactical level operations. At the start of this study, these technologies seemed promising. However, further research shows these technologies, due to relative size to power output, still require advancements to meet energy efficiency and fuel offsetting goals.

a. Hydroelectric Increased Fuel Efficiency

Current available literature challenges the accurate evaluation of a point absorber buoy's ability to offset energy requirements. Multiple reports conducted by Offshore Energy note that a one-year test conducted on the BOLT Lifesaver wave energy device conducted off the coast of Kaneohe Bay, Hawaii did not produce the energy expected of the device. Melo and Jeffrey note that while the WEC device is rated at a maximum output of 50 kW, it only averaged an "output of 3.2kW lasting 200 days, according to the project's website" (2017, p 144). An article in *Business Norway* details the dimensions of the BOLT Lifesaver WEC at 16 meters in diameter, weighing in at 60 metric tons (2024, para. 4). In assessing the fuel efficiency of this 60-ton behemoth, the study applies a similar approach to the solar power approach. Assuming the WEC averages 3.2 kW, meaning 3.2 kW per hour, suggests that it takes about 4 hours to produce 12 kWh of energy. Referencing earlier calculations, the 60-kW produces approximately 12 kWh per gallon at a 50% load capacity. Therefore, the Bolt Lifesaver WEC offsets approximately 6 gallons of fuel in a 24-hour period by averaging 12 kWh every four hours. The 12-kW solar capability offset almost the same number of gallons daily, factoring in 6 hours of sunlight. Therefore, this WEC is awarded an [.08] for an individual attribute score assessing increased fuel efficiency (refer to Table 2).

b. Technical Readiness Level of Hydroelectric Power

The LiquidGrid.com provides a database identifying approximately 60 companies globally conducting research and development on point absorber buoys. Each company seems intent on downsizing the WEC while making the technology output much greater. Research on devices much smaller than the BOLT Lifesaver places the current technology at a TRL-5 with a desire to reach a TRL-7 over the next couple of years. A company named AquabuOY presents a model rated at 250 kW (Figure 8). The company does not provide a buoy weight, but the diameter of their WEC is 6 meters, 10 meters smaller than the previously described device. Given the current TRL presented by several companies currently leading the market, the individual attribute value is assigned at [.19] as referenced by Table 4.

Figure 8. AquabuOY Wave Energy Converter. Source: University of Strathclyde (2024).

c. *Marine Corps Assets Capable of Transporting the System*

This study focuses predominantly on point absorber buoys, because they are the smallest WEC devices capable of producing energy. There are smaller point absorbers than the two compared in the previous sections, but those devices only create 300–400 watts of power and are designed to power small environmental collection devices while at sea. While these devices certainly have their applications, they do not currently possess the output capability to offset fueled generation. As previously mentioned, the size of these buoys prevent movement throughout the AO by Marine Corps transportation assets. Furthermore, many of these devices require heavy equipment at sea to emplace. These considerations give the transportation individual attribute for current WECs a [0] (refer to Table 9).

d. *Hydroelectric Buoy Emplacement and Displacement Timelines*

The previous section highlights both the size and the weight of point absorber buoys, noting a need for heavy equipment to aid in emplacement and displacement of these hydroelectric assets. To emplace or displace a point absorber buoy requires the Marine Corps to either rely on the Navy to support these efforts or contract host nation support to accomplish the task. Even with dedicated support, moving a WEC takes days to weeks to accomplish. These timelines far exceed the metrics of this individual attribute score, placing WEC's score at [0] (reference Table 11).

e. *Hydroelectric Observable Footprint Within the AO*

Even with the size and weight of these devices. The observable combat footprint is small. Consider once again the dimensions of the BOLT Lifesaver. At 16 meters in diameter and 60 metric tons, the observable footprint is still minimal due to the device being mostly submerged. Another factor considered for this attribute is that power is cabled ashore, providing standoff from the floating WEC to forces ashore. These considerations provide an individual attribute score of a [1] for even the largest WEC (reference Table 13).

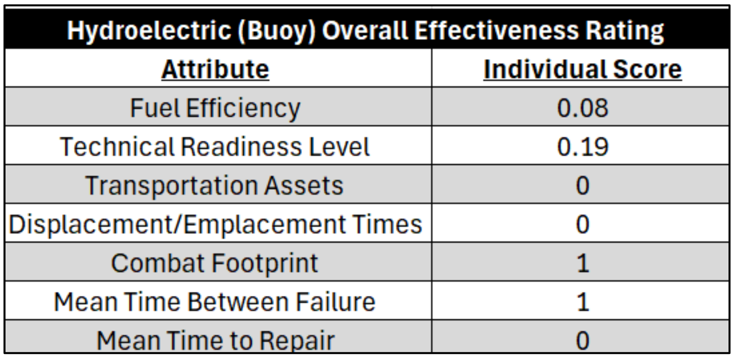
f. Hydroelectric Power Mean Time Between Failure and Mean Time to Repair

Current absorber buoys, being a relatively new technology, have varying MTBFs. Generally, MTBF can range from several months to a few years, depending on the technology and environmental conditions. Current technology from a company named "Ocean Power Technologies" boasts a MTBF of over three years. These portrayed MTBF metrics far exceed the individual attribute scores. The MTTR for buoy systems can be significant due to the challenges of working in marine environments. Repair times can range from a few days to several weeks, depending on the severity of the issue and accessibility. For these reasons the MTBF and the MTTR are assessed as [1] and [0] respectively (reference Table 15).

g. Hydroelectric Buoy Overall Effectiveness Score

All assignments to the individual attribute scores for power storage are represented in Table 17.

Table 17. Power Storage Individual Attribute Scores

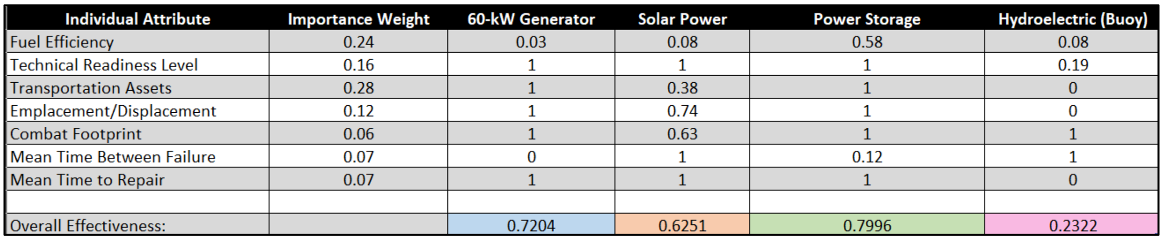


Hydroelectric (Buoy) Overall Effectiveness Rating	
Attribute	**Individual Score**
Fuel Efficiency	0.08
Technical Readiness Level	0.19
Transportation Assets	0
Displacement/Emplacement Times	0
Combat Footprint	1
Mean Time Between Failure	1
Mean Time to Repair	0

D. MOE SCORE AND COST-EFFECTIVE SOLUTION

This chapter concludes with the final measure of effectiveness for all alternative power capabilities. Now that all attributes are assigned for all power capabilities, the effectiveness measures are determined by adding together each value function product and the assigned importance weights. as referenced in Table 18.

Table 18. Capability Measures of Effectiveness



Individual Attribute	Importance Weight	60-kW Generator	Solar Power	Power Storage	Hydroelectric (Buoy)
Fuel Efficiency	0.24	0.03	0.08	0.58	0.08
Technical Readiness Level	0.16	1	1	1	0.19
Transportation Assets	0.28	1	0.38	1	0
Emplacement/Displacement	0.12	1	0.74	1	0
Combat Footprint	0.06	1	0.63	1	1
Mean Time Between Failure	0.07	0	1	0.12	1
Mean Time to Repair	0.07	1	1	1	0
Overall Effectiveness:		0.7204	0.6251	0.7996	0.2322

The next chapter of this study analyzes each program's life-cycle cost to develop the final cost estimation relationship. Once costs are applied, the CER is graphed to present the results. Wall and Mackenzie (2015) write, "The decision maker ultimately pursues two overall objectives when searching for a solution: (1) maximize effectiveness and (2) minimize cost" (p. 19).

IV. PROGRAM COST ANALYSIS

This chapter presents a comprehensive cost analysis of each of the four energy programs, focusing on their estimated life cycle costs over a period of 17 years at the MLR COC level. To ensure a consistent comparison, this analysis employs a constant dollar approach, wherein all monetary values are converted into 2024 calendar year (CY) dollars. This approach enables a straightforward comparison of costs by eliminating the distortive impact of inflation throughout the period of analysis. For each program, the life cycle costs capture two main components: procurement costs, which cover initial acquisition of per unit costs, and annual sustainment costs, which estimates maintenance and operational expenses, including fuel consumption. This analysis, coupled with the previous chapter's overall program effectiveness scores, aims to provide a clear financial perspective on each program's long-term economic viability and efficiency, serving as a critical resource for decision-making in energy program selection and investment.

A. DATA

This chapter comprises published cost data from three different sources to estimate each program's life cycle costs. First, U.S. Army's 2014 capability production document provides data for the current 60-kW generators, detailing both procurement and sustainment costs. Similarly, data for energy storage devices are gathered from a 2023 request for information on Tactical Power Systems (TPS) from the Government Works and Public Services Canada. Finally, this work relies on published commercially sourced data for both the solar power and hydroelectric buoy programs. Much like the previous chapter, hydroelectric buoy cost data is limited. The primary source of commercially available data is drawn scholarly work on estimated costs. Commercially available data for solar power and point absorber buoys is limited regarding annual sustainment costs.

1. Calendar Year Dollars and Inflation

This research converts all associated program costs into constant CY 2024 dollars to ensure the most accurate and equitable comparison across each alternative. Since gathered data extends from the generator's production document, estimated in constant

2010 dollars, to the energy storage's request for information document in constant 2023 dollars, converting all estimates to CY 2024 values neutralizes the effects of inflation and allows for a clear, apples-to-apples comparison of the programs' costs. This research uses the Joint inflation calculator to apply inflation indices across all program years.

2. Time Covered for Estimates

The 17-year cost analysis reflects the projected life of a 60-kW generator as outlined in the U.S. Army's 2014 capability production document. This study will assess procurement and sustainment for each power alternative for a 17-period beginning in 2024.

3. Updated Fuel Costs

In updating fuel costs for calculating fuel consumption, this analysis adheres to the Joint Inflation Calculator, rather than applying a fully burdened cost of fuel (FBCF). While the FBCF provides a comprehensive view of fuel-related expenditures by cost of logistics, support, and transportation to the point of use, these calculations can vary widely over time and across different regions. This chapter's analysis offers a more direct comparison of the programs' fuel efficiency and annual sustainment costs by simplifying the estimates based on inflation adjusted fuel costs.

4. Methodology

This section's cost analysis confines itself to MLR COC operations to determine the average procurement costs and sustainment costs of each program. Therefore, this analysis compares the current method of 60-kW power generation by the MLR COC, using current logged load capacities, to each alternative method. To expand further, as Chapter III previously notes, the MLR COC uses two running 60-kW generators with a third generator in reserve. The cost analysis focuses specifically on those three generators required to produce mission requirements, not considering any additional generators the MLR maintains in its inventory. Likewise, for each power alternative, since the compared energy alternative requires the use of fueled generators, this cost analysis factors the additional procurement costs of adding the alternative to the COC's current setup. Life cycle sustainment costs are adjusted over the 17-year period by adding each alternative's estimated sustainment costs while adjusting for any fuel consumption savings resulting from the alternative's fuel efficiency. While this work can be expanded to the whole of the Marine Corps, an enterprise-level costs analysis requires inclusion of far greater cost elements. Based on the results of this effort, future research is required to estimate any program's expansion to the Marine Corps level.

B. PROGRAM ESTIMATES

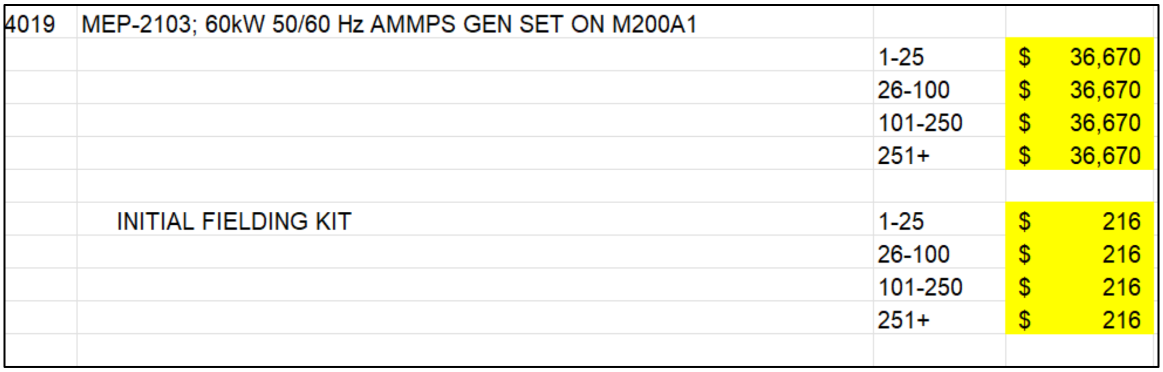
This section applies to the above methodology to each power generation or storage capability. As evidenced by Chapter III, this section begins with the current 60-kW generation capability to provide the foundation to compare the three energy alternatives. This chapter concludes with a chart depicting the estimated costs of each program's effort to supply the MLR COC's load capacity requirements.

1. 60-kW Generator Cost Analysis

There are four key factors analyzed in estimating the life cycle costs of the MLR's current power generation capability: procurement costs of each of the three generators, average annual operating hours, average annual maintenance costs (parts and man-hours), and average annual fuel consumption. Estimating operating hours, maintenance cost and annual fuel consumption provides the average annual operating and sustainment costs.

a. Procurement Cost

First, an Army working document (Figure 6) provides the latest contracted procurement cost of each 60-kW generator as of 2023. Therefore, this work applies the latest contracted price of $36,886 for each generator set, totaling $110,658 for the procurement costs of three generators used in the COC's power generation (U.S. Army, 2023).



4019	MEP-2103; 60kW 50/60 Hz AMMPS GEN SET ON M200A1		
		1-25	$ 36,670
		26-100	$ 36,670
		101-250	$ 36,670
		251+	$ 36,670
	INITIAL FIELDING KIT	1-25	$ 216
		26-100	$ 216
		101-250	$ 216
		251+	$ 216

Figure 9. Contracted Generator Price List. Source: Department of the Army, working document (2023).

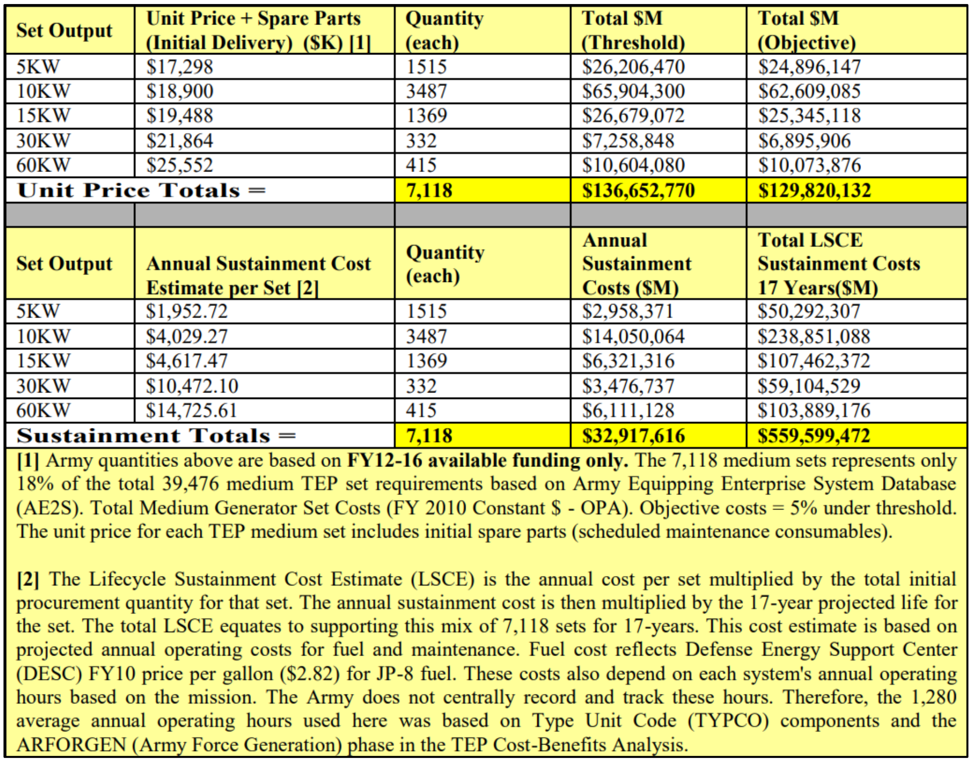
b. *Operations and Sustainment (Annual Fuel Costs)*

The next steps estimate the annual fuel consumption for the MLR's 60-kW generators. Referencing the CPD, the Army identifies an annual sustainment cost per set of $14,725.61, while applying 1,280 annual operating hours and the Defense Energy Support Center's FY10 price per gallon of $2.82 (Figure 7). This work applies the same 1,280 operational hours while incorporating the MLR's fuel consumption calculated in Chapter III. Referencing Chapter III's calculations, each MLR generator consumes approximately 2.3 gallons of fuel per hour while operating at or around a 40% load capacity. The Joint inflation calculator specifies that $2.83 (CY10 fuel cost) inflates to an average of $3.27 (CY 24). Therefore, if the MLR's two generators together consume approximately 4.6 gallons per hour, the annual cost of fuel consumption, assuming 1,280 operational hours, equates to $19,241.73 (Table 19).

Although the Army's CPD uses 1,280 operational hours (or 53.3 days) as a planning factor, a 3d MLR training and exercise plan for fiscal year 2024 reflects the MLR COC may anticipate far more 60-kW operational hours to support of various exercise and deployment requirements. Since the COC's operational setup varies greatly based on the situation, Table 15 provides two calculations; one for lower annual life cycle estimates, using the CPD's 1,280 operational hours; as well as a higher annual life cycle estimate, applying approximately 3600 operational hours (or 150 days) due to potential MLR operational support. It is worth noting that annual sustainment estimates vary greatly based on unit training and deployment timelines. MLR's estimated fuel costs for 3600 operational hours, consuming 4.6 gallons of fuel per hour (110.4 gallons per day) and at a fuel inflation cost of $3.27, results in an annual estimate of $54,151.20 (Table 19).

c. *Operations and Sustainment (Annual Maintenance Costs)*

The next cost analysis step extrapolates the average annual maintenance of each generator by using Figure 10 from the capability production document. At the time of this writing there was no identified database capturing annual maintenance metrics for the 60-kW generator, requiring some calculable assumptions. Referencing the CPD, the Army identifies an annual sustainment cost per set of $14,725.61, while applying 1,280 annual operating hours and the Defense Energy Support Center's FY10 price per gallon of $2.82.



Set Output	**Unit Price + Spare Parts (Initial Delivery) ($K) [1]**	**Quantity (each)**	**Total $M (Threshold)**	**Total $M (Objective)**
5KW	$17,298	1515	$26,206,470	$24,896,147
10KW	$18,900	3487	$65,904,300	$62,609,085
15KW	$19,488	1369	$26,679,072	$25,345,118
30KW	$21,864	332	$7,258,848	$6,895,906
60KW	$25,552	415	$10,604,080	$10,073,876
Unit Price Totals =		**7,118**	**$136,652,770**	**$129,820,132**

Set Output	**Annual Sustainment Cost Estimate per Set [2]**	**Quantity (each)**	**Annual Sustainment Costs ($M)**	**Total LSCE Sustainment Costs 17 Years($M)**
5KW	$1,952.72	1515	$2,958,371	$50,292,307
10KW	$4,029.27	3487	$14,050,064	$238,851,088
15KW	$4,617.47	1369	$6,321,316	$107,462,372
30KW	$10,472.10	332	$3,476,737	$59,104,529
60KW	$14,725.61	415	$6,111,128	$103,889,176
Sustainment Totals =		**7,118**	**$32,917,616**	**$559,599,472**

[1] Army quantities above are based on **FY12-16 available funding only.** The 7,118 medium sets represents only 18% of the total 39,476 medium TEP set requirements based on Army Equipping Enterprise System Database (AE2S). Total Medium Generator Set Costs (FY 2010 Constant $ - OPA). Objective costs = 5% under threshold. The unit price for each TEP medium set includes initial spare parts (scheduled maintenance consumables).

[2] The Lifecycle Sustainment Cost Estimate (LSCE) is the annual cost per set multiplied by the total initial procurement quantity for that set. The annual sustainment cost is then multiplied by the 17-year projected life for the set. The total LSCE equates to supporting this mix of 7,118 sets for 17-years. This cost estimate is based on projected annual operating costs for fuel and maintenance. Fuel cost reflects Defense Energy Support Center (DESC) FY10 price per gallon ($2.82) for JP-8 fuel. These costs also depend on each system's annual operating hours based on the mission. The Army does not centrally record and track these hours. Therefore, the 1,280 average annual operating hours used here was based on Type Unit Code (TYPCO) components and the ARFORGEN (Army Force Generation) phase in the TEP Cost-Benefits Analysis.

Figure 10. Program Affordability Estimates. Source: Department of the Army (2014).

Since the CPD's provided numbers do not separate the total sustainment costs by fuel consumption cost and maintenance costs, this work first estimates the annual fuel consumption using an average load capacity of 75% (3.51 gallons per hour) for each generator for two reasons. First, by applying a 100% load capacity at $2.82 per gallon and 1280 operating hours, fuel costs exceed the overall annual estimated sustainment costs ($16,134.91). Additionally, by applying a 50% load capacity to the CPD's estimated sustainment costs, annual fuel costs only account for $8,915.71, suggesting maintenance cost average almost $6,000 per generator, or approximately 40% of the CY10 total sustainment cost estimate. The application of a 75% load capacity at $2.82 per gallon over 1,280 operational hours results in fuel consumption cost of $12,669.70 in CY10 dollars. This fuel cost is subtracted from the overall sustainment costs to project the estimated maintenance cost of approximately $2,056 in the CPD's CY10 dollars, approximating 14% of the total estimated annual sustainment costs.

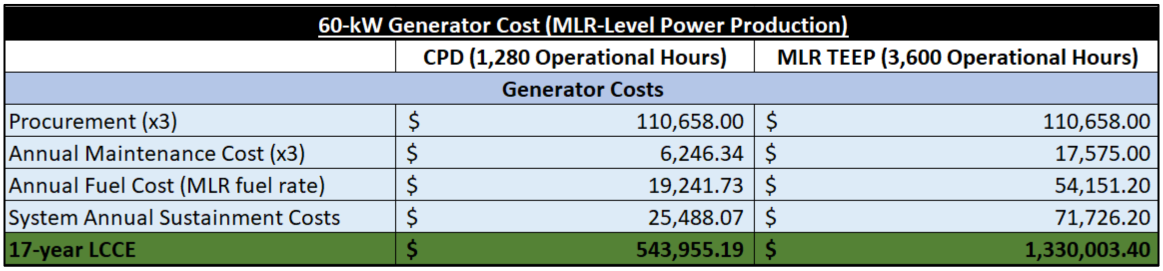
Due to the 60-kW AMMPS generator's preventative maintenance schedule, increasing the system's annual operational time results in increased annual maintenance costs. Therefore, calculations for annual maintenance follow the same method as fuel consumption costs; 14% is applied to both the CPD's 1,280 operational hours (low estimate) and to MLR's potential 3,600 operational hours (high estimate). Projected annual maintenance cost at 1,280 and 3,600 operational hours calculates to $3,124.30 and $8,760.23 per unit respectively. The estimated annual maintenance cost is applied to each of the three generators in CY 24 dollars (Table 19).

Rather than applying those total maintenance estimations across all three generators, this work assumes the most equitable division of the total required operational hours amongst all three generators. This method of estimating annual maintenance costs is carried out for all programs to evaluate how each program impacts annual maintenance costs. Using this method, dividing 1,280 operational hours by two running generators results in a total runtime of 2,560 hours. The most equitable split between three generators is approximately 854 hours per generator to fulfill mission requirements. The adjusted annual maintenance for each generator running at 854 hours is approximately $2,082.11 per unit or $6,246.34 for all three generators. Similarly, fulfilling the 3,600-hour operational requirement results in an equitable distribution of approximately 2,400 hours of runtime for each generator. This results in an approximate cost of $5,858 per generator rather than the previously estimated $ $8,760.23.

d. Generator 17-Year Life-Cycle Cost Estimate

As expressed in Table 19, the procurement costs extend to three 60-kW generators responsible for the COC's power. Two generators constantly run to provide the average load capacity of 50 kW, and a third generator is stationed in case one running generator malfunctions. The maintenance cost applies to the 14% total sustainment cost previously calculated and extends to all three generators. Fuel costs assume the average 40% load rate for the two generators constantly running, noting that the third generator only operates if one fails. Annual sustainment costs total the maintenance and fuel costs. Finally, the 17-year LCCE multiplies the 17-year period to the annual sustainment cost and adds the total procurement costs to provide the overall assessment.

Table 19. 60-kW Generator 17-year LCCE



60-kW Generator Cost (MLR-Level Power Production)		
	CPD (1,280 Operational Hours)	MLR TEEP (3,600 Operational Hours)
Generator Costs		
Procurement (x3)	$ 110,658.00	$ 110,658.00
Annual Maintenance Cost (x3)	$ 6,246.34	$ 17,575.00
Annual Fuel Cost (MLR fuel rate)	$ 19,241.73	$ 54,151.20
System Annual Sustainment Costs	$ 25,488.07	$ 71,726.20
17-year LCCE	**$ 543,955.19**	**$ 1,330,003.40**

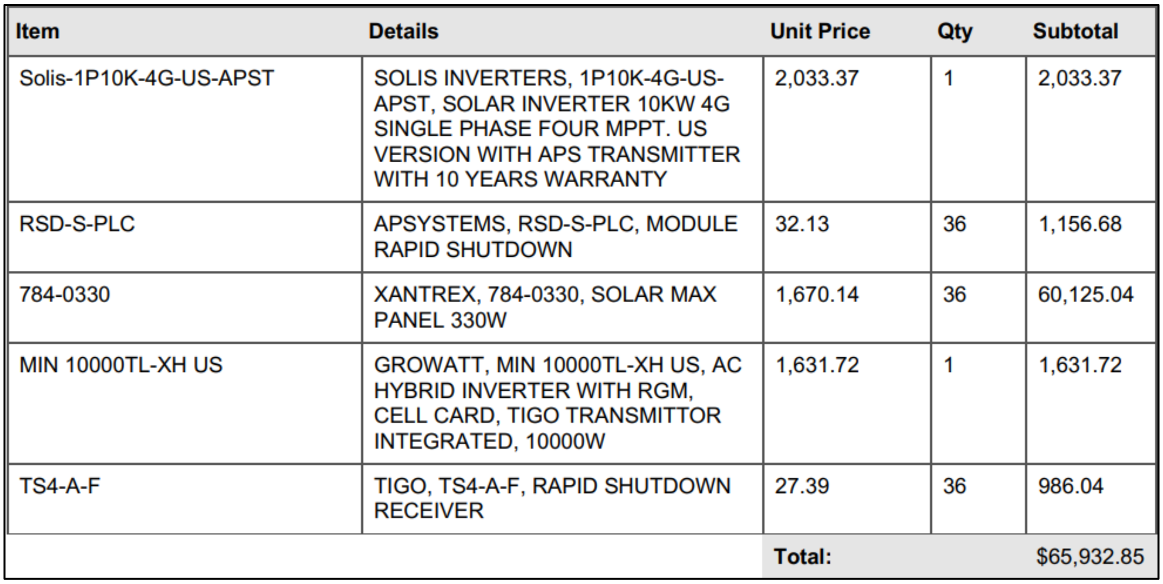
Factoring a low-end operational period of the CPD's 1,280 hours, an estimated 17-year LCCE is approximately $597,000. The high-end calculation for upwards of 3,600 operational hours increases the 17-year LCCE to approximately $1.5 million.

2. Solar Power Cost Analysis

Calculating solar power's addition to the MLR's 60-kW requires the three-generator construct to be maintained as the 12-kW system does not have the capacity to cover the COC's average load. Therefore, this estimate maintains the calculations for the generator LCCE and factors in procurement and maintenance of one 12-kW solar system. The fuel consumption estimation reduces based daily fuel saved from incorporating the solar capability.

a. Procurement Cost

Procurement costs for a 12-kW solar system are estimated from commercial vendors averaging prices for all necessary components to build the system across multiple vendors. System prices are subject to vary based on acquisition processes and competitive bidding. Emily Walker (2023) notes that "As of January 2022, the average cost of solar in the U.S. is $2.77 per watt or $33,240 for a 12-kilowatt system" (para 2). After accounting for inflation, the Cy 24 average price is $34,549. However, this average price provides a solar system with rigid PV panels. As has already been noted, a lightweight and survivable solar system requires flexible PV panels. An article published on *Solar.com* details cost planning for solar investments, stating that "today's premium monocrystalline solar panels typically cost between $1 and $1.50 per watt (2024, para 10). Using the median estimate of $1.25 for a 330 w rigid panel results in a price of $412.50 per panel. Flexible PV panels are far more expensive than rigid panels. An online search for flexible 330 w solar panels result in a limited number of vendors with prices ranging from approximately $1,200 to $1,700. Again, taking the median price equates to approximately $1,450 per flexible panel. Given a 12-kw system requires approximately 36 total 330 w panels, the price increase of flexible panels can increase the total cost of the system between approximately $28,000 and $46,000, with a median price increase of approximately $37,000. To provide greater validity to these estimates, consider the quote in Figure 8.



Item	Details	Unit Price	Qty	Subtotal
Solis-1P10K-4G-US-APST	SOLIS INVERTERS, 1P10K-4G-US-APST, SOLAR INVERTER 10KW 4G SINGLE PHASE FOUR MPPT. US VERSION WITH APS TRANSMITTER WITH 10 YEARS WARRANTY	2,033.37	1	2,033.37
RSD-S-PLC	APSYSTEMS, RSD-S-PLC, MODULE RAPID SHUTDOWN	32.13	36	1,156.68
784-0330	XANTREX, 784-0330, SOLAR MAX PANEL 330W	1,670.14	36	60,125.04
MIN 10000TL-XH US	GROWATT, MIN 10000TL-XH US, AC HYBRID INVERTER WITH RGM, CELL CARD, TIGO TRANSMITTOR INTEGRATED, 10000W	1,631.72	1	1,631.72
TS4-A-F	TIGO, TS4-A-F, RAPID SHUTDOWN RECEIVER	27.39	36	986.04
		Total:		$65,932.85

Figure 11. Online Solar Calculator Quote for 12-kW Solar System. Source: Inverter Supply (2024).

Figure 8 provides an online estimate provided by an online solar calculator for a like-sized system. Using the numbers previously calculated, this work estimates a flexible panel solar system at approximately $71,900. The system quote provided by the calculator equates to roughly $66,000, but it is worth noting that the quote only provides a 10-kW inverter. A commercial search of 12-kW inverters suggests they cost between 4 and $5,000 (Sunwatts, 2024). Given all considerations, this work applies the conservative estimate of $68,500 for a solar system procurement price.

b. Operations and Sustainment (Annual Fuel Costs and Savings)

Recalling the solar fuel efficiency section of Chapter III, a 12-kW offsets roughly six gallons of fuel over a 24-hour period by estimating six hours of sunlight. To provide another method of calculation for this 24-hour fuel consumption, consider the solar system provides 12-kW of power up front (when sunlight supports), reducing the generator’s requirement by that amount. Therefore, if each of the two generators split the new load capacity (38 kW), they average an approximate 30% load capacity. Solar’s employment lowers each generator’s fuel consumption to roughly 1.77 gallons per hour or 3.54 gallons per for both running generators, approximating a savings of around 1.06 gallons per hour, or 6.36 gallons for the six hours the solar system can provide power. Overall, the system saves approximately $1,115.46 over 1,280 operating hours and approximately $3,139.20 over 3,600 operating hours (Table 20).

c. Operations and Sustainment (Annual Maintenance Costs)

Solar power's annual maintenance estimates reflect little costs associated with maintaining the average system. Kimberly Magerl (2023) writes in a 2023 article that "the average cost of solar panel maintenance is $570 annually, but the cost typically varies from $400 to $740" (para 1). Annual solar maintenance averages, however, do not account for damage caused by emplacement and displacement of panels in a tactical environment. This work takes a conservative approach and estimates 10% of the solar panels will require repair or replacement annually from tactical employment considerations. Future research will need to review the estimate for panel damage as data is collected. Applying a 10% damage criterion to the provided quote (Figure 8) estimates an annual maintenance cost of approximately $6,125.50. The maintenance costs ($6,125.50) are applied to the high-end calculation, while a third of the cost ($2,041.83) is applied to the low-end calculation (Table 20).

d. Solar 17-Year Life-Cycle Cost Estimate

Again, the addition of a 12-kW solar system still requires the MLR to run two generators to meet load capacity of the COC. While the solar system does offset the generator's fuel consumption and cost, the offset does not result in a lower total life-cycle cost.

Table 20. 12-kW Solar System 17-year LCCE

12-kW Solar System Cost (MLR-Level Power Production)		
	CPD (1,280 Operational Hours)	MLR TEEP (3,600 Operational Hours)
Solar System Cost		
Generator Costs		
Procurement (x3)	$ 110,658.00	$ 110,658.00
Procurement (1 System)	$ 68,500.00	$ 68,500.00
Annual Maintenance Cost	$ 6,246.34	$ 17,575.00
Annual Maintenance Cost (System)	$ 2,041.83	$ 6,125.50
Annual Fuel Cost (MLR fuel rate)	$ 19,241.73	$ 54,151.20
Annual Fuel Savings	$ (1,115.46)	$ (3,139.20)
Total Annual Sustainment Costs	$ 26,414.44	$ 74,712.50
17-year LCCE	**$ 628,203.48**	**$ 1,449,270.50**

The calculations in Table 20 account for the procurement of both the generators and the solar system. Each system's assessed annual sustainment costs are calculated. Notice that annual fuel cost for the solar system reflects negative to account for fuel savings. Each system's annual sustainment cost is totaled. Finally, the 17-year LCCE multiplies the 17-year period to the total annual sustainment cost and adds the total procurement costs.

Recalling the generator's low-end cost estimate (1,280 operational hours) and the high-end cost estimate (3,600 operational hours) at $597,000 and $1.5 million respectively, the solar system fails to pay for itself for either estimate.

3. Energy Storage Cost Analysis

Like solar power capabilities, energy Storage systems are highly modular and can assume a wide variety of load capacities and associated price ranges. Energy Storage's greatest cost results from the size and number of batteries required to meet the system's load capacity requirements. At the time of this writing, the lithium-ion 6T-E battery is one of few batteries options found in the commercial market that both supplies an acceptable kilowatt hour (kWh) capacity and meets Naval Sea Commands (NAVSEA) certification requirements. NAVSEA's (2020) technical publication *Navy Lithium Battery Safety Program Responsibilities and Procedures* states, "Systems Commands (SYSCOM) with certification authority (CA) must ensure that concurrences have been obtained from all

SYSCOMs responsible for the platforms that will use, maintain, store, or transport" (p. 1-1). As Chapter III mentions, the Li-ion 6T-E battery is currently used in a wide variety of military vehicles. Therefore, this work's cost estimations use the costs and assessed life cycle of the Li-ion 6T-E battery for the LCCE. Acquisition experts evaluating future alternatives note that future Energy Storage efforts will likely witness an increase in NAVSEA certified Li-ion batteries, both increasing market options and lowering current battery pricing.

a. Procurement Cost

There are a multitude of scaling options capable of improving the MLR's 60-kW fuel consumption and lowering maintenance costs. As an example, purchasing a 25-kW storage capacity, coupled with a 30-kW generator allows the MLR to only use one generator, while using the storage capacity and 30-kW generator as a feasible back-up option in case of generator failure. While this option presents a lower-cost option, this effort maintains the three-generator procurement and estimates the procurement of a full 52-kW energy storage capability. Continuing to match cost with the MLR's three-generator procurement maintains a consistent comparison with the previous LCCE. Future acquisition efforts must evaluate the load balancing to best optimize system performance and costs.

Price estimates for the Li-ion 6T-E battery are not readily available online, requiring project submissions. Experts in the field note that the 6T-E battery ranges between $5,000 and $7,000 pending the project size and order quantity. As this research seeks to aid decision-making for future acquisitions, a price of $5,000 is applied to estimate the system's procurement costs. The major components of an energy storage system are the batteries, power inverters, and a control system. Prices for inverters and control systems are estimated based on current market prices as full military systems remain largely in the research and development phase, working towards prototyping like systems. Each li-ion 6T battery has a 2.1 kWh energy capacity, requiring 25 batteries to meet the MLR COC's average load capacity. Assuming a fuel 52-kW energy storage system, places the cost of the system's batteries at approximately $125,000. Various power inverters in the 30-kW range can be found commercially as household energy storage options grow. System inverters range considerably based on size. This estimate provides the cost of one 60-kW inverter priced at $19,750 (Solar Electric, 2024). Total procurement costs of the detailed is approximately $144,750 (Table 21).

b. *Operations and Sustainment (Annual Fuel Costs and Savings)*

Annual fuel savings using the procured system depends largely on the system's concept of employment. Considerable saving stems from the energy storage's ability to maintain the COC's full load capacity if the primary generator fails. Having energy storage, as previously mentioned, eliminates the need to have a second generator running. Another consideration for employing energy storage is the life of the batteries. The 6T-E life expectancy is discussed in more detail in the annual maintenance section, but the system's proposed concept of employment is to solely remain in back-up of the primary running generator in case of generator failure. This employment method limits the number of battery cycles and conserves fuel by eliminating the second generator. Future concepts of employment require more research to obtain the greatest efficiency.

With the energy storage in stand-by for the primary generator, approximately one-half gallon of fuel is saved each hour for a total of 12gallons saved daily. Although the second generator is no longer required, the primary generator now runs at just over 80% load capacity or approximately 4.1 gallons per hour rather the 4.6 gallons per hour when running two generators. This proposed concept of employment saves over 360 gallons of fuel per month, while limiting the batteries total cycle times. Saving 12 gallons of daily reduces fuel costs by approximately $5,300 over the low-estimated 1,280 operating hours and almost $15,000 over the 3,600 operating hours estimate (Table 21).

c. *Operations and Sustainment (Annual Maintenance Costs)*

Operations and sustainment costs are much harder to calculate for the combined or hybrid system. First, Table 21 reflects a reduction in the maintenance costs for the generators to approximately a third of the generator's original calculations. As previously mentioned, preventative and scheduled maintenance costs are reduced when the generators run less. Since the energy storage now removes the need for a second running generator, each generator can be cycled to spread the operational load evenly. For example, rather than having two generators running for 3600 operational hours, each generator can support a more even 1,200 operational hour distribution, reducing maintenance costs by approximately one third. The maintenance cost of the energy storage is a bit different from the maintenance costs of the other systems. While there will likely be routine preventative maintenance, the life of the battery is the life of the battery. Once the battery life is over, there is no maintenance to fix it. The battery must be replaced. In this procurement concept, the batteries make up approximately $125,000 of the total system. The 6T-E li-ion battery is far more capable than most in terms of life.

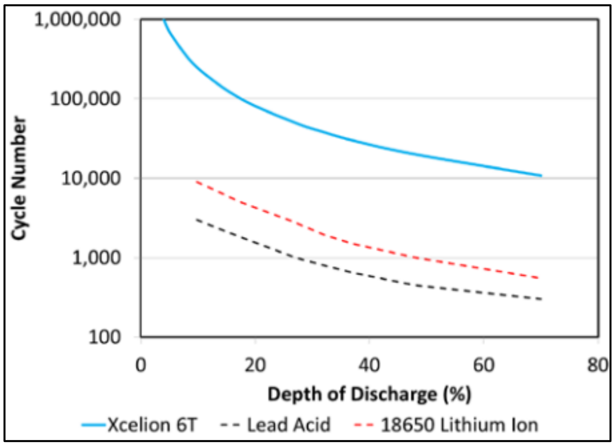


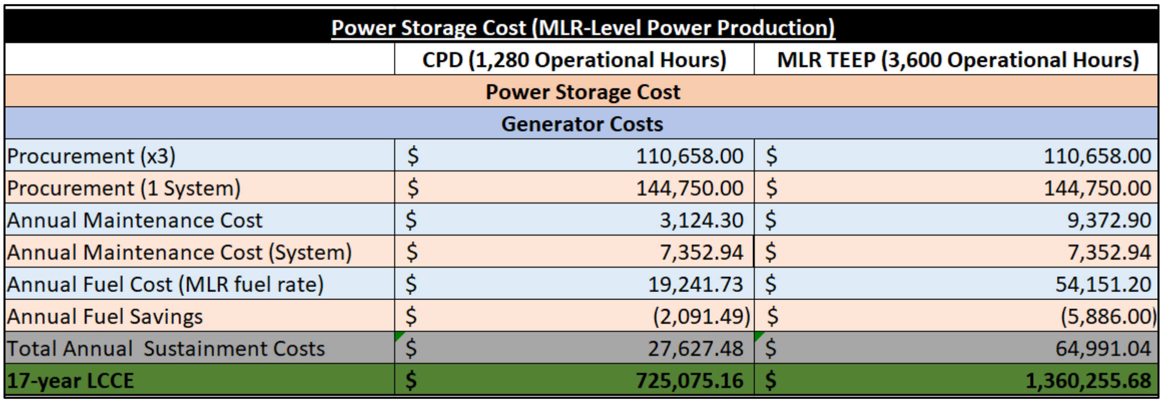
Figure 12. Cycle Life to 80% Capacity Loss. Source: Saft America (2023).

The 6T-E battery is "able to support an order of magnitude more cycles than traditional batteries and is designed for the high depth of discharge demands required for effective silent watch" (Xcellion, 2023). The estimated calendar life of the battery, up to 45 degrees Celsius (114 degrees Fahrenheit) is approximately 11 years. The previously mentioned concept of employment limits the number of cycles to extend the life of the battery. To account for a full battery replacement within the 17-year life cycle, this includes an average maintenance cost. This cost divides the cost of a full battery replacement ($125,000 evenly across the 17-year span, averaging an annual cost of approximately $7352.94.

d. *Energy Storage 17-Year Life-Cycle Cost Estimate*

There are multiple things to consider when evaluating the 17-year LCCE of an energy storage capability. First, the initial energy storage investment is costly, and having to replace expensive batteries halfway through the life cycle requires more use for the system to show value. Consider the low-end estimate at 1,280 operational hours (approximately 53 days). Although the system offsets fuel consumption, only using it 53 days per year does not offset the cost of the system. Recall the 17-LCCE for the MLR's three generator setup is estimated to around $597,000. Therefore, energy storage falls short of paying for itself by more than $70,000.

Table 21. Energy Storage 17-year LCCE



Power Storage Cost (MLR-Level Power Production)		
	CPD (1,280 Operational Hours)	**MLR TEEP (3,600 Operational Hours)**
Power Storage Cost		
Generator Costs		
Procurement (x3)	$ 110,658.00	$ 110,658.00
Procurement (1 System)	$ 144,750.00	$ 144,750.00
Annual Maintenance Cost	$ 3,124.30	$ 9,372.90
Annual Maintenance Cost (System)	$ 7,352.94	$ 7,352.94
Annual Fuel Cost (MLR fuel rate)	$ 19,241.73	$ 54,151.20
Annual Fuel Savings	$ (2,091.49)	$ (5,886.00)
Total Annual Sustainment Costs	$ 27,627.48	$ 64,991.04
17-year LCCE	**$ 725,075.16**	**$ 1,360,255.68**

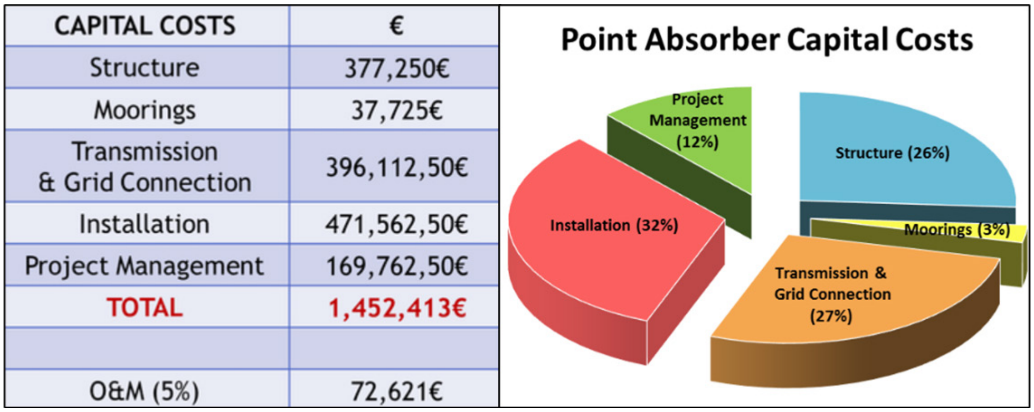
The high-end estimate, using 3,600 operational hours (150 days), represents a lower total LCCE than the current fueled generation by more than $280,000 dollars. Finally, a key consideration is this work only applies the Joint inflation calculator's inflation cost of fuel at $3.27 and does not factor any burdened costs of fuel.

4. Hydroelectric Buoy Costs Analysis

Cost data for hydroelectric point absorber buoys is difficult to find primarily due to commercial sensitivity and the proprietary nature of the technology. Most efforts in this sector are still largely in the prototyping phases. Therefore, the cost estimations in this section are provided by the University of Strathclyde, drawing data obtained from two different projects. Both projects, one from the Federal Energy Regulatory Commission in Washington D.C and one from a report of the Spanish Association of Renewable Energy Producers, estimate the cost of an AquabuOY (University of Strathclyde, 2023). Chapter III's references the AquabuOY while assessing system effectiveness.

a. Procurement Cost

Depicted in Figure 10, the University of Strathclyde's cost assessment provides costs in Euro, requiring a U.S. dollar conversion. In terms of procurement cost, this cost assessment assumes that future applications of such technology enables either the Marine Corps or the Navy to install and manage its own systems. While installation and management likely come in the form of military occupational specialties and/or contracted support, this research does not include those metrics in this evaluation.



CAPITAL COSTS	€
Structure	377,250€
Moorings	37,725€
Transmission & Grid Connection	396,112,50€
Installation	471,562,50€
Project Management	169,762,50€
TOTAL	**1,452,413€**
O&M (5%)	72,621€

Figure 13. AquabyOY 20-year LCCE. Source: University of Strathclyde (2023).

Therefore, the estimated procurement cost of the system is derived from the cost of structure, cost of the moorings, and transmission and grid connection costs. After conversion, these costs total approximately $875,099.53.

b. Operations and Sustainment (Annual Fuel Costs and Savings)

Assessing annual fuel costs requires a look back at Chapter III's calculation of average daily fuel savings from implementing a WEC. Again, using the average output of the Bolt Lifesaver WEC, one of few studies found that provides the devices output, results show the device creates an average output of 3.2 kW. This assessment gives credit that an employed system maintains an average output at or above 3.2 kW for all operational hours. Therefore, the system's fuel efficiency applies a period of about 4 hours to produce 12 kWh of energy (or 76.8 kWh over 24 hours). Taking the average energy produced by the WEC (76.8 kWh) and dividing it by the 12 kWh of production from one of the MLR's generators operating at 50% load capacity, results in a fuel saving of approximately 6.4 gallons of fuel in a 24-hour period. Recall the solar system's estimated fuel savings is 6.36 gallons per 24-hour period, making the fuel savings for the WEC essentially the same as the solar system's savings. Overall, the system saves approximately $1,115.46 over 1,280 operating hours and approximately $3,139.20 over 3,600 operating hours (Table 22).

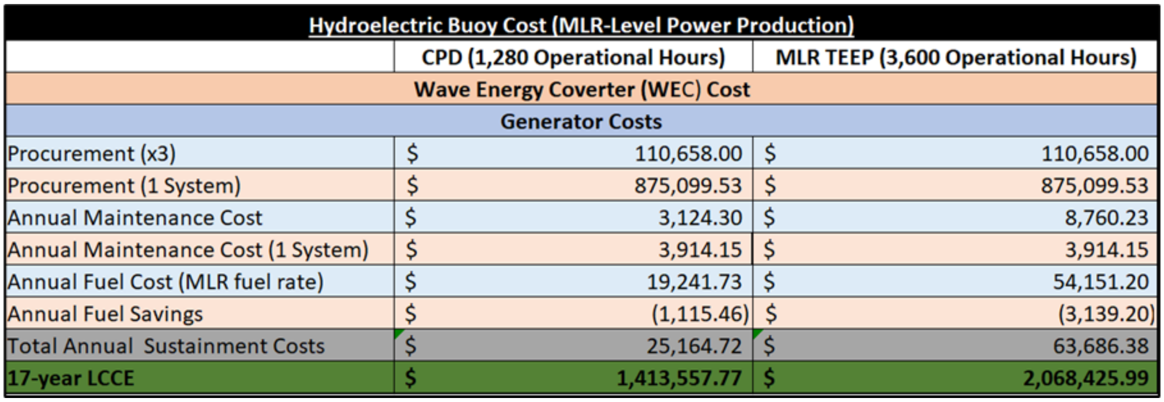
c. Operations and Sustainment (Annual Maintenance Costs)

Figure 10's estimated operations and maintenance costs are just over $78,000 for a twenty-year period. Most research supports that the operations and maintenance cost of a WEC is low, requiring little maintenance over the system's life. This study applies a maintenance cost ratio to assess a 17-year maintenance cost of approximately $66,650. Dividing the overall maintenance cost over a 17-year period is around $3,915 per year (Table 22).

d. Hydroelectric Buoy 17-Year Life-Cycle Cost Estimate

A wave energy buoy system, given procurement price and its limited ability to offset fuel consumption, is approximately 137% more expensive than the MLR's current generator over a 17-year period when using 1,280 operational hours. When applying the same calculations over 3,600 operational hours, a WEC is about 40% more expensive than current generator use (Table 22).

Table 22. Hydroelectric Buoy 17-year LCCE

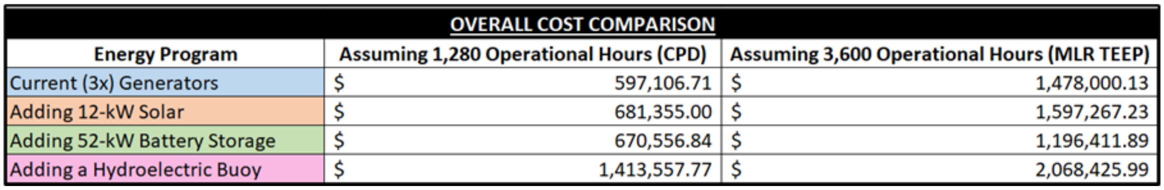


Hydroelectric Buoy Cost (MLR-Level Power Production)		
	CPD (1,280 Operational Hours)	MLR TEEP (3,600 Operational Hours)
Wave Energy Coverter (WEC) Cost		
Generator Costs		
Procurement (x3)	$ 110,658.00	$ 110,658.00
Procurement (1 System)	$ 875,099.53	$ 875,099.53
Annual Maintenance Cost	$ 3,124.30	$ 8,760.23
Annual Maintenance Cost (1 System)	$ 3,914.15	$ 3,914.15
Annual Fuel Cost (MLR fuel rate)	$ 19,241.73	$ 54,151.20
Annual Fuel Savings	$ (1,115.46)	$ (3,139.20)
Total Annual Sustainment Costs	$ 25,164.72	$ 63,686.38
17-year LCCE	**$ 1,413,557.77**	**$ 2,068,425.99**

C. OVERALL PROGRAM COSTS

Table 23 provides the final calculations for all programs. Assuming 1,280 operational hours of each system, the MLR's current generator employment provides the lowest cost over a 17-year period. However, after applying fuel savings and adjusting maintenance estimates, adding energy storage provide the lowest cost option for a 3,600 operational hours LCCE.

Table 23. 17-year LCCE for all Programs (1,280 / 3,600 Operational Hours)



OVERALL COST COMPARISON		
Energy Program	Assuming 1,280 Operational Hours (CPD)	Assuming 3,600 Operational Hours (MLR TEEP)
Current (3x) Generators	$ 597,106.71	$ 1,478,000.13
Adding 12-kW Solar	$ 681,355.00	$ 1,597,267.23
Adding 52-kW Battery Storage	$ 670,556.84	$ 1,196,411.89
Adding a Hydroelectric Buoy	$ 1,413,557.77	$ 2,068,425.99

The last chapter provides graphical displays of each program's cost estimation ratio (CER) between their 17-year LCCE and measure of effectiveness score, considering cost estimates for both 1,280 and annual operational hours (Figures 11 and 12). These CER allow a comparison of each program's costs and overall effectiveness. Chapter V also draws final conclusions and provides recommendations for future research.

D. COST-EFFECTIVENESS RESULTS

Cost-effectiveness ratios are graphed and presented in Figures 14 and 15. When comparing each program's overall effectiveness score and its estimated life cycle costs, assessing system usage of 1,280 operational hours, the current method of employing 60-kW generators dominates solar power. Power storage is more effective than both solar and the 60-kW employment, but adding energy storage is also more costly than both. Due to high cost and low effectiveness, the hydroelectric buoy (WEC) is dominated by all other power capabilities (Figure 14).

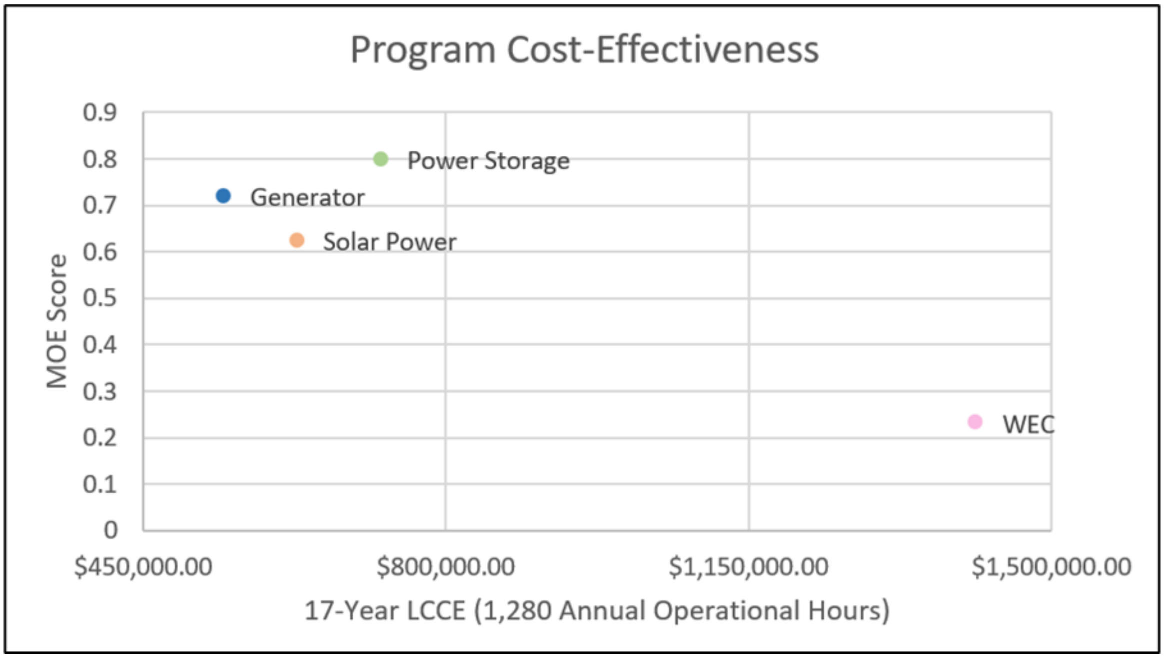


Figure 14. All Programs 17-year (1,280 Operational Hours)

Interestingly, Figure 15 reflects a change when comparing each system's overall effectiveness score and its estimated life cycle costs when the systems are used 3,600 annual operational hours. Due to solar power's lower effectiveness scores, energy storage becomes the dominant alternative energy capability. Also notice that the cost gap closes between the current 60-kW employment method and the addition of energy storage the longer the system is employed.

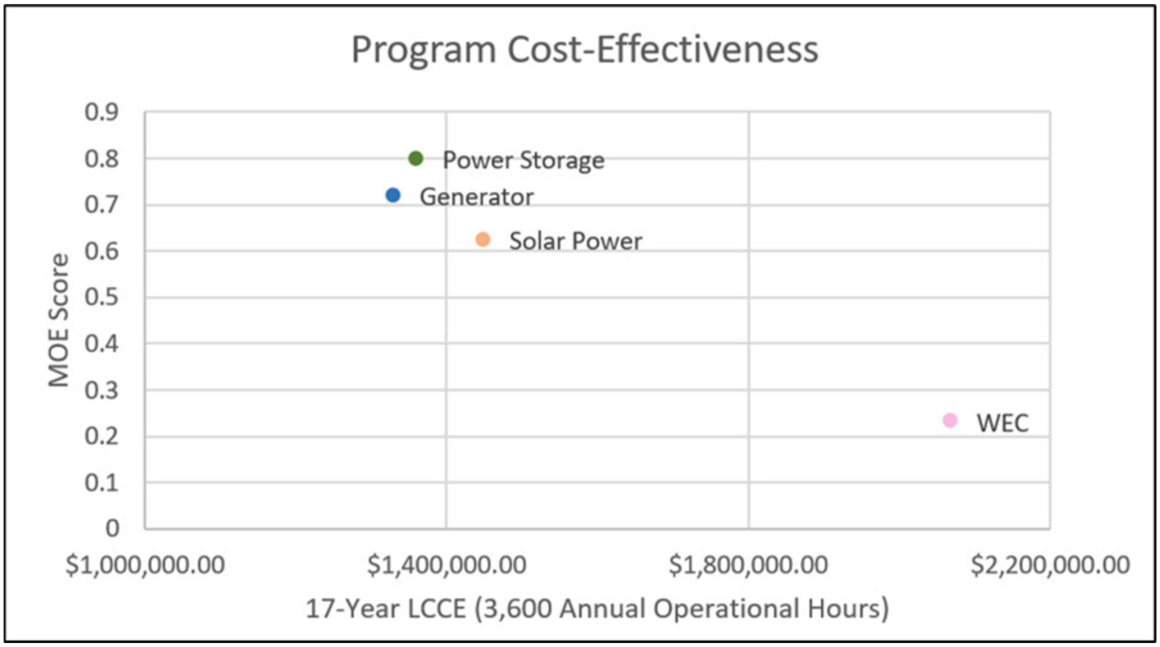


Figure 15. All Programs 17-year (3,600 Operational Hours)

Energy storage's ability to reduce maintenance costs and conserve fuel buys down costs over the 17-year period. Overall, energy storage is more effective than the 60-kW generator but is still more expensive.

V. CONCLUSIONS AND RECOMMENDATIONS

This chapter presents the study's findings, draws final conclusions, and recommends future research. Cost-effectiveness ratios are graphed and presented in Figures 14 and 15.

A. CONCLUSION

The intent of a cost-effectiveness analysis is to identify programs that maximize effectiveness and minimize the costs. The results of this study do present challenges to that effort, largely dependent on how much each system will be used. Both estimates presented in Figures 14 and 15 show generators are effective at providing tactical power. Both figures also show that additional energy storage has the highest level of effectiveness. Again, the costs change slightly based on annual system use. These results suggest that decision-makers will need to trade-off costs to maximize effectiveness. If decisionmakers are most concerned about costs, the best decision may be to stay with the generator, however, if effectiveness is the most important consideration, energy storage presents the best option.

In answering the two primary research questions, consider first the costs of each emerging technology to their viability of providing expeditionary energy. The costs of both energy storage and solar power present viable options of offsetting fuel consumption. Wave energy converters present a high-cost option that is limited in tactical application. Therefore, this assessment concludes that current buoy technology does not offer a viable cost-effective tactical energy alternative. Finally, in addressing the most efficient method, energy storage is the only technology that eliminates a need for a second running generator while providing adequate backup power. Coupling this with energy storage's mobility makes this technology both efficient and suitable in meeting the Marine Corps mission. Solar power requires an increasingly larger combat footprint to effectively offset fuel consumption. Therefore, this study concludes that energy storage offers the most efficient method of offsetting fuel consumption.

This study conducted minimal sensitivity analysis, primarily altering weights associated with mobility, survivability, and operational persistence. Sensitivity analysis consisted of altering each value by plus or minus [.1]. As an example, measures of effectiveness scores were compared with operational persistence weights between [.2] and [.4], mobility weights between [.3] and [.5], and survivability weights between [.2] and [.4]. In all instances of sensitivity analysis, energy storage displays the highest MOE, with the lowest overall MOE of .7328 and ranking more than 13% more effective than solar power. For solar power to gain a higher overall effectiveness score, survivability's weight must increase to approximately [.7], dropping the system's persistence and mobility weights to [.1] and [.2] respectively.

B. FUTURE RESEARCH

Many assumptions are made in the conduct of this research. The first step for improving this research is gaining senior leadership's refinement to the measures of effectiveness and each one's respective weights. Overall program effectiveness measures are largely subjective in assignment, so receiving decision-makers' inputs will improve metrics to best identify future program requirements.

Once the measures of effectiveness are refined and solidified, this research can provide a foundation by which other energy programs may be assessed. This research does not include small nuclear reactors or hydrogen alternatives due to limited data availability, but these alternatives are worth researching as the technologies mature. Technologies, like wave energy converters, can also be revisited as the capability improves. The future of hydroelectric buoys may prove beneficial when supporting sea basing operations.

Finally, the concepts of operations for the compared energy alternatives require refinement. While solar power seems less suitable at the MLR-level, other applications may improve the system's overall effectiveness. As a consideration, suppose an energy storage is containerized with solar panel lining the top of the container. Even with the smaller footprint, the solar panels may provide "free energy" by aiding with charging the energy storage system. The capability's footprint does not change considerably but allows more efficiency from the system. Also, with respect to concepts of employment for each system, should the Marine Corps decide to adopt an energy storage capability, future research is required to determine to what level the system will be employed. The level of employment will support an enterprise-wide cost estimate.

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF REFERENCES

10 USC 2911. (2024). *Energy policy of the Department of Defense*. https://uscode.house .gov/view .xhtml?req=(title:10%20section: 2911(b)%20edition:prelim)

Ansari, Y. (2022). *Save 40% on generator fuel consumption with Solar. Payperwatt*. https://www.payperwatt.com/post/save-generator-fuel-with-solar#:~:text=If %20the%20generated%20power%20from,and%20increase%20the%20maintenance%20cost.

Boardman, A. E., Greenberg, D. H., & Vining, A. R., & Weimer, D. L. (2018). *Cost-Benefit Analysis*. https://doi.org/10.1017/9781108235594

Bowen, T., Chernyakhovskiy, & I., Denholm, p. (2019). Grid-Scale Battery Storage. *National Renewable Energy Laboratory*. https://www.nrel.gov/docs/ fy19osti/ 74426.pdf

Business Norway. (2024). *BOLT Lifesaver enables offshore remote operations with wave energy*. https://businessnorway.com/solutions/Fred-Olsen-bolt-lifesaver-enables-offshore-remote-operations-with-wave-energy

Carpenter, M. Sullivan, P. & Nussbaum, D. (n.d.). *Operational Energy—Essential Knowledge for Military Officers*. Naval Postgraduate School. https://nps.edu /web/eag/operational-energy-essential-knowledge-for-military-officers

Carter, T. (2022). *Technology for innovative entrepreneurs and businesses. TechLink*. https://techlinkcenter.org/news/technology-readiness-level-dod/

Cheng, J., Tang, Y., & Yu, M. (2019). The reliability of solar energy generating system with inverters in series under common cause failure. *Applied Mathematical Modelling*, 68, 509–522. https://doi.org/10.1016/j.apm.2018.11.03

Cost Estimations – Analysis of cost reduction opportunities in the wave energy industry. (n.d.). https://www.esru.strath.ac.uk/EandE/Web_sites/14-15/Wave_Energy/cost-estimations.html#:~:text=The%20cost%20estimation%20for%20the%20point%20absorber%20device%20is%20obtained,was%20around%201%20million%20USD.

Defense Science Board. (2016). *Task Force on Energy Systems for Forward/Remote Operating Bases*. https://apps.dtic.mil/sti/pdfs/AD1022571.pdf

Department of National Defense, Canada. (2023). *Request for information: Tactical power system (TPS)*.

Diesel Generator Fuel Consumption Guide. (2023). *Blue Diamond*. https://www. bluedm.com.au /blog/diesel-generator-fuel-consumption-guide-/#:~:text=As %20a%20general%20rule %2C%20diesel,for%20your%20power %20requirements %20here.

Eisner, C. (2022). What Is Mean Time Between Failure (MTBF)? *MaintainX*. https://www.getmaintainx.com/learning-center/what-is-mean-time-between-failure/

Elshurafa, A. M. (2020). The value of storage in electricity generation: A qualitative and quantitative review. *Journal of Energy Storage*, 32, 101872. https://doi.org/ 10.1016/ j.est.2020.101872

Erickson, J. (2023). *Tips for extending the lifetime of lithium-ion batteries*. University of Michigan News. https://news.umich.edu/tips-for-extending-the-lifetime-of-lithium-ion-batteries/

ETP clean energy technology guide – Data tools – IEA. (n.d.). IEA. https://www. iea.org/ data-and-statistics/data-tools/etp-clean-energy-technology-guide

Ferguson, S., & Hensly, K. (2018). *Saft's Xcelion 6T 28V lithium ion battery for military vehiclespower sources 2018 digest*. Retrieved from https://www. powersourcesconference .com/Power%20Sources%202018 %20Digest/docs/33-4.pdf

Fu, R., Feldman, D., Margolis, R., Woodhouse, M., & Ardani, K. (2017). *U.S. solar photovoltaic System cost benchmark: Q1 2017*. https://doi.org/10.2172/1395932

Gorsich, D., & Boehman, A. (2020). Driving fuel choices. U.S Army Acquisition Support Center. https://www.dvidshub.net/news/384947/driving-fuel-choices

Guo, B., Wang, T., Jin, S., Duan, S., Yang, K., & Zhao, Y. (2022). A review of Point Absorber Wave Energy Converters. *Journal of Marine Science and Engineering*, 10(10), 1534. https://doi.org/10.3390/jmse10101534

International Energy Agency. (2023). *ETP clean energy technology guide*. https://www.iea.org/data-and-statistics/data-tools/etp-clean-energy-technology-guide

Katalenich, S. M., & Jacobson, M. Z. (2021). Renewable energy and energy storage to offset diesel generators at expeditionary contingency bases. *The Journal of Defense Modeling and Simulation*, 154851292110513. https://doi.org/10.1177/ 15485129211051377

Li, H., Sun, X., & Zhou, H. (2022). Wave Energy: History, implementations, environmental impacts, and economics. *Proceedings of SPIE*. https://doi.org/ 10.1117/12.2646119

Magerl, K. (2023). *How much does solar panel maintenance cost in 2024?* Roof Gnome. https://roofgnome.com/blog/cost/solar-panel-maintenance-price/

Marqusee, J., Ericson, S., & Jenket, D. R. (2020). *Emergency diesel generator reliability and installation energy security*. https://doi.org/10.2172/1659892

Moreau, P. (2022). *A Cost-Effectiveness Analysis of C-12 Variant Airborne ISR Capabilities in the Marine Corps* [Master's thesis, Naval Postgraduate School]

Melo, A., & Jeffrey, H., (2017). Annual Report: An overview of activities in 2017. *Ocean Energy Systems*. https://report2017.ocean-energy-systems.org/documents/OES-Annual-Report-2017/

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

NAZ Solar Electric. (2024). *Sol-Ark 60K-3P-480V pre-wired hybrid inverter system*. https://www.solar-electric.com/sol-ark-sa-60k-3p-480v-n-pre-wired-hybrid-inverter-system.html

Newcomer, K. E. (2015). *Handbook of practical program evaluation* (4th ed.). Jossey-Bass.

Office of the Assistant Secretary of Defense for Sustainment. (n.d.). *Operational energy*. https://www.acq.osd.mil/eie/OE/OE_index.html

Researchers at NREL find fewer failures of PV panels and different degradation modes in systems installed after 2000. (2017). https://www.nrel.gov/news/ program/2017/ failures-pv-panels-degradation.html

Rocha, A. V., Maia, T. a. C., & Filho, B. J. C. (2022). Improving the battery energy storage system performance in peak load shaving applications. *Energies*, 16(1), 382. https://doi.org/10.3390/en16010382

Said, H. A., & Ringwood, J. V. (2021). Grid integration aspects of wave energy—Overview and perspectives. *Iet Renewable Power Generation*, 15(14), 3045–3064. https://doi.org/10.1049/rpg2.12179

Sciencing. (2019). *How to calculate MBH*. https://sciencing.com/calculate-mbh-7484494.html

Siegel, J. E., Weinstein, M. C., Russell, L. B., & Gold, M. R. (1996). Recommendations for reporting cost-effectiveness analyses. Panel on Cost-Effectiveness in Health and Medicine. *JAMA*, 276(16), 1339–1341. https://doi.org/10.1001/ jama.276.16.1339

Sprague, J. (2015). *Optimal scheduling of time-shiftable electric loads in expeditionary power grids* [Master's thesis, Naval Postgraduate School]. https://calhoun.nps.edu/ bitstream/handle/10945/47332/ 15Sep_Sprague_John.pdf?sequence=1&isAllowed=y

Sunwatts. (2024). *12000 watt DC solar inverters*. https://sunwatts.com/12kw-solar-inverters/

Trevizan, R.D., Headley, A.J., & Geer, R. (2021). Integration of energy storage with diesel generation in remote communities. *MRS Energy & Sustainability* 8, 57–74. https://doi.org/10.1557/s43581-021-00013-9

UEC Electronics. (2024). *Ground Renewable Expeditionary Energy Network System (GREENS)*. https://www.uec-electronics.com/design-manufacturing/catalog-pricing/greens-components/

United States Code. (n.d.). Title 10, Section 2911: Energy policy of the Department of Defense. Retrieved from https://www.govinfo.gov/content/pkg/USCODE-2011-title10/html/USCODE-2011-title10-subtitleB-partIV-chap157-sec2911.htm

United States Army Communications-Electronics Research, Development and Engineering Center. (n.d.). *Small tactical electric power* [Presentation slides]. Retrieved from https://arpa-e.energy.gov/sites/default/files/Matthew_ CERDEC_GENSETS_FINAL.pdf

United States Marine Corps Combat Development and Integration. (2023). *Family of mobile power systems concept of employment*.

United States Marine Corps Energy Status Section. (2011). *United State Marine Corps expeditionary energy strategy and implementation plan*. Headquarters Marine Corps. https://www.hqmc.marines.mil/Portals /160/Docs/USMC %20Expeditionary %20Energy%20Strategy%20%20Implementation %20Planning%20Guidance.pdf

United States Marine Corps. (2011). *Generator set, skid mounted 60kW advanced medium mobile power sources (AMMPS)*. Technical Manual No. 09244C/ 09245C-OI.

United States Marine Corps. (2023). *Principal technical characteristics of Marine Corps family of power systems and environmental control equipment*. Technical Manual No. 11300-15/1.

University of Strathclyde. (2024). *Point Absorber – Analysis of cost reduction opportunities in the wave energy industry*. https://www.esru.strath.ac.uk/EandE/ Web_sites/14-15/Wave_Energy/point-absorber.html

Wall, K., & MacKenzie, C. (2015). *Multiple objective decision making*. Defense Resources Management Institute. https://faculty.nps.edu/camacken/docs/ Wall%20and%0MacKenzie%20Multiple%20Objective%20Decision%20Making.pdf

Wave devices: EMEC: European Marine Energy Centre. (2024). https://www.emec.org.uk/marine-energy/wave-devices/#:~:text=A%20point%20absorber %20is%20a,the%20base%20into%20electrical%20power.

Williams, L. (2022). *Adding energy storage to an off-grid generator plant: Is the complexity worth the headache?* Ageto Energy. https://agetoenergy.com/adding-energy-storage-to-an-off-grid-generator-plant-is-the-complexity-worth-the-headache/

Victanis. (2017). *Market review of energy storage systems*. https://www.victanis.com /market-review-of-energy-storage-systems

Xantrex 784–0330 – Inverter Supply. (2024). *Inverter supply*. https://www.inverterspply.com/index.php?main_page=product_info&cPath=41_4005&products_id=202052

Acquisition Research Program
Naval Postgraduate School
555 Dyer Road, Ingersoll Hall
Monterey, CA 93943

www.acquisitionresearch.net