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THESIS

APPLICATIONS AND SUITABILITY OF RENEWABLE AND HYBRID POWER SYSTEMS FOR REMOTE DISTRIBUTED SPECIAL OPERATIONS AND U.S. MARINE CORPS EXPEDITIONARY FORCES IN CONTESTED ENVIRONMENTS

by

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March 2022

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Expeditionary forces are overwhelmingly reliant on diesel generators to sustain mission-critical command, control, communications, computers, combat systems intelligence, surveillance, and reconnaissance (C5ISR) and life support systems on small- to medium-sized tactical power grids. This reliance presents significant logistics and maintenance challenges when employed in support of remote Special Operations Forces (SOF) and Marine Corps expeditionary operations in contested environments. The primary objective of the research is to measure the effectiveness of current or near- to- market energy storage and photovoltaic (PV) charging solutions to augment or replace diesel fuel power generators in support of expeditionary military operations. The secondary objective is to measure the impact of running these energy storage and charging solutions in tandem with diesel fuel generators on a unit's fuel consumption, particularly the effect on existing fuel resupply schedules. This research concludes that existing and near-to-market renewable energy systems can effectively integrate with tactical diesel generators and produce enough energy to meet a substantial portion of the energy required in support of expeditionary operations in remote locations.

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ABSTRACT

Expeditionary forces are overwhelmingly reliant on diesel generators to sustain mission-critical command, control, communications, computers, combat systems intelligence, surveillance, and reconnaissance (C5ISR) and life support systems on small- to medium-sized tactical power grids. This reliance presents significant logistics and maintenance challenges when employed in support of remote Special Operations Forces (SOF) and Marine Corps expeditionary operations in contested environments. The primary objective of the research is to measure the effectiveness of current or near-to-market energy storage and photovoltaic (PV) charging solutions to augment or replace diesel fuel power generators in support of expeditionary military operations. The secondary objective is to measure the impact of running these energy storage and charging solutions in tandem with diesel fuel generators on a unit's fuel consumption, particularly the effect on existing fuel resupply schedules. This research concludes that existing and near-to-market renewable energy systems can effectively integrate with tactical diesel generators and produce enough energy to meet a substantial portion of the energy required in support of expeditionary operations in remote locations.

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LIST OF ACRONYMS AND ABBREVIATIONS

1MPG	One Man Portable Generator
A	ampere
ac	alternating current
Ah	ampere-hour
AISPCA	Advanced Integrated Solar Panel Case Assemblies
AFIT	Air Force Institute of Technology
AUPEC	Australasian Universities Power Engineering Conference
BN	battalion
C	Celsius
C2	command and control
C5ISR	command, control, communications, computers, combat systems intelligence, surveillance, and reconnaissance
CLS	contractor logistics support
CMC	Commandant of the Marine Corps
CNO	Chief of Naval Operations
COC	combat operations center
COLS	concept of logistics support
CONUS	continental United States
COOP	continuity of operations
COTS	commercial-off-the-shelf
CPSS	China Power Supply Society
CSG	carrier strike group
dc	direct current
DNI	direct normal irradiance
DOD	Department of Defense
DOE	Department of Energy

DOTMLPF-P	doctrine, organization, training, materiel, leadership and education, personnel, facilities, and policy
ECCE	Energy Conversion Congress and Exposition
ExFOB	experimental forward operating base
°F	Fahrenheit
FOB	forward operating base
ft.	feet
GFE	government-furnished equipment
GHI	global horizontal irradiance
GOTS	government-off-the-shelf
GPS	Global Positioning System
GREENS	ground renewable expeditionary energy network system
h.	hour
HEDB	high energy density battery
HEDBS	high energy density battery system
HOMER	Hybrid Optimization Model for Electric Renewables
HQMC	Headquarters, United States Marine Corps
HZ	Hertz
ICIT	International Conference on Industrial Technology
IEEE	Institute of Electric and Electronics Engineering
in.	inch
Inc.	Incorporated
IQR	intra-quartile range
JCS	Joint Chiefs of Staff
JP8	jet propulsion fuel, type 8
JTF	joint task force
JWICS	Joint Worldwide Intelligence Communications System
kW	kilowatt

kWh	kilowatt-hour
L	liter
LAN	local area network
LCE	logistics combat element
LCD	liquid-crystal display
LED	light-emitting diode
LiFePO4	lithium iron phosphate
LLC	limited liability company
LRT	logistics response time
LSA	logistics support analysis
LSSS	logistics support, supplies, and services
LSV	logistics support vessel
M	million
m.	meter
MAGTF	Marine air-ground task force
MARSOC	Marine Special Operations Command
MCSC	Marine Corps Systems Command
MCWL	Marine Corps Warfighting Laboratory
MEF	Marine expeditionary force
MEHPS	mobile electric hybrid power sources
METOC	meteorological and oceanographic
MEU	Marine expeditionary unit
MCDM	multi-criteria decision-making
mi.	mile
MLG	Marine logistics group
MPPT	maximum power point tracking
MRR	Marine Raider Regiment
MSOC	Marine special operations company

MSOR	Marine special operations regiment
MSOT	Marine special operations team
NASA	National Aeronautics and Space Administration
NATO	North Atlantic Treaty Organization
NDS	National Defense Strategy
NIPRNET	Non-classified Internet Protocol Router Network
NM	nautical mile
NOAA	National Oceanic and Atmospheric Administration
NPS	Naval Postgraduate School
NSN	national stock number
NSW	naval special warfare
OBFS	offshore bulk fuel system
OEM	original equipment manufacturer
OPA	output paralleling adapter
OPNAV	Office of the Chief of Naval Operations
ORM	operational risk management
O&M	operation and maintenance
PD21	Education Consortium for Leadership in Product Development in the 21st Century
PDK	power distribution kit
PDU	power distribution unit
PLT	platoon
POWER	Prediction of Worldwide Energy Resources Project
PV	photovoltaic
QP	Quiet Power
QUADCON	quadruple container
R&D	research and development
SCRM	supply chain risk management

SAPS	small autonomous power systems
SATCOM	satellite communications
SDN	Satellite Deployable Node
SEAL	sea air land
SEM-	systems engineering management
SIF	Stand-in Forces
SIPRNET	SECRET Internet Protocol Router Network
SOF	special operations forces
TOC	tactical operations center
TSCIF	temporary sensitive compartmented information facility
UAS	unmanned aircraft system
UL	Underwriters Laboratories
U.S.	United States
USMC	United States Marine Corps
USN	United States Navy
USON	universal statement of need
USSOCOM	United States Special Operations Command
V	volt
VDC	volts direct current
W	watt

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EXECUTIVE SUMMARY

Meeting the energy requirements necessary to sustain complex long-haul communication networks, tactical radios, command, control, communications, computers, combat systems intelligence, surveillance, reconnaissance (C5ISR), and life support systems presents a unique challenge when facing sustained strategic competition in contested and gray zone environments. The cost of operating diesel fuel powered tactical generators that support these systems, coupled with the extensive logistics infrastructure necessary to maintain them, is substantial. Since 2009, the United States (U.S.) Department of Defense (DOD) has been pursuing renewable energy options to establish energy security on the battlefield. This effort was primarily driven by the fiscal and human cost of fueling operations in Iraq and Afghanistan from 2001 to 2021, where the fully burdened rate of fuel cost between $15–$42 (Solis 2009) per gallon and casualties were incurred at a rate one per 24 fuel convoys (Wald 2009, 19). As the National Security Strategy (NSS) shifts from counter insurgency in Southwest Asia to sustained strategic competition in the South Pacific and Eastern Europe, robust logistics pipelines may not be readily available, and force survivability will be based upon the ability to achieve logistic sustainability inside contested areas. (Commandant of the Marine Corps 2021). In order to achieve energy security while conducting operations in these environments, renewable energy sources will need to be leveraged.

This research aims to examine whether photovoltaic (PV) lithium-ion energy solutions deployed in a hybrid configuration will significantly extend the operating capacity of prepositioned fuel supplies that power conventional diesel generators; and ultimately, whether such a system can sustain operations independently via PV solar charging solutions in remote locations. While there has been limited focus on increasing energy efficiency and employing renewable energy resources at the tactical squad, platoon, and company level, the majority of DOD’s energy conservation initiatives have impacted large-scale garrison infrastructure. The primary objective of the research is to measure the effectiveness of current or near-to-market COTS/GOTS energy storage and PV charging solutions to augment or replace diesel fuel power generators in support of expeditionary

military operations. The secondary objective is to measure the impact of running the COTS/GOTS energy storage and charging solutions in tandem with diesel fuel generators on a unit's fuel consumption, particularly the effect on existing fuel resupply schedules. The trade-off between the upfront systems acquisition cost and life cycle operating cost savings is also discussed.

A review of the existing research and literature to support this thesis demonstrated that most of the existing body of work is focused on large-scale implementations of renewable energy systems to power remote villages or large garrison and expeditionary military installations. The review also identifies relevant operational after-action reports detailing equipment strings, energy demands, generator power output, and fuel consumption rates for platoon to company sized elements. Additional resources selected were related to the Hybrid Optimization Model for Electric Renewables (HOMER) program utilized to perform modeling and simulation of COTS/GOTS renewable energy solutions and technical documentation for fielded, near-to-market, and notional COTS/GOTS energy solutions.

An engineering evaluation consisting of four energy production configurations was conducted against two force compositions to address the primary and secondary objectives. configuration A consisted of traditional tactical generators, configuration B is Ground Renewable Expeditionary Energy Network System (GREENS), which is currently fielded as a USMC program of record, configuration C is the Mobile Electric Hybrid Power Sources (MEHPS) which is in the acquisition process, and configuration D is a COTS system consisting of generic PV collection panels and Tesla Powerpacks. The force compositions were a SOF Team sized element (Force 1) with energy requirements defined by the TOC equipment string and a USMC Company sized element (Force 2) with energy requirements based on a COC equipment string. Each energy production configuration was modeled in HOMER and analyzed against the power demands created by the two force compositions. In addition to analyzing power demand inputs based on system specifications, HOMER also factors in environmental variables based on location, seasons, and historical solar irradiance data to forecast renewable energy production.

An analysis of results from the evaluation revealed that neither configuration B nor configuration C could produce enough energy to effectively meet 100% of the power demands of Force1 or Force 2. However, both systems generated enough power in a hybrid configuration with tactical generators to substantially reduce the fuel burn rate and extend the logistics resupply window. configuration B produces 30% of the energy required by Force 1 and extends the fuel resupply window from 10 days to 29 days, assuming 200 gallons of prepositioned fuel stores. While configuration B only produces 9% of the power required by Force 2, that translates to a 128-day fuel resupply window assuming 3000 gallons of prepositioned fuel stores. Configuration C was only able to be evaluated against Force 1 due to insufficient generator options as the system is currently designed. Configuration C features enhanced battery storage and an automated hybrid management system that simultaneously provides generator power to the TOC and charges depleted batteries with the excess generator capacity. As a result, configuration C generates 52.6% of the power required by Force 1 and extends the fuel resupply window to 55 days. Configuration D provided 100% of the power required by Force 1, eliminating the need for fuel resupply and requiring minimal backup generator infrastructure and prepositioned fuel. Although the power requirements of the Force 2 COC equipment exceed the capacity of the COTS solution, the renewable energy penetration in this scenario is considerable at 56%, extending the fuel re-supply window to 270 days.

This research concludes that existing and near-to-market COTS/GOTS renewable energy systems can effectively integrate with tactical diesel generators and produce enough energy to meet a substantial portion of the energy required in support of expeditionary operations. The impacts regarding fuel consumption evidence that even nominal renewable penetration of 9% can extend the fuel resupply window by 56%. Each of the renewable energy systems evaluated in this thesis could be scaled to better fit specific requirements from the SOF Team to USMC Company sized force disposition. Additional investments in batter research, PV materials, and energy management software are recommended to increase the impacts of renewable energy systems designed to support expeditionary operations.

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I. INTRODUCTION

As the United States (U.S.) National Security Strategy (NSS) pivots to address shifting global dynamics and the ever-increasing pacing threats from more assertive strategic competitors, there is an increasing need for distributed operations in contested and gray zone environments in support of a national integrated deterrence strategy. The nation will undoubtedly call upon U.S. Marine Corps (USMC) and U.S. Special Operations Command (USSOCOM) expeditionary forces to conduct distributed operations "to disrupt an adversary's plans at every point on the competition continuum."(Commandant of the Marine Corps 2021, 1) These distributed expeditionary forces will require more complex logistics sustainment and support through areas that will become increasingly challenged and contested.

According to a July 2019 report to Congress, the federal government is the largest single energy consumer, with the Department of Defense (DOD) accounting for over 76% of that energy consumption (Greenley 2019, 1). In fiscal year (FY) 2017, the DOD spent over $11.9 billion, or 2% of the DOD's total budget for energy. The DOD energy policy is "to enhance military capability, improve energy security and resilience, and mitigate costs in its use and management of energy" (Department of Defense 2018, 1). To accomplish this, the DOD aims to "diversify and expand energy supplies and sources, including renewable energy sources and alternative fuels" (2018, 2).

The cost of operating and maintaining diesel fuel power generators to provide operational energy to expeditionary armed forces, coupled with the logistics infrastructure necessary to reliably deliver fuel resupplies, may put distributed U.S. forces at a strategic disadvantage. As a recent example of the logistics challenges of resupplying fuel to meet the DOD's operational energy needs, during the conflicts in Iraq and Afghanistan, the fully burdened cost of fuel ranged from $15 to $42 per gallon, costing between $2.25 and $4.5 million per day to support fueling operations (Solis 2009).

This thesis analyzes the feasibility of employing high-density lithium-ion battery banks to complement or replace traditional diesel fuel generators to meet the operational energy requirements of remote expeditionary forces. This research aims to examine whether photovoltaic (PV) lithium-ion energy solutions deployed in a hybrid configuration will significantly extend the operating capacity of prepositioned fuel supplies that power conventional diesel generators; and ultimately, whether such a system can sustain operations independently via PV solar charging solutions in remote locations. This chapter will discuss the background, research objective(s), methodology, impact, and limitations of this research effort.

A. BACKGROUND

Acquiring and delivering diesel fuel to power mission-critical command, control, communications, computers, combat systems intelligence, surveillance, and reconnaissance (C5ISR) as well as essential life support systems at remote out stations over the past twenty years during the Global War on Terror; specifically for Operation Enduring Freedom, Operation Iraqi Freedom, and Operation Inherent Resolve; has proven to be a challenging and an expensive endeavor for the DOD, the USMC, and the U.S. Navy (USN). Further, USSOCOM special operations forces (SOF) and USMC expeditionary operations require reliable sources of electrical energy to operate Combat Operations Centers (COC)/Tactical Operations Centers (TOC), communications systems, sensor platforms, weapon systems, and other mission-essential life support systems. Sources of energy range from tactical diesel fuel power generators, PV solar arrays coupled with battery storage systems, and occasionally commercial infrastructure. As integrated USN and USMC operations shift from counterinsurgency operations in Southwest Asia to great powers competition on remote island chains in the South Pacific, robust logistics pipelines cannot be assumed to be available. Energy security to conduct combat operations in resource-constrained environments will need to be achieved by utilizing renewable energy sources integrated with existing fossil fuel power generation infrastructure.

The authors have witnessed firsthand how challenging and expensive America's war on terror has proven to be for the DOD over the past 20 years. We formed our perspectives while conducting combat deployments to Iraq, Afghanistan, Somalia, and Syria, where in addition to the financial burdens, there were human costs as well in the form of fuel convoy casualties. According to General Wald's report, *Energy Security—America's Best Defense*, fuel convoy casualties in Afghanistan occurred at a rate of .0042, meaning that a person was killed or injured approximately every 24 convoys (Wald and Captain 2010). "These casualties highlight how energy-particularly fuel and batteries transported via convoy-can be a critical vulnerability," which will only increase as the DOD's demand for energy continues to increase (Pollman 2013, 70). Energy security will continue to become an increasingly pressing concern, as well as a priority for the DOD, due to the emerging great powers competition, combined with the rapid improvements in the fields of renewable energy generation and storage technologies.

The current global security reality is such that, "The distribution of power across the world is changing [and] creating new threats." President Biden expounded further on this statement from his March 2021 *Interim National Security Strategic Guidance* stating in part,

> China, in particular, has become more assertive. It is the only competitor potentially capable of combining its economic, diplomat, military, and technological power to mount a sustained challenge to a stable and open international system. (The White House 2021, 8)

Additionally, President Biden emphasized that "Russia remains determined to enhance its global influence and play a disruptive role on the world stage" (The White House 2021, 8). The president expounded further by stating, "Both Beijing and Moscow have invested heavily in efforts meant to check U.S. strengths and prevent us from defending our interests and allies around the world." (The White House 2021, 8). This is unfolding with "gray zone" actions by China in the Pacific and by Russia across Central Asia and Eastern Europe. Additionally, both China and Russia are also making bold moves in the Arctic region as well. President Biden's Interim National Security Strategy guidance is that the U.S. will "develop capabilities to better compete and deter [these] gray zone actions," while also "prioritize [ing] defense investments in climate resiliency and clean energy" (The White House 2021, 14).

While impeding the interests of the U.S. and partner nations, these adversaries will look to exploit U.S. logistics supply chains to limit operational capabilities. The ability to forward deploy U.S. Marine Corps Littoral Regiments, Marine Expeditionary Units (MEUs), and SOF teams on remote islands in the Pacific is part of the DOD's underlying strategy to counter Chinese aggression in the region. Unlike forces potentially deployed in Eastern Europe, these units will not have the luxury of leveraging an established power grid infrastructure or extensive established supply lines to sustain their warfighting effort. Specifically, diesel fuel, which is required to maintain generator power to essential life support, and critical C5ISR systems, cannot be reliably delivered to these covert outposts, and regular supply drops could eventually compromise their positions and missions. This research assesses the energy requirements for USMC and USSOCOM expeditionary forces and measures whether lithium-ion battery packs charged primarily via PV solar arrays can meet the energy needs of these units in either a hybrid or standalone mode.

As early as 2009, when operations in Iraq started to draw down and the U.S. military primary effort shifted back to Afghanistan, commanders realized the emerging requirements for and gained an appreciation of renewable energy solutions. Both the Chief of Naval Operations (CNO) and Commandant of the Marine Corps (CMC) began aggressively adopting policies to reduce reliance on fossil fuels. These service chief led renewable energy initiatives have continued to grow and mature during the past 12 years, resulting in significant improvements in each services' energy independence. The majority of these efforts are centered around administrative garrison and base operations, including deriving 50% of energy needs from renewable sources, the reduction of petroleum use in non-tactical vehicles by 50%, and the demonstration of a "green strike group" (Schwartz, Blakeley, and O'Rourke 2012, 18). While limited efforts have propagated down to the operational and tactical level, such as solar charging for tactical radio batteries and replacing fluorescent lights with more energy-efficient light-emitting diodes (LEDs), the focus has been predominantly on administrative garrison bases in the continental united states (CONUS) and higher echelon operational units.

This research aims to aggregate these proven DOD best practices and scale them to provide the tactical company, platoon, squad, or team-level units with operational stand-alone renewable energy sources that meet President Biden's prioritization on defense investments in climate resiliency and clean energy. (The White House 2021, 14) The following questions anchor this research:

1. To what extent is it possible for PV solar arrays and commercial-off-the-shelf (COTS) lithium-ion batteries to replace diesel fuel power generators in remote and austere operating environments as a primary operational energy source?
2. How much of a tactical advantage can renewable energy systems provide by reducing the frequency of complex fuel resupply operations to support diesel fuel power generators?
3. When considering the total life cycle and operational costs, in which categories are the renewable energy alternatives more affordable?
4. Are currently available and near-to-market commercial COTS and government-off-the-shelf (GOTS) solutions sufficiently scalable and customizable to meet the operational energy requirements of deployed team to company-sized elements?

Concerning these questions, this research assesses the current operating requirements of USMC expeditionary forces and USSOCOM SOF teams at the company level and below. Additionally, both stand-alone and hybrid PV storage and diesel fuel generator solutions are modeled and evaluated based on potential operational deployments to remote islands in the South Pacific.

B. RESEARCH OBJECTIVE

The primary objective of this research is to measure the effectiveness of current or near to market COTS/GOTS energy storage and PV charging solutions to augment or replace diesel fuel power generators in support of expeditionary military operations. The authors accomplish this objective by assessing the current energy requirements of team to company-sized elements and measuring the ability of renewable energy systems to meet the operational electrical energy demand of those units. The stand-alone and hybrid COTS/

GOTS energy storage and charging solutions are modeled and simulated in the hybrid optimization model for electric renewables (HOMER) program.

The secondary objective of this research is to measure the impact of running the COTS energy storage and charging solutions in tandem with diesel fuel generators; specifically, how much longer could prepositioned fuel stores support remote operations when augmented by renewable energy solutions? While not an objective, cost-effectiveness for system acquisition and operating cost is a viable consideration when pursuing new technology. The total system operating costs for the renewable systems being analyzed in this thesis will be measured against the baseline total systems operation costs of tactical generators.

C. SCOPE

This research is limited to existing or near-market PV power generation systems, accompanied by lithium-ion energy storage solutions. While there are several current and emerging global conflict areas, including the Arctic region, Eastern Europe, the Horn of Africa, and the Middle East, the analysis in this thesis focuses on systems hypothetically deployed to remote islands in the South Pacific. In addition to power distribution capacity, cost, maintenance, usability, and survivability are also examined. This thesis remains vendor-agnostic; however, existing capabilities are derived and modeled in HOMER utilizing specifications of current and upcoming products from UEC Electronics limited liability company (LLC), Cummins Incorporated (Inc.), and Tesla Inc.

D. STRUCTURE

This thesis consists of five chapters; Chapter II covers literature review and is broken into sections that cover previous master’s theses and doctoral dissertations, followed by a second section which covers professional and academic peer-reviewed articles, professional and academic conference proceedings, reports, books, and academic presentations. These resources include, but are not limited to, initiatives pursued by the Marine Corps Expeditionary Energy Office (EEO), DOD units use of renewable energy at Forward Operating Bases (FOBs), data collected to build the energy profiles for squad to company-sized elements, and prior research utilizing HOMER to model energy use in expeditionary environments. Additionally, other sources pertinent to PV storage in remote environments and expeditionary energy requirements, including the existing U.S. Marine Corps programs of record (PoR) for remote renewable energy, are discussed in Chapter II. Chapter III is devoted to the methodology this thesis utilized, including how the models were configured in HOMER and the chosen course of action rationale. The methodology chapter also details how the research and modeling in this thesis differentiate from previous research. Chapter IV analyzes modeling results conducted in the methodology phase and confirms which areas of the proposed stand-alone systems worked and which areas fell short of the requirements identified in earlier chapters. Our conclusions are summarized, and our recommendations are discussed as the thesis wraps up in Chapter V. These findings cover what the team learned, how the knowledge gained stacked up to expectations, and identify knowledge gaps that still need to be researched. Additionally, the recommendations explore new energy storage technologies and devices that could augment the existing research.

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II. LITERATURE REVIEW

This chapter presents the literature review of the work that guided our team's research. The literature review first identifies the work and findings of other researchers in the field of renewable energy systems and renewable energy microgrids both in remote and non-remote environments.

We reviewed interdisciplinary works ranging from master's thesis, doctoral dissertations, professional and academic peer-reviewed articles, as well as professional and academic conference proceedings and reports, books, and academic presentations. We also reviewed several applicable military and government documents, policies, and after-action reports.

Additionally, in this literature review, we define and then decompose the existing military expeditionary renewable energy systems and introduce the COTS energy solutions that we use for the research of this thesis.

A. THESES; DISSERTATIONS; AND PEER-REVIEWED ARTICLES, PAPERS, AND REPORTS

1. HOMER Use Cases for Modeling and Optimizing Systems

As the authors began our research into how to leverage renewable energy systems for military use, we discovered many sources directed us to an early work on this subject conducted in the first decade of the global war on terror, specifically during the height of the operational surge in Afghanistan in 2009. That work was Naval Postgraduate School Electrical Engineering graduate Brandon H. Newell's September 2010 master's thesis that evaluates HOMER as a pre-deployment tool for the U.S. Marine Corps (Newell 2010). Newell's work was groundbreaking in identifying early the U.S. Marine Corps' need to investigate renewable energy solutions for the warfighter. His work evaluates the suitability of HOMER's modeling capabilities for U.S. Marine Corps use. He did this by using two unique month-long experiments to create testable HOMER models to verify their accuracy. Newell argues that his findings show that the U.S. Marine Corps' Experimental Forward Operating Base (ExFOB) program would have benefited from using the HOMER modeling system (2010). Newell's early work in this field has been a starting point for numerous researchers exploring HOMER optimization for military use. Newell's work also served as our introduction to the HOMER software and as our starting point for research.

Building further upon the HOMER body of knowledge is Matthew M. Morse's June 2014 master's thesis that assesses the suitability and operational robustness of HOMER modeling for use by the U.S. Marine Corps (Morse 2014). Morse analyzes and ultimately validates how HOMER micropower optimization models and simulation may provide the U.S. Marine Corps with a robust planning tool that has operational potential to improve energy planning and achieve greater efficiencies in expeditionary operations (Morse 2014). Morse's work was additional evidence to us that HOMER was the best option for us to use for our system modeling.

One example of the use of the HOMER software for commercial purposes is University of Strathclyde Sustainable Engineering graduate Lewis Breen's work on modeling and optimizing civilian renewable networks in remote locations. His work examines the renewable centric microgrid of the Isle of Eigg, "a small non-grid connected island on the West coast of Scotland" (2015, 13). He models the Isle of Eigg's microgrid using the HOMER system and analyzes how to optimize the microgrid for maximum "renewable penetration"(2015, 13). In the Isle of Eigg case, Breen determined that for maximum renewable penetration, there is both a need for mixed sources of renewable energy generation as well as a need for increased energy storage capacity. Breen's work demonstrated to us the versatility of the HOMER software, its applicability to remote civilian microgrid modeling, and potential applicability for our military-focused work in this thesis.

Adding to the HOMER software modeling body of knowledge, is the work presented at the October 2016 *IEEE Electrical Power and Energy Conference (EPEC)*, that is a case study of a remote water pumping station in the Australian outback that historically used two diesel generators for power. The authors used HOMER modeling and simulation to compare the original diesel-only power generation system to a combined diesel and solar system and then to a combined diesel, solar, and battery storage system.

Their findings show "that renewable energy can be a viable alternative for remote area power applications if effective engineering analysis is performed" (Markovic, Nedic, and Nafalski 2016, 5). Their demonstration of the viability of renewable energy systems validated that we should further investigate the suitability of renewable energy systems to meet the power requirements of operationally deployed teams to company-sized elements. Additionally, the use of HOMER in their research validated HOMER to us as the best choice software tool for our work.

A final use case for the HOMER software Christopher J. Peterson's (2019) work on systems architecture design for DOD microgrid systems, which developed a new system engineering metrics analysis methodology for the "design, verification, and validation of microgrids for resiliency objectives." Peterson argues that his methodology, which he terms "expected life cycle mission impact (ELMI)," enables the DOD to use microgrids to increase power distribution resiliency. He also details HOMER and 12 additional modeling software programs used in this field of work (2019, 13). Peterson's work in comparing HOMER to the 12 other systems helped us decide that HOMER was indeed the appropriate software modeling tool for us to use for the systems in this thesis.

An example of a use case for one of these other modeling and optimization software program tools was Kyle D. Kobold's December 2017 work with green microgrids on remote U.S. Navy locations. Instead of using HOMER, he uses the EnergyPLAN software tool to create multifactor optimization models that he recommends the U.S. Navy use to manage microgrid power systems more efficiently in remote areas. Kobold's work demonstrates how an alternative modeling software to HOMER is used to optimize USN microgrids on remote islands. We evaluated Kobold's work, but we decided that the HOMER software tool was the best choice for our research.

2. Energy Modeling and Optimization Research Approaches Designed for DOD Use

Several authors have contributed to the body of knowledge but have approached the question of how to optimize DOD's energy use in ways that differ from our approach. Colorado State University's Nathan C. McCaskey's (2010) work simulating and optimizing renewable energy systems on FOBs quantifies "the impact of installing renewable energy sources on the fuel consumption, supply-line casualty rate, and operating cost of a U.S. (FOB) using computer simulations." His work uses simulation and modeling tools, different from HOMER, to "aid in site-specific planning for installing renewable energy systems" which he applied to hypothetical case studies for much larger scale U.S. Air Force FOBs in Afghanistan(2010, 41). McCaskey's models show that his proposed large-scale FOB systems will "reduce fuel consumption by 17%, supply-line casualties by 15%, and yearly operating costs by $5.5 million" (2010, 41). Additionally, his research demonstrates the correlation between fuel consumption rates, operating costs, and casualty rates in combat zones.

In their peer-reviewed article published in the March 2019 edition of *Marine Corps Gazette*, David J. Chester, Torrey J. Wagner, and Douglas S. Dudis examined the optimal combination of power generation and energy storage technology into a proof-of-concept for Marne Corps FOBs. Their work shows that they can reduce current fuel use on a FOB by 36 percent and reduce the capital costs of the energy system by 24 percent (Chester, Wagner, and Dudis 2019, 49). The authors further demonstrate that the benefits of this fuel use reduction decrease fuel requirements at outlying FOBs not only saves money but also reduces resupply convoys and "time spent outside the wire by servicemembers," which ultimately saves lives (2019, 51). Their work validated and motivated our primary research question for this thesis. Specifically, on the feasibility of employing high-density lithium-ion battery banks to complement or replace traditional diesel fuel power generators to meet the operational energy requirements of remote expeditionary forces.

It is important to note in our work how U.S. forces can not only implement supply-side decreases in fuel use, but they could also implement energy use conservation best practices that will reduce the demand-side of operational energy. The Commandant of the U.S. Marine Corps, General David H. Berger has called for the development of new capabilities that will reduce demand "across the life-cycle of stand-in forces, from their design to their employment" (2021, 21). Craparo, Karatas,and Sprague's October 2017 paper modeled military expeditionary systems, specifically battlefield heating and cooling systems, to analyze the performance of existing systems and to identify potential savings through optimized coordinated management. Their work quantitatively demonstrates that they can increase hybrid smart microgrid power production efficiency by using both supply-side and demand-side optimized management.

Nicholas A. Ulmer (2014) uses historical solar and wind data to create planning models that optimize the microgrid architecture of much larger-scale permanent DOD installations to select the best potential energy sources to maximize microgrid power resiliency. He uses sensitivity analysis to quantitatively show that increases in capital investment will increase microgrid resiliency. He further demonstrates that increases in reliance on renewable energy decrease sensitivity to fuel costs (2014, 65). Ulmer's work encouraged us to examine whether our modeled system configurations could meet the General Berger's challenge "to achieve logistics sustainability inside a contested area" for small operational units forward (Commandant of the Marine Corps 2021, 21).

Researchers from other fields have contributed to the overall body of knowledge in energy modeling and optimization research designed for DOD use. Taking an applied mathematical approach, Kevin E Garcia's work develops two of his own mixed-integer linear programs to optimize microgrid operations at remote military base camps. These mixed-integer linear programs minimize microgrid "total cost of electricity production" and minimize microgrid fuel consumption "through the scheduling of generators, energy storage systems, and alternative energy production" (Garcia 2017, 51). He ultimately found that a photovoltaic solar array "produced significant fuel savings" when used in a microgrid. Garcia's work demonstrates mathematically both the feasibility of using a hybrid system for our research and that a hybrid system with storage capacity could be much more efficient. Conversely, Charles Y. Hirsch's (2020) work examines how a "physics-based model of a three-phase microgrid set up with three commercial-off-the-shelf (COTS) inverters and a battery bank" conforms to IEEE standard 519 and establishes that it is suitable for further studies into microgrid employment in support of DOD renewable energy efforts. Hirsch's work inspired us to investigate potential COTS solutions to meet the needs of our system requirements.

In "Auto-Tuning for Military Microgrids" presented by Thomas Podlesak and his team at the September 2019 IEEE Energy Conversion Congress and Exposition (ECCE), the authors established that "microgrids for tactical military applications present unique challenges." The military most commonly uses diesel generator sizes of 30kW and 60kW to meet the intermittent tactical intermittent power needs. The authors articulated their plans for an automated system to analyze power load changes and adjust multiple generators' responses. (Podlesak et al. 2019). This work helped form our arguments for optimizing our energy systems to meet the intermittent tactical power needs of the U.S. Marine Corps and USSOCOM SOF teams in the scope of our work.

The most recent work we reviewed that focuses on remote military energy solutions is Air Force Institute of Technology's Nathan J. Thomsen's (2020) thesis that uses case studies to examine the ways for DOD solar renewable energy systems, optimized for the practical logistics concerns of each case, could replace traditional diesel generators at remote and isolated DOD locations. Thomsen's work focused on creating an innovative renewable energy system optimization model to determine optimal solar array and energy storage sizes by developing "logistics-based multi-objective optimization models" that minimize the logistics variables, specifically system weight, volume, and the land area of renewable systems, while using multi-objective optimization methods for planning, designing, and selecting these systems. Like many of the other works in this body of knowledge, Thomsen examined renewable energy systems that are much larger than the needs of the U.S. Marine Corps and USSOCOM SOTF Team's covered in our research.

3. Energy Optimization in Civilian Applications

Small-scale energy generation is gaining an ever-increasing share of the global energy market. This is providing more of the world's population with access to energy and the societal improvements that come along with this access. In their work published in the May 2016 issue of *Renewable and Sustainable Energy Reviews*, Stefano Mandelli, Jacopo Barbieri, Riccardo Mereu, and Emanuela Colombo conducted a comprehensive analytical review of the literature in over 350 publications that address rural off-grid energy systems between the years 2000 and 2014. (Mandelli et al. 2016). Their work compiling, defining, and classifying the greater body of work in this field was important for us in gaining an understanding of the uses and best practices for currently available off-grid energy systems.

With the focus of their work on rural off-grid systems, these best practices are directly transferable to future remote military operational energy systems. In their work published in the July 2018 issue of *Renewable and Sustainable Energy Reviews*, Adam Hirsch, Yael Parag, and Josep Guerrero define what constitutes a microgrid and then characterize and classify its numerous forms and real-world applications and discuss their challenges. The authors argue that microgrids are best poised to manage the energy challenges of the future "by balancing supply and demand locally while ensuring reliability and resilience against what appear to be escalating natural and man-made disturbances" (Hirsch, Parag, and Guerrero 2018, 409). Although our ultimate objective is to examine microgrids that will provide DOD units operational energy at remote locations, their work validated to us that locally managed microgrids are best suited for the increased reliability and resiliency required by our deployed forces.

Further advocating for the benefits that remote microgrids will provide in the future, Alireza Askarsadeh's article published in the March 2017 edition of *Energy* argues that hybrid photovoltaic-diesel power generation systems are best suited for stand-alone remote areas. The author focuses on determining the optimal sizing of hybrid photovoltaic-diesel systems to best balance both power sources as to reduce system costs and "pollutant emissions." Asharsadeh's work validated our investigation of hybrid PV systems for our research. Additionally, although we did not pursue the environmental factors, this research highlights the added benefits of reducing pollutant emissions.

There has been significant international research into how to optimally size and configure remote microgrids. A recent work by Mohammed A. Abdulgalil, Mohamad N. Khater, Muhammad Khalid, and Fahad Alisamail's presented at the February 2018 *IEEE International Conference on Industrial Technology (ICIT)* demonstrates "how to optimally size an energy storage system for a specific microgrid and a specific interval" (Abdulgalil et al. 2018, 1307). This work forced us to consider the scope of our work and helped us determine that we wanted to focus specifically on the optimally sized operational energy requirements of U.S. Marine Corps expeditionary forces and USSOCOM SOF teams at the company level and below.

Additionally, Farazam Nejabatkhah, Yen Wei Li, Alexandre B. Nassif, and Taeho Kang's March 2018 China Power Supply Society (CPSS) Transactions on Power Electronics and Applications article shows that Chinese researchers are considering how "high operational costs, environmental concerns, and fuel handling challenges in diesel-based off-grid systems have prompted the application of alternative sources of energy and energy storage systems"(Nejabatkhah et al. 2018, 3). These researchers lay out a large-scale design for an isolated hybrid photovoltaic power generation system with battery energy storage that supplements an existing diesel power generation system and demonstrates "both cost-saving and power quality improvement" with an optimized design that seeks to minimize annual system costs and minimize total system power loss (Nejabatkhah et al. 2018, 3). As we examine similar operational costs and fuel handling challenges of the current DOD diesel-based microgrid systems, we wanted to see if we could find the same cost-saving and power quality improvements in our optimized systems that these Chinese researchers found.

Shervin Mizani and Amirnaser Yazdani, in their work presented to the 2009 Annual Conference of the Institute of Electrical and Electronics Engineers, demonstrate that "the incorporation of optimally-rated energy storage units and renewable generators into a remote microgrid, in conjunction with an optimal dispatching strategy, can result in a substantial reduction in the microgrid lifetime cost and emission" (Mizani and Yazdani 2009, 4299). The authors presented a mathematical model and optimization algorithm they used to demonstrate the optimal microgrid configuration and dispatching of generators in a remote community in Northern Ontario, Canada (2009). There are similarities of these isolated civilian microgrids to what we wanted to study in that DOD microgrids must be resilient. Mariam Ibrahim and Asma Alkhraibat establish that "measuring resiliency of smart grid systems is one of the vital topics toward maintaining a reliable and efficient operation under attacks" (Ibrahim and Alkhraibat 2020, 1). The resiliency of remote military microgrids, as well as the resiliency of the logistics supporting them, are crucial to our design considerations. Furthermore, although we did not study it in this thesis, we recommend further study into the resiliency needs of operational energy microgrids in remote military outposts in differing climates such as the Arctic and far north.

Building on this idea, R.K. Akikur, R. Saidur, H.W. Ping, and K.R. Ullah's work published in the November 2013 issue of *Renewable and Sustainable Energy Reviews*, uses comparative case studies to demonstrate that geography will ultimately determine whether stand-alone or hybrid (PV) technology is the most optimal energy system for a given location (Akikur et al. 2013). This argument made by the authors is central to the arguments in our thesis as we examine both the specific climate characteristics and the energy requirements of remote FOBs in the South Pacific.

B. EXPEDITIONARY ENERGY SYSTEMS

1. Ground Renewable Expeditionary Energy Network System (GREENS)

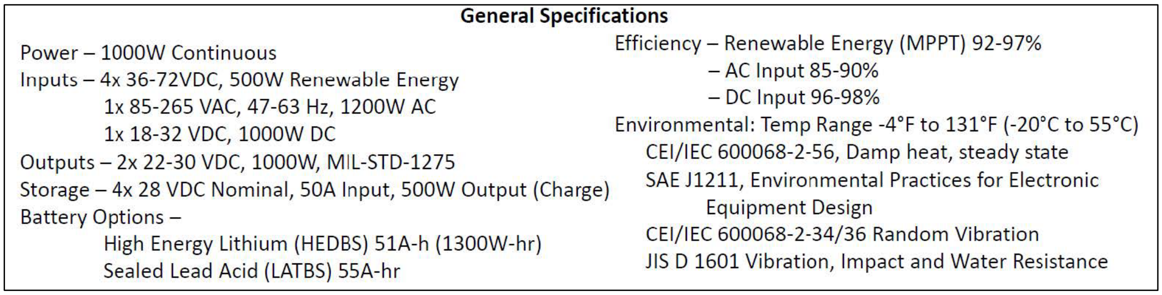
GREENS is "a modular, man-portable solar energy conversion and management system that harvests solar energy using photovoltaic solar panels, distributes that energy using an intelligent management system, and stores excess energy in High Energy Density Battery (HEDB) packs" first fielded to the USMC units by Marine Corps Systems Command (MCSC) in 2018 (MCSC, 2018). The original equipment manufacturer (OEM) for the GREENS is UEC Electronics. The current version, GREENS 1000W, will provide up to 1kW of power for each system, and up to five systems may be placed in parallel to provide 5kW of total power. The GREENS 1000W and its major components are depicted in Figure 1 and listed individually in Table 1. The GREENS 1000W general specifications are listed in Figure 2.

Controller (middle row center), High Energy Density Battery (HEDB) (middle row left), Output Paralleling Adapter (OPA), (middle row right), Direct Current Power Distribution Kit (DC PDK) (middle row right), Advanced Integrated Solar Panel Case Assembly (AISPCA) (top row).

Figure 1. GREENS Major Components. Source: MCSC (2018).

Table 1. GREENS Major Component Parts. Adapted from UEC Electronics (2019).

Standard Configuration				
Quantity	Description	Part Number	Dimensions	Weight
1	Controller	0754A08	21.2” X 16 .0” X 8.3”	51 lbs.
4	Battery (HEDBS)	0754A12	16.5” X 1 4.0” X 7.0”	40 lbs.
2	External Cable Kit	0754A09	24.8” X 1 9.4” X 13.9”	64 lbs.
1	Power Distribution Kit	0754A11	24.8” X 9 .4” X 13.9”	52 lbs.
1	Output Parallel Adapter	0754A07	16.0” X 13 .0” X 6.9”	17 lbs.
1	Autostart	0920A01	19.8” X 15 .8” X 7.4”	38 lbs.
1	Lead Acid Battery {LATBS)	0754A06	20.9” X 1 2.7” X 12.8 “	110 lbs.



General Specifications

Power – 1000W Continuous
Inputs – 4x 36-72VDC, 500W Renewable Energy
1x 85-265 VAC, 47-63 Hz, 1200W AC
1x 18-32 VDC, 1000W DC
Outputs – 2x 22-30 VDC, 1000W, MIL-STD-1275
Storage – 4x 28 VDC Nominal, 50A Input, 500W Output (Charge)
Battery Options –
High Energy Lithium (HEDBS) 51A-h (1300W-hr)
Sealed Lead Acid (LATBS) 55A-hr

Efficiency – Renewable Energy (MPPT) 92-97%
– AC Input 85-90%
– DC Input 96-98%
Environmental: Temp Range -4°F to 131°F (-20°C to 55°C)
CEI/IEC 600068-2-56, Damp heat, steady state
SAE J1211, Environmental Practices for Electronic Equipment Design
CEI/IEC 600068-2-34/36 Random Vibration
JIS D 1601 Vibration, Impact and Water Resistance

Figure 2. GREENS 1000W General Specifications. Source: UEC Electronics (2019).

The functional description of GREENS, as found in the universal statement of need (USON), “consist of modular man transportable components that when assembled into a system, accepts energy from different sources, distributes the energy using an intelligent management system, and stores excess energy to provide an average continuous output of 1kW (peak)” (UEC Electronics 2021, x). The GREENS functional flow block diagram is shown in Figure 3.

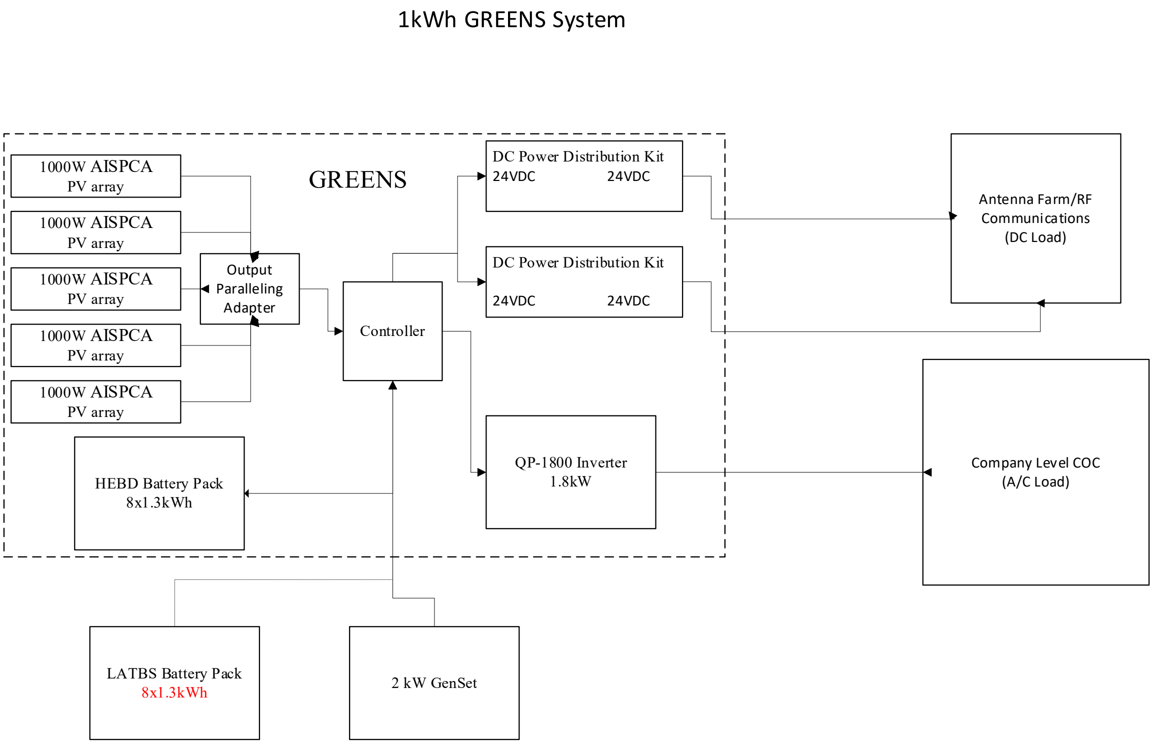


Figure 3. 1 kWh GREENS Functional Flow Block Diagram

a. GREENS Controller

Central to the GREENS system, the controller (Figure 1 and Figure 4) provides overall system management and circuit protection for the entire system. The controller converts and regulates energy received from various power sources, including photovoltaic arrays, battery storage banks, and generator sets. The controller then distributes that power via two outputs as non-regulated 22 to 30 Volts Direct Current (VDC) or regulated 24–28VDC output. The GREENS controller directs surplus energy to be stored in the four HEDB packs or optional lead-acid battery banks and will also draw upon that HEDB stored energy to support loads when required.

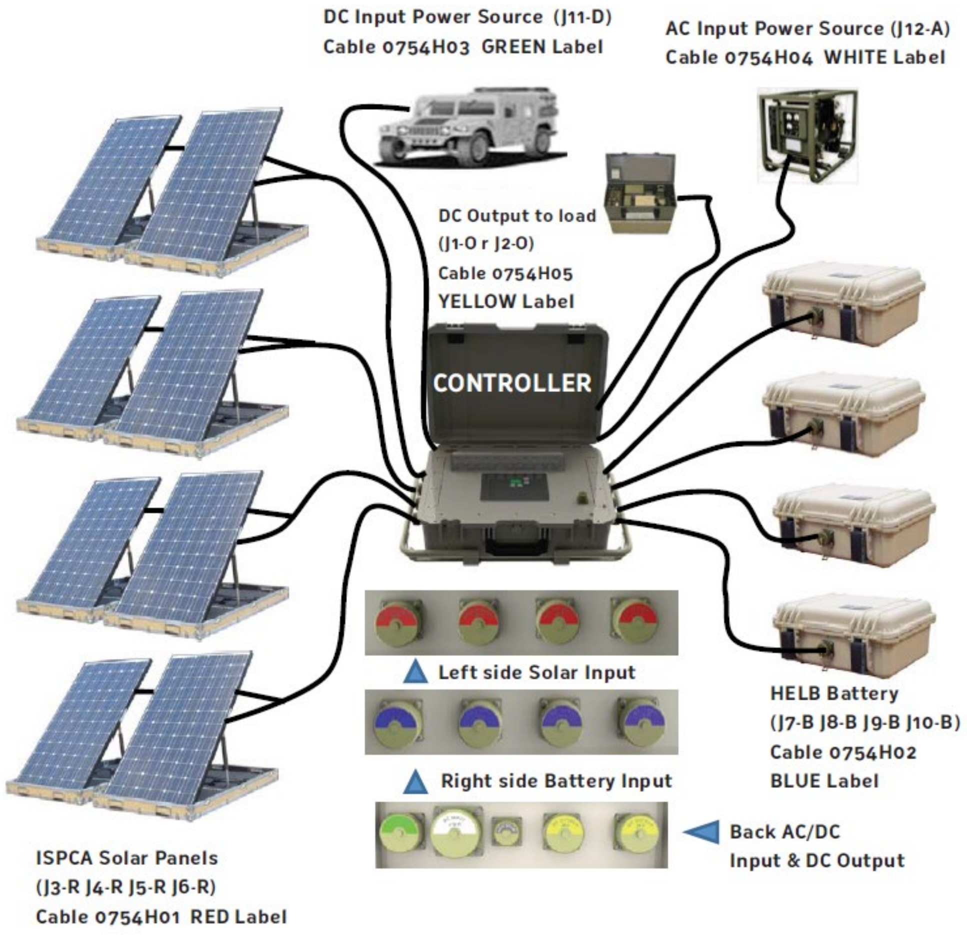


Figure 4. GREENS 1000W Controller System Architecture. Source: UEC Electronics (2021).

b. GREENS High Energy Battery System (HEDBS)

The HEDBS (Figure 1 and Figure 4) is the GREENS 1000W primary battery and consists of four 28VDC, 51 ampere-hours (A-h), 1.3kW-hr, Lithium Iron Phosphate (LiFePO4) battery packs with 500W output of charge each. GREENS 1kW has the option to utilize additional 51A-h sealed lead-acid batteries (LATBS) for additional energy storage.

c. GREENS Output Paralleling Adapter (OPA)

The OPA (Figure 1) is an adapter that can place up to a maximum of five GREENS in parallel, allowing for a maximum nominal output of 5kW of regulated 24VDC directional power. These maximum power measurements reflect OPA efficiency losses to GREENS power output. The available power from paralleled GREENS is depicted in Table 2.

Table 2. Available Power from Paralleled GREENS. Adapted from MCSC (2018).

Number ofGREENS	Continuous Power Provided
2	2 kW
3	3 kW
4	4 kW
5	5 kW

d. GREENS Advanced Integrated Solar Panel Case Assembly (AISPCA)

The AISPCA (Figure 1, Figure 4, and Figure 5) consists of four 250W rugged and lightweight tri-fold solar panel arrays that combine to harvest 1000W of solar energy. Each GREENS consists of four AISPCA solar panel arrays that can collect a total of .1.6kW of energy.

Figure 5. Advanced Integrated Solar Panel Case Assembly (AISPCA). Source: MCSC (2018).

e. GREENS Direct Power Distribution Kit (DC PDK)

The DC PDK distributes DC power from the Controller to the end-user devices in a combat operations center (COC) or a tactical operations center (TOC). Each DC PDK consists of two Power Distribution Units (PDUs) (Figure 1) and assorted cables.

f. GREENS Quiet Power (QP)-1800 DC to AC Inverter

The QP-1800 DC to AC inverter (Figure 6) converts 24VDC GREENS power into 115Volts Alternating Current (VAC) power. The QP-1800 inverter will support nominal loads of 1.8kW and peak loads of 2.9kW. The QP-1800 inverter causes an approximate 20% DC power to AC power conversion. Additionally, the QP-1800 consumes 7% of total power with no load.

Figure 6. QP-1800 DC to AC Inverter. Source: MCSC (2018).

2. Generator, Light Weight, Man-Portable

The USMC MEP-531A 2kW light weight (LTWT), man-portable generator set (Figure 7) is a Yanmar OEM one cylinder generator that runs on diesel fuel or jet propulsion fuel type 8 (JP-8). The MEP-531A can produce 2kW of 120V power at 60Hz. The MEP-531A generator set is commonly used by the USMC for small AC power needs.

Figure 7. USMC MEP-531A 2kW LTWT, Man-Portable Generator Set.
Source: MCSC (2018).

3. Mobile Electric Hybrid Power Sources (MEHPS)

The UEC Electronics MEHPS is a modular, rugged, and scalable expeditionary hybrid power generation system that seeks to replace standard diesel fuel generators for deployed forces. MEHPS can be configured to support 5kW, 10kW, and 15kW load requirements. MEHPS "accepts and regulates power from a scalable variety of renewable energy sources, batter arrays, and auxiliary AC and DC sources while smartly managing the power available from each source to minimize fuel consumption" (UEC 2021). The man-portable 5kW MEHPS (Figure 8) and trailer-mounted 10kW MEHPS (Figure 9) are depicted below.

Figure 8. 5kW MEHPS. Source: UEC Electronics (2018).

Figure 9. 10kW MEHPS. Source: UEC Electronics (2018).

MEHPS is scalable to meet expeditionary energy needs. The PV arrays collect up to 4kW of soler energy. The MEHPS control unit optimizes PV power input with energy stored in DC battery banks as well as DC power generated from the load-balanced integrated generator sets and provides stable and conditioned 28VDC, 100VAC, and 208VAC power output. The general specifications of the 5kW MEHPS are listed in Figure 1, and the functional block diagram of the 10kW MEPHS is shown in Figure 14 and Figure 15.

General Specifications:

Power: 5000W Continuous, 6000W Peak	Environmental: Temp Range -4°F to 131°F
Inputs: (AC) 80-150 VAC, 54-66Hz, 30 amps (max)	Corrosion Resistance: MIL-STD-810F, Method 509.4
(DC) 28 VDC, 2kW	Shock Resistance: MIL-STD-810F, Method 516.5, Proc IV
(Solar) 0-4kW-hrs	Rain Resistance: MIL-STD-810F, Method 506.4
Outputs: (AC) 120 VAC, 60Hz, 30Amp	Battery Options: High Energy Lithium (HEDBS) 103.6A-h
(DC) 24 VDC, 1kW (max)	
Storage: 7 x 2.6kW/hr Battery	

Figure 10. 5kW MEHPS General Specifications. Source: UEC Electronics (2018).

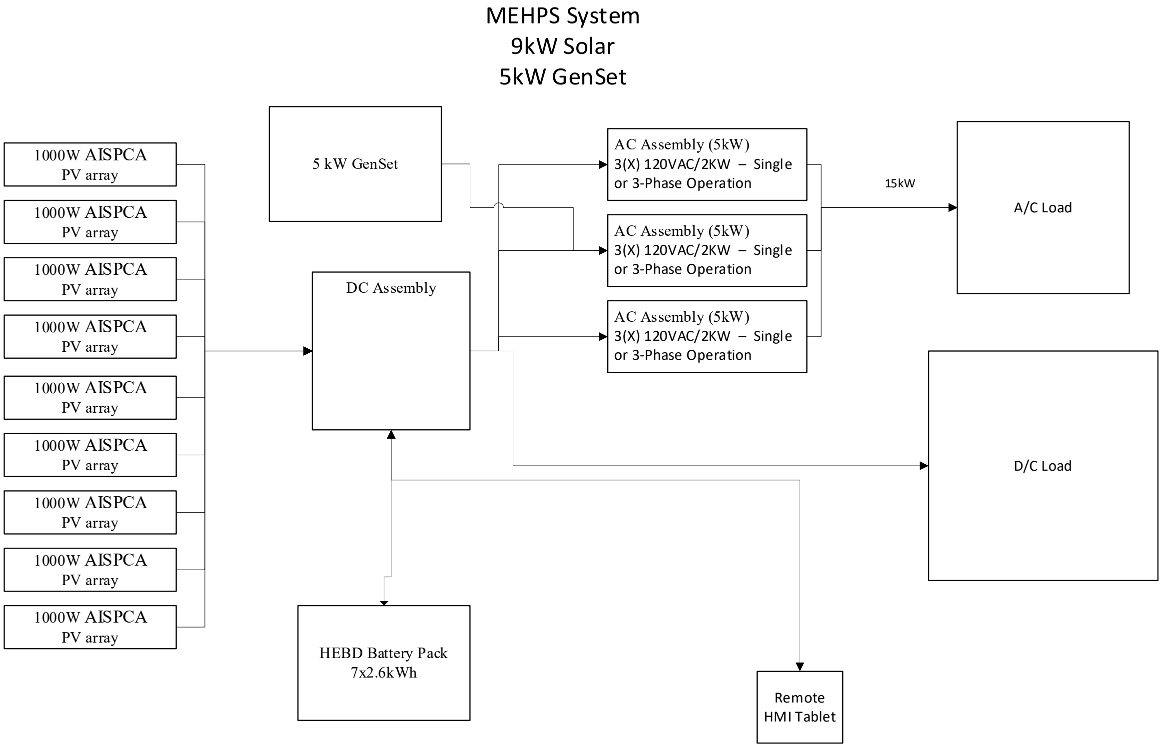
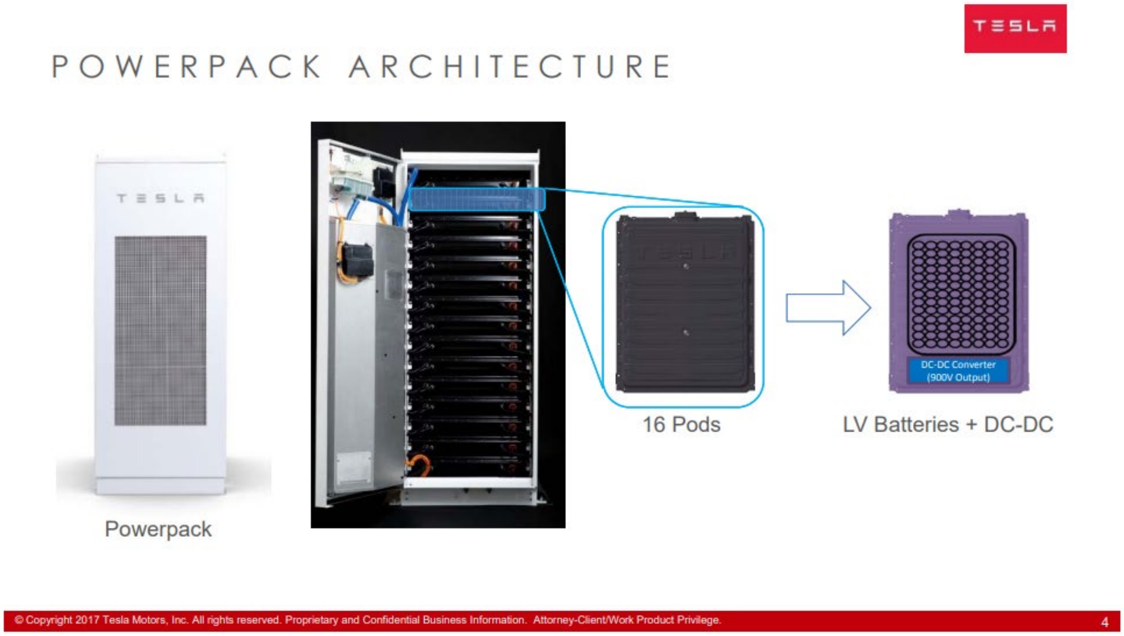


Figure 11. MEHPS System Functional Block Diagram

4. COTS Tesla Powerpack System

Tesla Inc. has provided custom-designed rechargeable lithium-ion energy storage solutions in the form of the Tesla Powerpack to commercial industry and government customers since 2012. Tesla Powerpack customers include Southern California Edison and the South Australia government, among many others.



POWERPACK ARCHITECTURE

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Figure 12. Tesla Powerpack System Internal. Source: Tesla (2017, 4).

According to Tesla Inc. CEO Elon Musk, the refrigerator-sized Powerpack (Figure 12), which can store 232 kWh per unit, are "infinitely scalable" because they may be combined with as many units as needed (Figure 13) to meet large-scale energy requirements (Boshart 2015; Davies 2015). As of 2021, the largest Tesla Powerpack installation is the 100MW and 129MWh project for the renewable energy provider Noen at the Hornsdale Wind Farm project near Jamestown, South Australia (Harvey 2017). The Hornsdale project eclipsed the 20MW and 80MWh Southern California Edison project installed in Mira Loma, CA in 2015 (Lambert 2017).

Customer

Southern California Edison

Location

Ontario, CA

Project Size

20 MW / 80 MWh

Applications

Peaker plant replacement

Commissioned

2016. Three months from deployment to operation

Figure 13. Example Tesla Powerpack System. Source: Tesla (2017, 6).

III. METHODOLOGY

This study collects data from existing USMC PoR tactical generators, USMC solar PV and battery storage PoR systems, and commercially available solar PV and battery storage systems. These power generation and energy storage systems are assessed in both standalone and hybrid configurations to determine their ability to meet the operational electrical energy requirements needed to sustain military operations in remote and austere environments and determine which configurations require the least logistical support. We will use the HOMER Micropower Optimization Model developed by the National Renewable Energy Laboratory (NREL) to model these power generation and energy storage configurations and perform simulations, optimizations, and sensitivity analysis on each configuration to extract the data we will use to compare and evaluate each configuration. The data extracted from these scenarios will be used to measure each configuration against the four questions stated in the introduction. The solar global horizon irradiance (GHI) and monthly average temperature data used in our models were downloaded from the NASA prediction of world energy resource (POWER) database. Additional factors to be considered in this experiment are location, unit composition, electrical load, and renewable energy architecture.

A. DATA COLLECTION

The data required to model and simulate electrical loads for the squad, team, and company sized elements were acquired from a combination of PoR technical and operations manuals for C5ISR and life support systems, operational planning, and after-action reports from USSOCOM, Naval Special Warfare (NSW), Marine Corps Special Operations Command (MARSOC) and Fleet Marine Force (FMF) units. This data was informed by the authors' combined forty-plus years of field experience. The data gathered was vetted for accuracy against output and fuel burn rates collected from operational records downloaded directly from generators in use by operational units. Utilization was calculated from a combination of technical data retrieved from the TM/OM documents and the authors' forty-plus years of experience operating in TOC/COC environments.

1. Program of Record Documentation

The authors downloaded PoR documentation from U.S. Marine Corps Systems Command (MARCORSYSCOM) and USSCOM tactical systems knowledge management portals to establish standardized maximum power consumption profiles for COC/TOC components. The types of documentation include TMs, which provide detailed diagrams of component assemblies and power requirements, and Operations Manuals (OMs), which guide the equipment operator through the setup and operations phases and trouble-shooting steps in addition to power consumption information. Network infrastructure, compute resources, and satellite communications systems power requirements were gathered primarily from PoR and vendor TMs, while tactical radios, encryption devices, and supporting hardware, Satellite Deployable Node (SDN) systems infrastructure, and man-portable satellite communication system requirements were pulled from OMs.

2. After-Action Reports (AAR)

The team acquired AARs and generator utilization logbook records from MARSOC and from USMC 9th Communications Battalion (9th Comm Bn.) to ascertain the equipment strings and current operational power requirements to support Team and Company level force compositions. Once we identified the equipment strings for the respective unit sizes, we analyzed these components to determine realistic demand within a 24-hour period. We then calculated energy usage in watts based upon the minimum-maximum power range divided by the number of hours utilized per day. This method of determining power requirements is more accurate than simply planning based on maximum power requirements and utilization, known as the peak of peaks. When utilizing a peak of peaks power planning approach, the generators are typically underloaded, resulting in wasted fuel and maintenance issues resulting from wet stacking. The method utilized in this thesis is not as accurate as utilizing power monitoring devices such as the Fluke 3540 or single-phase power meters for individual components. The authors followed a broader approach to account for minor changes in equipment strings as well as systems life cycle events such as component and system upgrades, the fielding and integration of new systems, and the disposition of retiring systems.

3. Power Requirements

(1) USSOCOM SOF Team TOC

As depicted in Table 3, a USSOCOM SOF Team, composed of between 12 to 16 personnel, has power requirements that consume between 64kW and 76kW per day. This large power consumption range is due in large part to the variance in power consumption of the Panther II satellite communications terminal. During the initial set up and establishment of services, the Panther II satellite communications terminal power draw will peak at 619W. However, during the normal operation of satellite tracking and low utilization periods, the Panther II system will only draw around 213W of power. The Panther II system is also capable of being powered directly by re-chargeable BB-2590 batteries. The Panther II system power consumption in Table 3 reflects the terminal operating on battery power for 12 hours per day. Additionally, the Panther II satellite communications terminal power requirements in Table 3 accounts for charging cycles for the BB-2590 batteries via the PP-8498 8 port battery charger. The Switch and Enclave stacks, along with the APC-1500 UPS, are also critical components with a high rate of power consumption due to the fact they operate 24 hours a day, seven days a week (24/7). The Transport stack utilization will fluctuate depending on the frequency of traffic traversing the Panther II terminal and will likely experience periods of low utilization throughout the day. While the CF-52 laptops do not run 24 hours per day, they do operate in large quantities and present a considerable draw when not utilizing battery power. Although the ECU does not run 24/7, it consumes the largest amount of energy for any single component of the TOC layout. Lastly, the two large-screen televisions and coffee maker each consume over 1kW throughout a 24-hour period. Operational tempo plays a large role in actual power consumption; therefore, the selected range accounts for moderate to low and moderate to high utilization.

Table 3. USSOCOM SOF Team TOC Equipment

SOCOM SOF Team Equipment					
Component	**Model**	**Quantity**	**Power Consumption (Watts)**	**Daily Use (in hours)**	**Watts**
SATCOM TERMINAL	Panther II	1	213-619	12*	2556-7428
TRANSPORT STACK	ME-SE3 / M3-SE-DSL-SW / M3-SE-TVM3 / ME-SE-PA-P	1	57.5	12	690
ENCLAVE STACK	ME-SE3 / M3-SE-SVR /ME-SE-PA-P	2	241.2	24	5788.8
SWITCH STACK	M3-SE-SW24	2	35.8	24	1718.4
UPS	APC-1500 (charged)	2	120	24	2880
NAS	Buffalo Terastation	1	62	4	248
LAPTOP	CF-19	1	60	4	240
LAPTOP	CF-52	15	1050	4	4200
PRINTER	HP 4700	1	567	0.75	425.25
PRINTER	XEROX PHASER 6280	1	450	0.75	337.5
IP PHONE	CISCO 7942	8	PoE	6	0
In-line IP Encryptor	KG-250X	3	42	24	1008
SCANNER	CANOSCAN LiDE210	1	2.5	4	10
HF Radio	TRC-209	1	1290	3	3870
VHF/UHF Radio	AN/PRC-117F	?	20	6	120
VHF/UHF/ ANW2 Radio	AN/PRC-117G	?	20	6	120
2590 8 PORT CHARGER	PP-8498	1	300	24	7200
PRC-148 6 PORT CHARGER	PRC-148 6 PORT CHARGER	1	60	24	1440

SOCOM SOF Team Equipment					
SKL CHARGER	Sierra Nevada Corp	1	2	0.25	0.5
NANO CHARGER	Iridium	1	7.5	4	30
IRIDIUM CHARGER	Iridium	1	9	4	36
Environmental Control Unit	1.5-Ton 29000 BTU	1	3833	8	30644
Coffee Maker	Mr Coffee		600	3	1800
Flat Screen TV	Generic 55”	2	160	12	1920
				Total Watts:	**63724.53-76239.57**

*Also powered by BB-2590 (207wh), three batteries provide approximately 3 hours of operation. Assuming Panther II is powered 12 hrs. a day on BB2590s

(2) USMC Company COC

The USMC Company COC equipment string listed in Table 4 consumes substantially more energy than the previous SOF team-sized element averaging between 189kW to 231kW. The Company level COC is designed to provide information technology resources and communications infrastructure to support an average of 80 to 120 personnel. The satellite communications equipment, computer hardware, network infrastructure, and environmental control unit (ECU) also utilize a larger share of energy in this configuration. The VSAT-M is not capable of running on portable battery power like the Panther II system described in the previous table, and as a result, it is a constant drain on energy resources. Aside from the additional quantity of equipment, the Combat Data Network components are more robust and resource-intensive than the smaller form factor kits used by Platoon-size and smaller elements. The Company COC also employs High-Capacity Line of Sight (HCLOS) terrestrial radio systems to extend services to lower echelon elements or connect to connect up to Battalion level resources. In this case, the Wireless Point to Point Link (WPPL) is being modeled. The WPPL is far more efficient than the AN/MRC-142 that is nearing its end-of-life phase.

Table 4. USMC Company COC Equipment

USMC Company COC Equipment					
Component	**Model**	**Quantity**	**Power Consumption (watts)**	**Daily Use (hours)**	**Watts**
SatCom Terminal	VSAT-M	1	1100	24	26400
Application Server Module	AN/TYQ-147A	1	437	24	10488
Communications Security Module	CDN	1	174	24	4176
Data Storage Module	CDN	1	420	4	1680
Enterprise Switch Module	CDN	1	1000	24	24000
Information Assurance Module	CDN	1	452	24	10848
LAN Extension Module	CDN	1	200	24	4800
LAN Services Module	CDN	1	481	24	11544
Multimedia Control Module	CDN	1	362	24	8688
Multimedia Distribution Module	CDN	1	460	24	11040
Power Module	CDN	1	74	24	1776
WAN Services Module (V)1	CDN	1	440	24	10560
WAN Services Module (V)2	CDN	1	270	24	6480
Configuration Module	CDN	1	100		100
LAPTOP	Engineering	5	500	4	2000
LAPTOP	Generic	35	2275	4	9100
PRINTER	HP 4700	1	567	0.75	425.25
PRINTER	XEROX PHASER 6280	1	450	0.75	337.5
IP PHONE	CISCO 7942	12	PoE	6	0

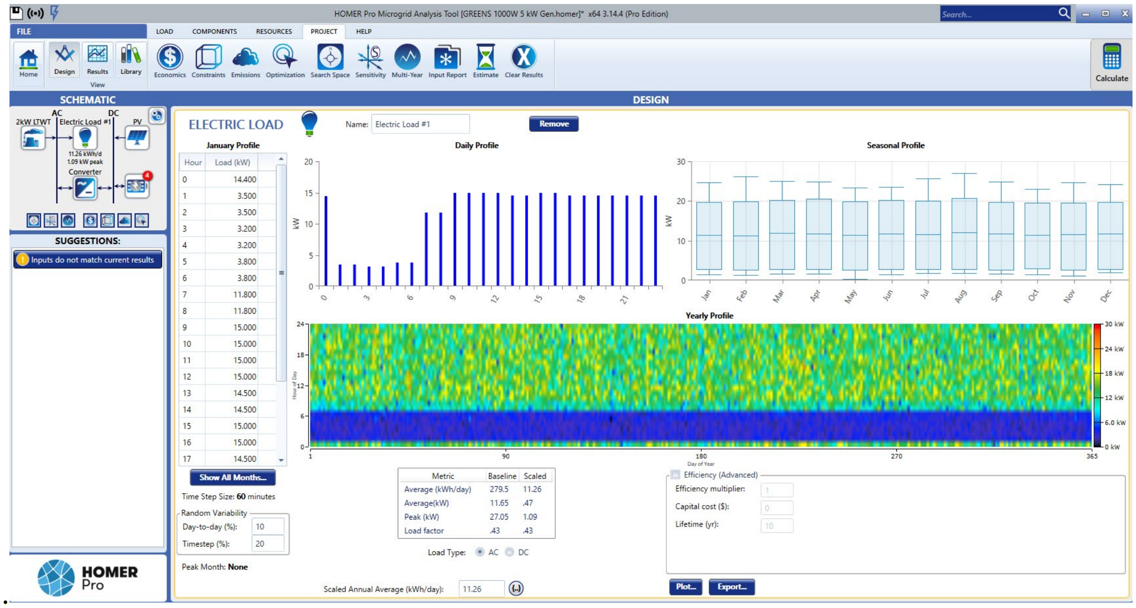
USMC Company COC Equipment					
IP Encryptor	KG-175D	3	60	24	1440
SCANNER	CANOSCAN LiDE210	1	2.5	4	10
HCLOS Radio	WPPL-T	1	20	16	320
TRC-209	L3/Harris	1	1290	3	3870
AN/PRC-117F	L3/Harris	10	200	6	1200
AN/PRC-117G	L3/Harris	20	400	6	2400
2590 8 PORT CHARGER	Bren-Tronics	1	300	24	7200
SKL CHARGER	Sierra Nevada Corp	1	2	0.25	0.5
Environmental Control Unit	3-Ton 36000 BTU	1	5760	8	46080
Coffee Maker	Mr Coffee		600	3	1800
Flat Screen TV	Generic 55”	2	160	12	1920
				Total Watts:	**189614.93-231751.58**

4. HOMER Micropower Optimization Model

Peter Lilienthal developed the HOMER Micropower Optimization Model during his 17-year career at the U.S. Department of Energy’s (DOE) NREL “to assist in the design of micropower systems and to facilitate the comparison of power generation technologies across a wide range of applications.”(Lambert, Gilman, and Lilienthal 2006, 379) He went on to form HOMER Energy LLC and launch HOMER commercially in 2009, with the stated vision to “empower people around the world with tools, services, and information to accelerate the adoption of renewable and distributed energy systems”(Homer Energy 2021, x). HOMER LLC is now wholly owned by Underwriters Laboratories (UL). As of 2021, the HOMER software, currently available as the commercial HOMER PRO, has been downloaded by over 250,000 users in 193 countries. (HOMER Energy 2021). HOMER is universally recognized as a global leader in hybrid power system modeling in the energy industry.

HOMER is a design optimization model intended to significantly simplify the microgrid design process by performing simulation, optimization, and sensitivity analysis. “HOMER’s fundamental capability is simulating the long-term operation of a micropower system” by determining “how a particular system configuration, a combination of system components of specific sizes, and an operating strategy that defines how those components work together, would behave in a given setting over a long period of time.” (Lambert, Gilman, and Lilienthal 2006, 381) HOMER’s simulation process ultimately determines whether a model is physically feasible, that is, whether it can satisfy the energy load demands of the system while also satisfying all of the user-specified constraints. Additionally, HOMER’s simulation also determines whether a model is economically feasible in quantifiable life-cycle costs that include initial capital costs, projected lifetime component replacement costs, maintenance costs, and fuel costs. (2006) HOMER optimizes microgrid design by determining a “configuration, dispatch, and load management strategy that minimizes life-cycle costs for a particular site and application”(Lilienthal, Flowers, and Rossmann 1995, x).

We used the HOMER Pro software in our research to model four energy production configurations and simulated their performance in support of two distinct unit compositions, the USSOCOM SOF Team TOC and the USMC Company level COC. In the optimization process, our goal was to use the HOMER Pro software to determine the optimal value of each decision variable we defined in order to identify the overall optimal system model from many possibilities. Our modeling and simulation design of experiment is discussed in depth later in this chapter. HOMER analyzes engineering, economic considerations, and design trade-offs that simulate multiple instantiations of equipment and systems for a given geographic location, as depicted in Figure 14.



Inputs do not match current results

Name: Electric Load #1

January Profile

Hour	Load (kW)
0	14.400
1	3.500
2	3.500
3	3.200
4	3.200
5	3.800
6	3.800
7	11.800
8	11.800
9	15.000
10	15.000
11	15.000
12	15.000
13	14.500
14	14.500
15	15.000
16	15.000
17	14.500

Time Step Size: **60** minutes

Random Variability

Day-to-day (%): 10

Timestep (%): 20

Peak Month: **None**

Metric	Baseline	Scaled
Average (kWh/day)	279.5	11.26
Average(kW)	11.65	.47
Peak (kW)	27.05	1.09
Load factor	.43	.43

Load Type: ● AC ○ DC

Scaled Annual Average (kWh/day): 11.26

☐ Efficiency (Advanced)

Efficiency multiplier: 1

Capital cost ($): 0

Lifetime (yr): 10

Figure 14. HOMER Pro Microgrid Analysis Tool

What exactly HOMER does, is best described by NREL:

> HOMER simulates the operation of a system by making energy balance calculations for each of the 8,760 hours in a year. For each hour, HOMER compares the electric and thermal load in the hour to the energy that the system can supply in that hour. For systems that include batteries or fuel-powered generators, HOMER also decides for each hour how to operate the generators and whether to charge or discharge the batteries. If the system meets the loads for the entire year, HOMER estimates the life cycle costs of the system, accounting for the capital, replacement, operation and maintenance, fuel and interest costs. After simulating all of the possible system configurations, HOMER displays a list of feasible systems, sorted by life cycle cost. You can easily find the least cost system at the top of the list, or you can scan the list for other feasible options. ("HOMER: The Micropower Optimization Model" 2004, 1–2)

The proprietary trademarked HOMER optimization algorithm examines all possible microgrid system combinations and sorts the results according to user-defined optimization variables to identify optimal systems. Additionally, HOMER provides sensitivity analysis tools that allow the user to change any input and specify any sensitivity variables to compare results further and identify the impacts of variables on optimal systems (Homer Energy 2021). HOMER will also incorporate NREL, NASA, and National

Oceanic and Atmospheric Administration (NOAA) meteorological and oceanographic (METOC) data for each given location to provide accurate solar radiation profiles and wind pattern profiles.

5. Location

The key component of any microgrid power simulation consisting of renewable energy components is the geographic location. The physical location of the microgrid will determine the local climate, seasonal, and weather pattern factors unique to that location on the earth's surface. Including these environmental variables in the assessment increases the accuracy of our analysis of the proposed configuration of energy storage and power generation systems. This experiment focuses specifically on renewable solar energy resources, which vary highly in availability and intensity by both locations and by the time of day. For this experiment, we selected a single location that was constant for all our simulations, located at Ebbett Field, Naval Base Guam 13.426146° North, 144.648259° East (Figure 15). This location provides a hypothetical operational site for a remote FOB on a remote island in the South Pacific.

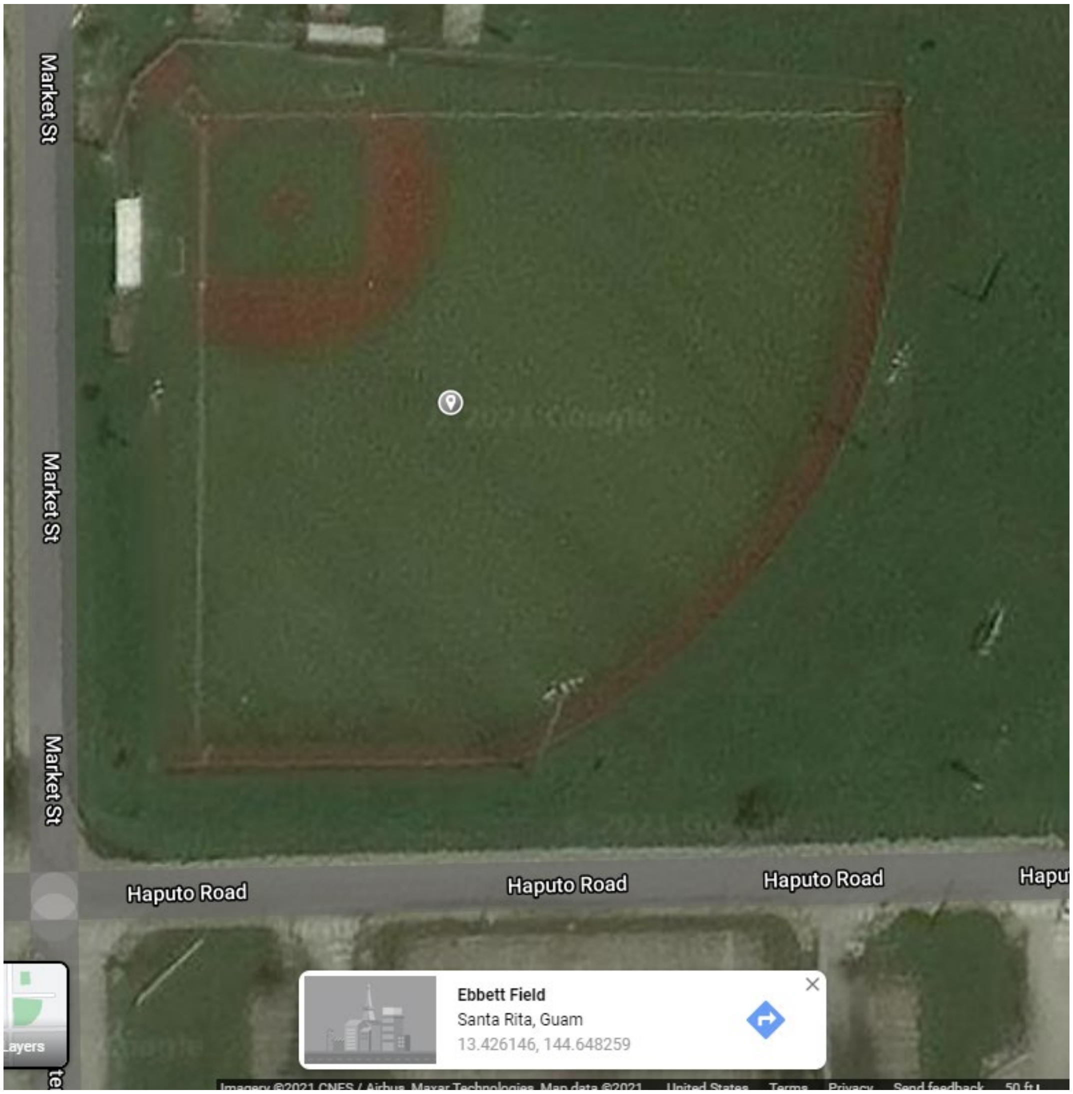
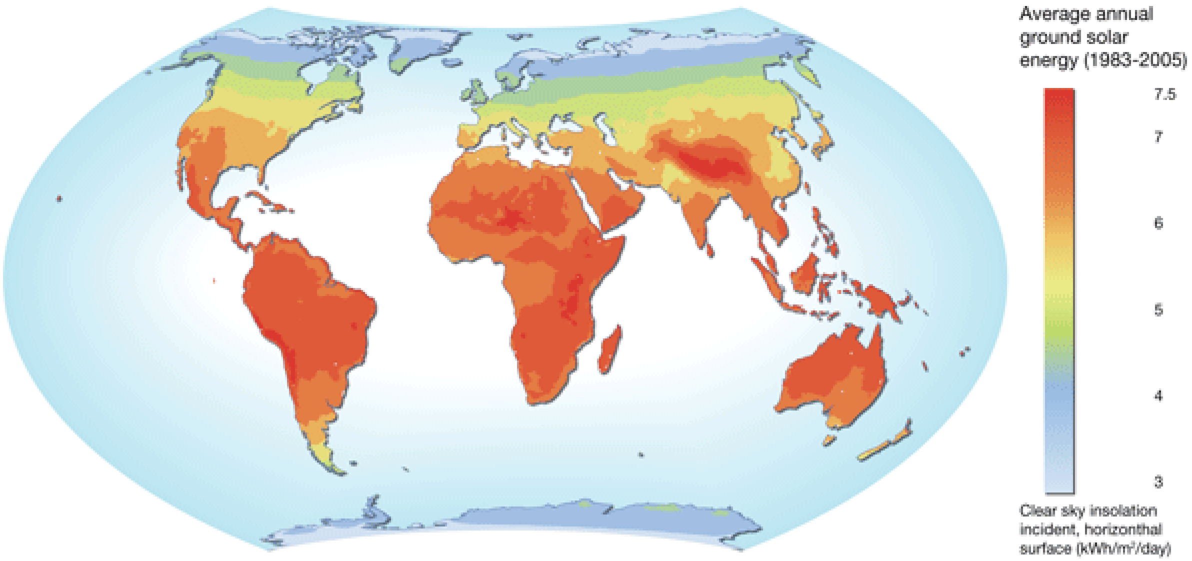


Figure 15. Experiment Location Ebbett Field, Naval Base, Guam

(1) Solar Irradiance Data

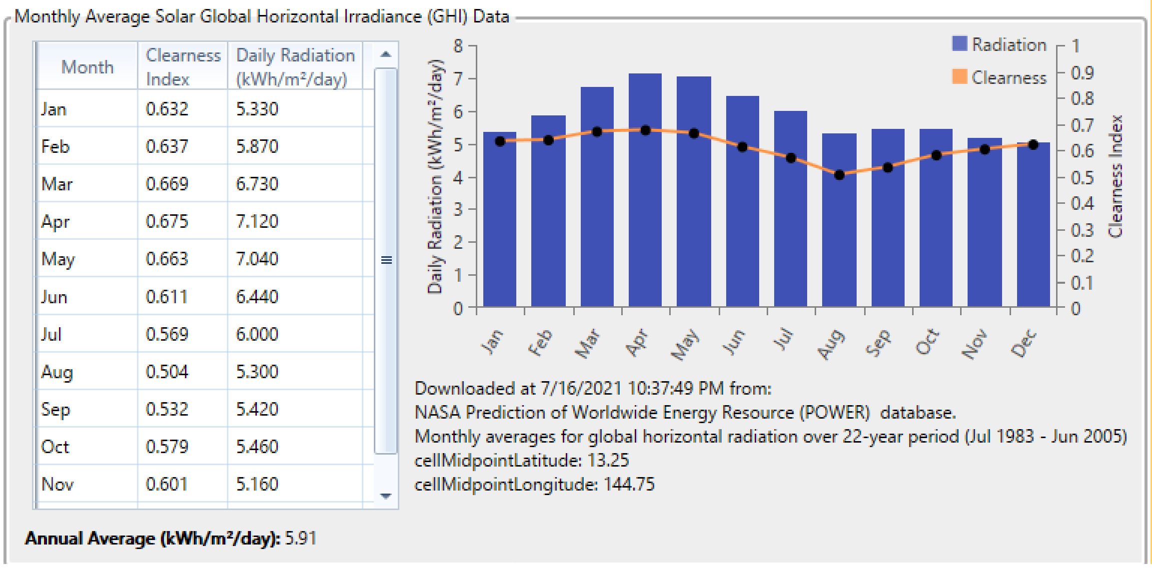
Solar irradiance is a central measurement to forecasting the potential energy generation of any given location on Earth. The amount of the Sun's rays, or solar radiation, that reaches any point on the Earth varies by location, landscape, time of day, season, and weather conditions, as depicted in Figure 16 (United States Department of Energy 2021).



Source: NASA 2008

Figure 16. Average Daily Global Solar Radiation. Source: U.S. Energy Information Administration (2021).

Radiance is a measure of the "density of [solar] radiation incident on a given surface usually expressed in watts per square meter"(Merriam-Webster 2021). HOMER uses the NASA Prediction of Worldwide Energy Resources (POWER) Project data for calculating solar irradiance in its models ("NASA POWER | Prediction Of Worldwide Energy Resources" n.d.). The monthly average solar global horizontal irradiance (GHI) and the annual averages for our selected location in Guam are depicted in Figure 17.



Monthly Average Solar Global Horizontal Irradiance (GHI) Data

Month	Clearness Index	Daily Radiation (kWh/m²/day)
Jan	0.632	5.330
Feb	0.637	5.870
Mar	0.669	6.730
Apr	0.675	7.120
May	0.663	7.040
Jun	0.611	6.440
Jul	0.569	6.000
Aug	0.504	5.300
Sep	0.532	5.420
Oct	0.579	5.460
Nov	0.601	5.160

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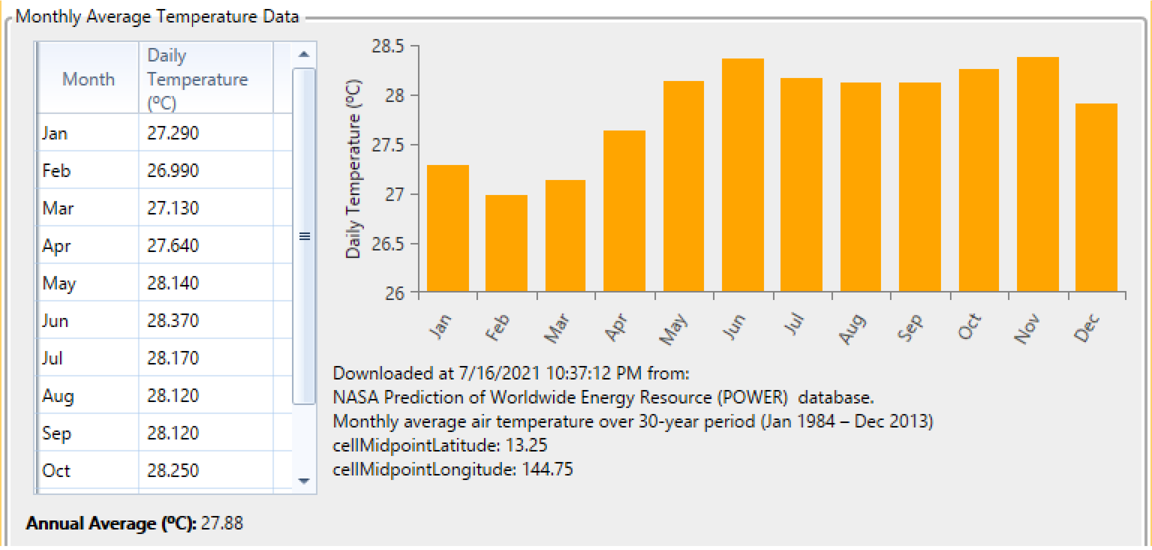
NASA Prediction of Worldwide Energy Resource (POWER) database.
Monthly averages for global horizontal radiation over 22-year period (Jul 1983 - Jun 2005)
cellMidpointLatitude: 13.25
cellMidpointLongitude: 144.75

Annual Average (kWh/m²/day): 5.91

Figure 17. Solar Irradiance Data for Guam

(2) Temperature Data

We also gathered the temperature data for our selected experiment location from the NASA POWER Project databases, as shown in Figure 18. This data was obtained from the NASA Langley Research Center (LaRC) POWER Project funded through the NASA Earth Science/Applied Science Program ("NASA POWER | Prediction Of Worldwide Energy Resources" n.d.).



Monthly Average Temperature Data

Month	Daily Temperature (ºC)
Jan	27.290
Feb	26.990
Mar	27.130
Apr	27.640
May	28.140
Jun	28.370
Jul	28.170
Aug	28.120
Sep	28.120
Oct	28.250

Downloaded at 7/16/2021 10:37:12 PM from:
NASA Prediction of Worldwide Energy Resource (POWER) database.
Monthly average air temperature over 30-year period (Jan 1984 – Dec 2013)
cellMidpointLatitude: 13.25
cellMidpointLongitude: 144.75

Annual Average (ºC): 27.88

Figure 18. Temperature Data for Guam

B. DESIGN OF EXPERIMENT

To assess the capacity of PV collection systems and Li-ion battery storage to augment or replace tactical diesel generators supporting military operations, the authors designed a simple experiment to analyze the ability of four energy production systems to meet the operational power requirements of two distinct unit compositions. The experiment is implemented in the HOMER application and simulated on the island of Guam. In the simulation, several scenarios are evaluated monthly over a one-year period. The first two factors in the experiment are the unit compositions, consisting of a SOCOM SOF team TOC (Force 1) and a USMC Company Level COC (Force 2). The equipment strings in Table 3 and Table 4 from the previous section are sub-factors tied to these respective units, which compose the systems architecture and determine the electrical loads. The additional factor evaluated includes the four energy production systems that consist of tactical diesel generators, a currently fielded USMC PoR renewable energy system (GREENS), a scalable hybrid renewable energy system that is currently in the acquisition process (MEHPS), and a COTS renewable energy solution (TESLA Powerpack System). These energy production systems will be identified throughout the thesis as configurations A, B, C, and D, respectively. The experiment will feature eight scenarios in which Force 1 and Force 2 will each be evaluated against configurations A, B, C, and D by simulating and analyzing their performance in HOMER. Configuration A (diesel generators) will be run first to establish a baseline from which to measure fuel consumption rates, fuel resupply demand, annualized system acquisition, and operation costs against the other three configurations.

1. Force Composition

The experiment features two distinct unit types and sizes to demonstrate the impact that different force compositions will have on each of the objectives being measured. Measured factors will include the ability of each configuration to meet power demands, the fuel burn rate and resupply requirement for each configuration, and total system operation cost. The unit sizes are restricted to Company and below due to the limited penetration of renewable energy technologies on larger units, which present more robust operational energy requirements. Additionally, the authors see USMC Company and USSOCOM SOF Teams as ideal units to conduct distributed operations in contested and gray zone environments, thereby adding more value to the study. In general, this simulation focuses on the operational power requirements of mission essential equipment and does not consider the power considerations of personal electronic devices.

(1) Force 1

The SOCOM SOF Team TOC element is usually comprised of between 12 and 16 personnel, equipped with rechargeable handheld tactical radios, .96m VSAT communications terminals, rack-mounted HF/VHF/UHF and ANW2 radios, small form factor network, and server infrastructure to support classified and unclassified networks and applications, 16 laptops, two LCD televisions, and a coffee maker. Additional life support items and personal electronic devices will not be factored into the simulation. The operational electrical load for a team-sized element is estimated to be between 33kW and 46kW per day, depending on operational tempo.

(2) Force 2

The USMC Company COC-sized element consists of between 80 and 120 personnel, with a similar systems architecture to the USSOCOM SOF TOC; however, the USMC Company COC is much more robust. Long haul communications are established with VSAT-M terminals and HCLOS radios to extend high-speed data communications to outlying sites. The USMC Company also deploys with a combination of tactical handheld radios for security patrols and intra-camp communication, man-packable and rack-mounted HF/VHF/UHF and ANW2 radio systems, data center equivalent network and server infrastructure that is rack-mounted in portable tactical cases, and a set number of laptops which are dictated by the number of users. This simulation assumes 35 laptops. As with the USSOCOM SOF TOC, 2 LCD televisions and a coffee maker are included in the simulation. Personal electronic devices are not accounted for in the USMC Company COC planning. Additionally, a 3-ton environmental control unit (ECU) is also included in the Company level energy profile. It is planned that the ECU will run eight hours per day to maintain an acceptable operating temperature for the network infrastructure and communications equipment.

2. Energy Production Systems

The power generation equipment featured in the experiment falls into one of two categories, either tactical quiet generators that run on diesel fuel or renewable PV panel systems with battery storage. The tactical generators are evaluated as stand-alone power sources to best establish a baseline from which to measure the effectiveness of the PV and battery storage renewable energy systems. The renewable energy systems are evaluated in a hybrid configuration with the tactical generators to measure the system's capital costs, fully burdened fueling costs, fuel burn rate, and renewable energy penetration.

a. Configuration A

This is the baseline configuration for each force design and consists of standalone tactical quiet diesel generators ranging from 2kW man-portable generator to 60kW trailer-mounted systems, which depend on electrical load demand and paired renewable energy production capacity.

b. Configuration B

This is composed of the GREENS 5kW renewable energy system battery storage system. GREENS is scalable; however, it is not robust enough to provide power independently. Therefore, this configuration will run in a hybrid mode with a 10kW to 30kW generator.

c. Configuration C

The MEHPS configuration is a hybrid renewable energy system that supports up to 9kW of PV collection. This configuration has built-in battery storage that scales from 2.6kWh to 18.2kWh of battery storage. The system also has its own dedicated tactical generator available with 5kW, 10kW, or 15kW capacity.

d. Configuration D

This configuration is a notional system that is comprised of a 210kWh Tesla Powerpack battery storage unit and a commercial 25kW PV solar collection array. This configuration is being modeled to demonstrate the potential benefits of using COTS equipment. Configuration D has not been formally tested or evaluated for military applications at the time of this writing.

3. Measures of Effectiveness and Impact

The energy production systems described in the previous section are subjected to two primary measures from HOMER data. Fuel burn rates calculate Liters consumed per day and per year in standalone and hybrid configurations, which in turn predicts how often a remote location would need to be refueled during a deployment. The level of renewable energy penetration determines the effectiveness of PV collection and battery storage systems by calculating the amount of energy produced by PV collection and distributed by battery storage for a given configuration. Renewable penetration data assists in confirming a configuration's ability to integrate with, or even to replace, diesel generators by assessing the system's ability to meet electrical load requirements for a respective force design. The design matrix depicted in Table 5 aligns the two force design concepts (USSOCOM SOF Team TOC and USMC Company COC) with the four configurations resulting in eight design points represented by the corresponding binary (0 or 1) indicators in the table. While cost is not the primary criteria for measurement in this experiment, it should be a consideration when weighing the risk of the initial investment in emerging technologies against potential cost savings later in the life cycle. System costs include both the initial acquisition capital costs as well as life cycle maintenance costs for each system. System costs are an important consideration when analyzing alternatives to power the TOC/COC configurations. However, it is critical to think about these costs holistically with respect to additional measures. The fuel costs will evaluate the fully burdened expense to purchase and deliver fuel to sustain standalone diesel fuel power generators and hybrid electric configurations in remote locations.

Table 5. Design Matrix

Design Point	Force 1	Force 2	Config-A	Config-B	Config-C	Config-D
1	1	0	1	0	0	0
2	1	0	0	1	0	0
3	1	0	0	0	1	0
4	1	0	0	0	0	1
5	0	1	1	0	0	0
6	0	1	0	1	0	0
7	0	1	0	0	1	0
8	0	1	0	0	0	1

IV. RESULTS AND ANALYSIS

This chapter presents the results from modeling, simulation, and optimization of four distinct design points for the USSOCOM SOF Team TOC (Force 1) and the USMC Company level COC (Force 2) unit compositions discussed in the previous chapter. These cases were run in the simulation model, HOMER, to develop power production solutions. The output from these simulations provides evidentiary support whether or not existing or near- to- market GOTS/COTS PV battery storage systems can effectively augment or provide an alternative to traditional diesel tactical generators that currently provide expeditionary energy to forward-deployed units. The results are organized into four sections representing configurations A, B, C, and D. The first section consists of configuration A, the baseline diesel generator results, establishing reference data for existing system capital costs, fuel consumption, and fuel resupply windows. After the baseline section, GREENS, MEHPS, and COTS solution data for each unit composition are evaluated.

All four sections feature boxplot charts to display renewable energy production data for each system configuration. This chart style shows a data set in a five-number summary, including lower, median, and upper intra-quartile values which make up the intra-quartile range (IQR), as well as minimum (lower quartile - 1.5 * IQR) and maximum (upper quartile + 1.5 * IQR) values. In the results sections for each system, only the median quartile and minimum/maximum values are labeled and discussed in the charts. These values are used to effectively highlight the average renewable energy production for each configuration and discuss operational and environmental variables that drive the minimum/maximum average energy production data points. These charts also contain horizontal lines that represent the daily electrical power demand for each force composition, Force 1 (76.2 kWh) is represented by the orange line and Force 2 (231.7 kWh) is represented by the blue line. The delta between the maximum intra-quartile values and electrical power demands in configurations B, C, and D are compensated by tactical diesel generators.

The baseline fuel consumption data for configuration A (tactical generators) is displayed in tables that account for force composition, tactical generator size, and the daily/

weekly/annual fuel burn rate. The fuel comparison section displays hourly, daily fuel, and annual fuel consumption data for the renewable energy configurations measured against configuration A. This data is presented in summary tables that show fuel burn rates and the resulting fuel resupply window lengths for each system and force composition. The results from this section will equip team leaders, company commanders, higher echelon leadership, and decision-makers with the data required to implement hybrid and standalone renewable energy solutions.

A. CONFIGURATION A - DIESEL GENERATOR BASELINE RESULTS

This section reviews the performance data for tactical diesel fuel power generators currently supporting Force 1 and Force 2 in expeditionary environments. The performance data measured will illustrate configuration A's tactical generator's ability to meet the power requirements for both USSOCOM SOF teams and USMC expeditionary units. Additionally, the burn rate of the diesel fuel required to power the generators will be examined to determine how long the force compositions can operate without being refueled in remote expeditionary environments.

1. Force 1 – Configuration A

The USSOCOM SOF team requires, at a minimum, one 30kW Generator to power the team TOC; this simulation was limited to the power requirements for the TOC and its associated equipment list detailed in the previous chapter. Additional generators would be required for collateral power requirements, including billeting tents and camp services. The annual operating costs reflected in the system cost section are for one 30kW Generator. The data in Figure 19 displays maximum, median average, and minimum values for daily power produced by the 30kW diesel generator compared to the USSOCOM SOF Team power requirements. The power production varies slightly throughout the year based on weather, operational tempo, and hours of sunlight per day, all of which dictate the electrical power demand for environmental control units, C5ISR systems utilization, and lighting.

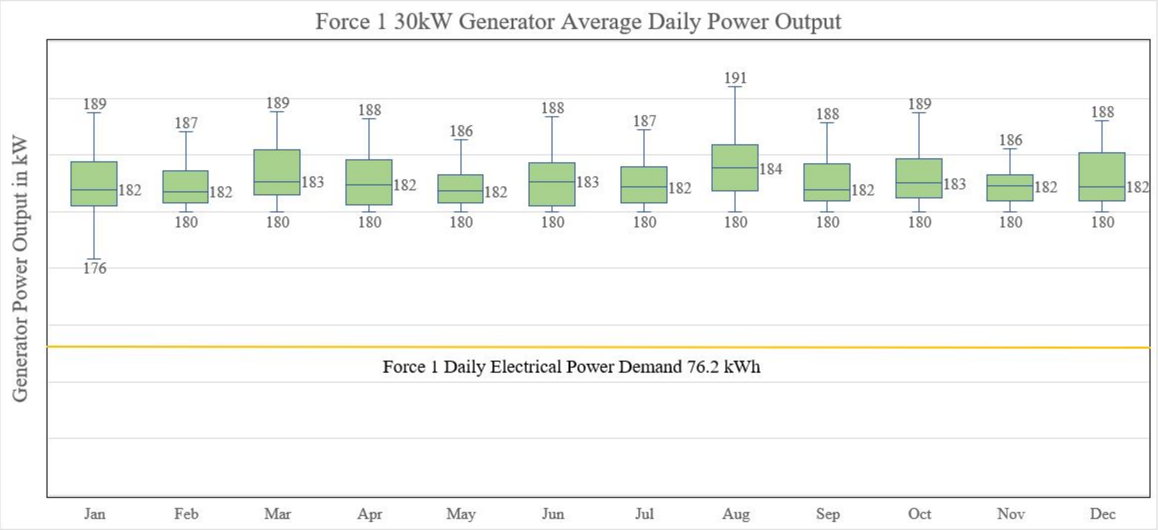


Figure 19. 30kW Tactical Generator Baseline

The average amount of power produced per day was 182.4kWh, which exceeded the average demand requirement of 76.2kWh per day. The lowest daily average of power produced was 176kWh in January, whereas the highest average was 191kWh in August.

Table 6. Force 1 – Config. A Fuel Consumption

Force Composition	Power Configuration	Avg. Hourly Fuel Consumption (L)	Avg. Daily Fuel Consumption (L)	Annual Fuel Consumption (L)
Force 1	Config. A (30kW)	3.07	73.7	26,896

Configuration A supplies a surplus electrical power capacity based on the power demand requirement for Force 1. As shown in Table 6, this configuration consumes an average of 73 L of fuel per day. Assuming that the unit deployed with 200 gallons of fuel, Force 1 would need to be resupplied with fuel every ten days.

2. Force 2 – Configuration A

The USMC Company COC will require a larger tactical diesel generator to meet the power demands of additional electrical requirements. As with the Force 1 configuration, the operating costs in the system cost section account for the acquisition and operation of a single generator annualized over a period of 10 years. The USMC Company COC diesel fuel power generator described throughout this chapter will provide power to COC operational equipment only. Additional generators would be required to provide power to collateral electrical loads.

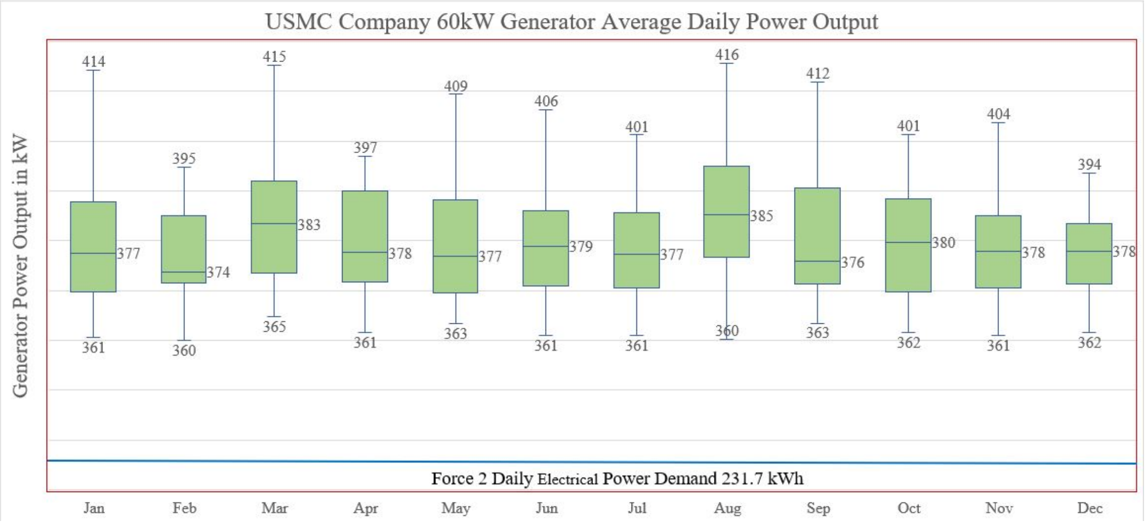


Figure 20. USMC COC 60kW Average Power Output

The USMC Company COC has significantly higher electrical load requirements than the USSOCOM SOF Team and is supported by a 60kW tactical generator. This is reflected in Figure 20, which displays the high, low, and median average daily energy output for each month. The average daily energy output for the year was 378.5 kWh, which supported the operational requirement of 231.8 kWh. The low daily average was 360kWh in the months of February and August. Notably, the highest daily average of 416kWh was recorded in August as well.

Table 7. Force 2 – Config A Fuel Consumption

Force Composition	Power Configuration	Avg. Hourly Fuel Consumption (L)	Avg. Daily Fuel Consumption (L)	Annual Fuel Consumption (L)
Force 2	Config. A (60kW)	5.69	137	49869

Force 2 – Configuration A’s average fuel burn rate is approximately 5.7 L per hour, resulting in 137 L per day and just under 50,000 L per year (Table 7). At this rate, a 3000-gallon pre-positioned fuel supply would support operations for approximately 82 days before a fuel resupply would be required.

B. CONFIGURATION B - GREENS 5KW HYBRID RESULTS

Configuration B is a PoR solar PV collection system with lead-acid and Li-Ion battery storage options. The system also has a DC controller, power distribution components, and an AC inverter. In configuration B, GREENS was configured with five sets of PV panel kits responsible for collecting and generating 5kWh of energy. As depicted in Figure 21, the GREENS 5kW system generates an average of 23.1 kWh of renewable energy per day, with a high average of 29.3kWh and a minimum average of 4.7kWh. However, the amount of renewable energy produced by the GREENS 5kW is insufficient to power the Force 1 and Force 2 compositions; therefore, configuration B was evaluated in HOMER utilizing a hybrid architecture augmented by a 10kW or 30kW tactical generator, respectively.

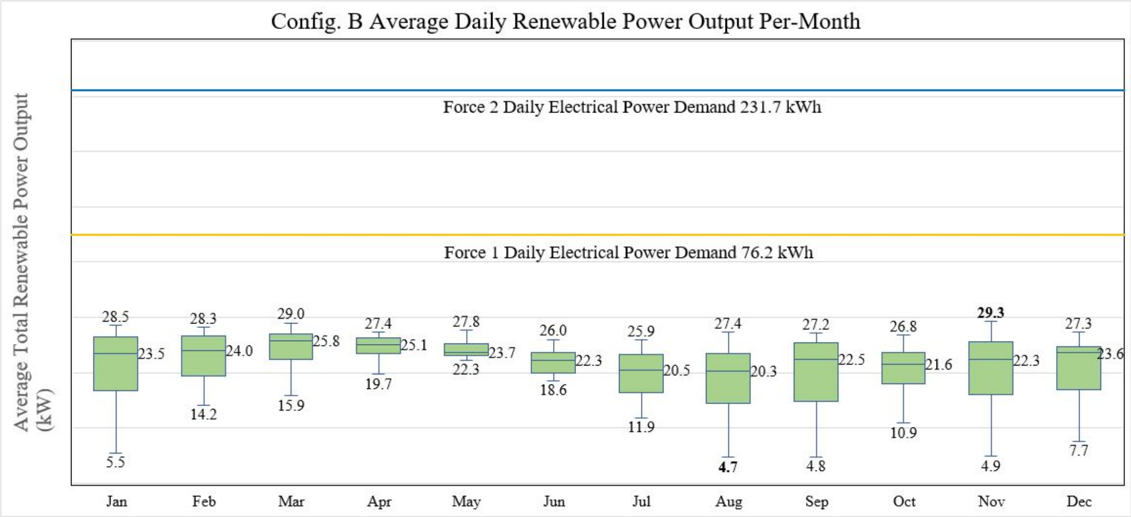


Figure 21. Config B. Average Renewable Output

Force 1 – Configuration B's average fuel burn rate is approximately 1.1 L per hour, resulting in 26 L per day and just under 9,500 L per year (Table 8). At this rate, a 200-gallon pre-positioned fuel supply would support operations for approximately 29 days before a fuel resupply would be required. Force 2 – Configuration B's average fuel burn rate is 3.68 L per hour, resulting in 88.3 L per day and 32238 L per year (Table 8). At this rate, a 3000-gallon pre-positioned fuel supply would support operations for approximately 128 days before a fuel resupply would be required.

Table 8. Force 1 and Force 2 – Config B Fuel Consumption

Force Composition	Power Configuration	Avg. Hourly Fuel Consumption (L)	Avg. Daily Fuel Consumption (L)	Annual Fuel Consumption (L)
Force 1	Config B (10kW Generator)	1.08	26	9475
Force 2	Config B (30kW Generator)	3.68	88.3	32238

1. Force 1 – Configuration B

The Force 1 composition has an operational power requirement of 76.2 kWh per day. The GREENS 5kW PV solar power system generates an average of 23.1kWh per day with a maximum production of 29.3kWh and a minimum of 4.7kWh of power, as shown in Figure 21. The average amount of energy produced meets approximately 28% of the Force 1 operational power requirements of 76.2kW. The remaining 72% of the power required by Force 1 is generated by tactical diesel generators that augment the system. In addition to producing energy, GREENS also has the capability to store up to 10.4 kWh of energy in Li-ion battery packs. This capability allows the system to run in hybrid mode when the PV panels are not being energized and results in an additional 3–5% renewable energy penetration in this configuration. In this configuration, GREENS is augmented by a 10kW tactical generator to compensate for the energy production requirement not met by GREENS for the USSOCOM SOF Team TOC. The 28% renewable energy offset provided by GREENS enables the Force 1 composition to scale down from a 30kW tactical generator to a 10kW generator resulting in additional fuel efficiencies

2. Force 2 – Configuration B

The Force 2 composition has an operational energy requirement of 231.8kWh per day. The effectiveness of configuration B for Force 2 is also significant, as depicted in Figure 21; however, the scale of impact in meeting energy requirements is reduced for Force 2 due to increased electrical load demand. The GREENS 5kW PV solar and battery storage system achieves 14.3% renewable penetration based on an average production of 29.3 kWh hours of energy and 10.4kWh of battery storage, and the Force 2 daily operational electrical power requirement of 231.8 kWh. The remaining 85.7% of Force 2's energy requirement is met by the tactical diesel generators that augment this configuration. In this configuration GREENS is augmented by a 30kW tactical generator to compensate for the energy production requirement not met by GREENS for the USMC Company COC. The nominal renewable energy offset provided by GREENS enables the Force 2 composition to scale down from a 60kW tactical generator to a 30kW generator resulting in additional fuel efficiencies.

C. CONFIGURATION C - MEHPS RESULTS

Configuration C is still in the initial acquisition process and will not be fielded until FY2024. Therefore, the energy production data has been estimated based on a combination of prototype specification data as well as components currently found in the GREENS kit that carried over to MEHPS. The configuration C system modeled for this evaluation consists of a 9kW PV panel kit, seven 2.6kW HEDBs, a power inverter, AC/DC controllers, and a tactical diesel generator mounted on a trailer. MEHPS has four available generator options, consisting of 3kW, 5kW, 10kW, and 15kW variants. As demonstrated in Figure 22, configuration C produces an average of 40.1kWh of renewable electrical energy per day, with a high average of 52.8kWh and a low of 8.5kWh. The PV generation and battery storage components alone do not meet the operational power requirements of either Force 1 or Force 2; therefore, configuration C will still require tactical generator support to compensate for the difference.

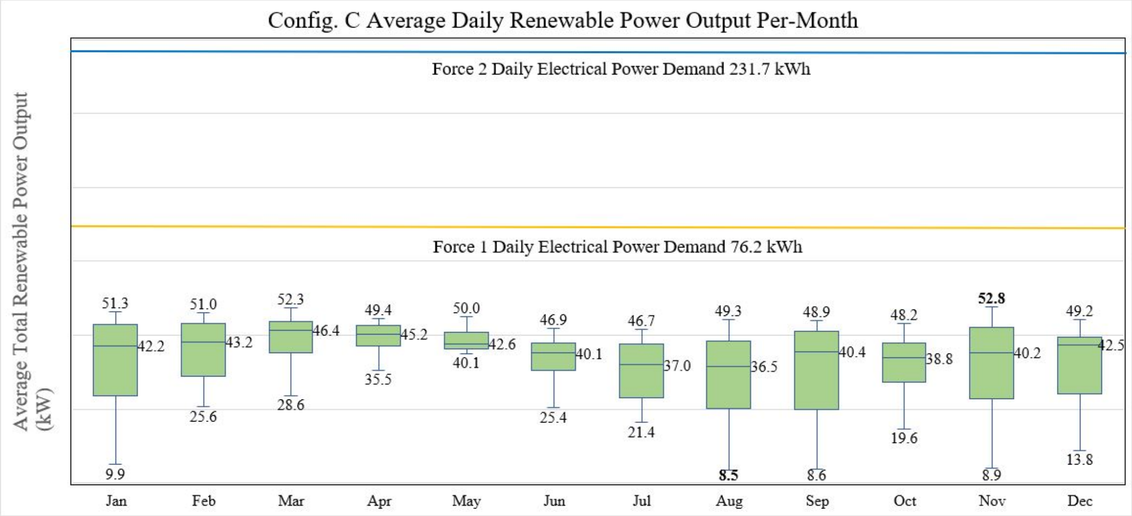


Figure 22. Config C. Average Renewable Output

Force 1 – Configuration C's average fuel burn rate is approximately .6 L per hour, resulting in 13.8 L per day and just over 5000 L per year (Table 9). At this rate, a 200-gallon pre-positioned fuel supply would support operations for approximately 55 days before a fuel resupply would be required. Force 2 – Configuration C was not observed due to insufficient generator options to meet the electrical requirements for the force composition.

Table 9. Force 1 and Force 2 – Config C. Fuel Consumption

Force Composition	Power Configuration	Avg. Hourly Fuel Consumption (L)	Avg. Daily Fuel Consumption (L)	Annual Fuel Consumption (L)
Force 1	Config C (10kW Generator)	.57	13.8	5045
Force 2				

1. Force 1 – Configuration C

Configuration C, as reflected in Figure 22, effectively provides 52.6 % of the Force 1 power requirement of 76.2 kWh per day by producing an average of 40.1kWh of renewable energy per day with a maximum of 52.1kWh and a minimum of 8.5kWh. The remaining 47.8% of the power required by Force 1 is provided by the integrated tactical generator that is part of the MEHPS. In addition to producing up to 52.1 kWh per day, the HEDB Li-ion batteries provide 18.2kWh of energy storage that optimize power distribution by running in hybrid mode with the diesel fuel power generator when the PV panels are not energized. The Force 1 composition requires a 10kW tactical generator to compensate for the power demand not provided by the renewable energy components of configuration C.

2. Force 2 – Configuration C

The Force 2 operational energy requirement of 231.8 kWh per day is unable to be met by the combined renewable and tactical generator architecture featured in configuration C. The MEHPS documentation indicates the system is being fielded in three tactical generator options. The 5kW generator system is considered a lightweight kit and is not trailer mounted; the 10kW and 15kW systems are trailer mounted and pre-configured from the factory to support either 4kW or 9kW PV systems. While the system is scalable, existing options are limited to the 5kW-15kW tactical generators. When evaluating configuration C against the Force 2 requirements, no feasible solution could be found due to the USMC Company level COC's daily operational energy demands outweighing the capacity of all available configuration C PV, battery storage, and tactical diesel generator combinations. If configuration C were paired with a 30kW tactical generator, the renewable energy production would provide 15.5% of Force 2's power requirement, and the remaining requirement would be met by the tactical generator.

D. CONFIGURATION D - CUSTOM COTS RESULTS

Configuration D is a notional renewable energy system that consists of commercially available components. These components include a generic 25kW PV system, a Tesla Powerpack, and a bi-directional 250kW converter. This system was evaluated in HOMER to assess whether 100% renewable power generation is achievable for either the USSOCOM SOF Team TOC or USMC Company level COC. Due to the risk of outages from intermittent sunlight during multi-day weather events, a 10kW backup generator is factored into the simulation. Configuration D produces an average of 131kWh of energy per day, as demonstrated in Figure 23, and can store 210kWh of energy in the

Tesla Powerpack 2 battery backup. This meets and exceeds the operational energy requirements of Force 1; however, the system falls short of meeting Force 2 energy demands and requires tactical generator support to augment the configuration.

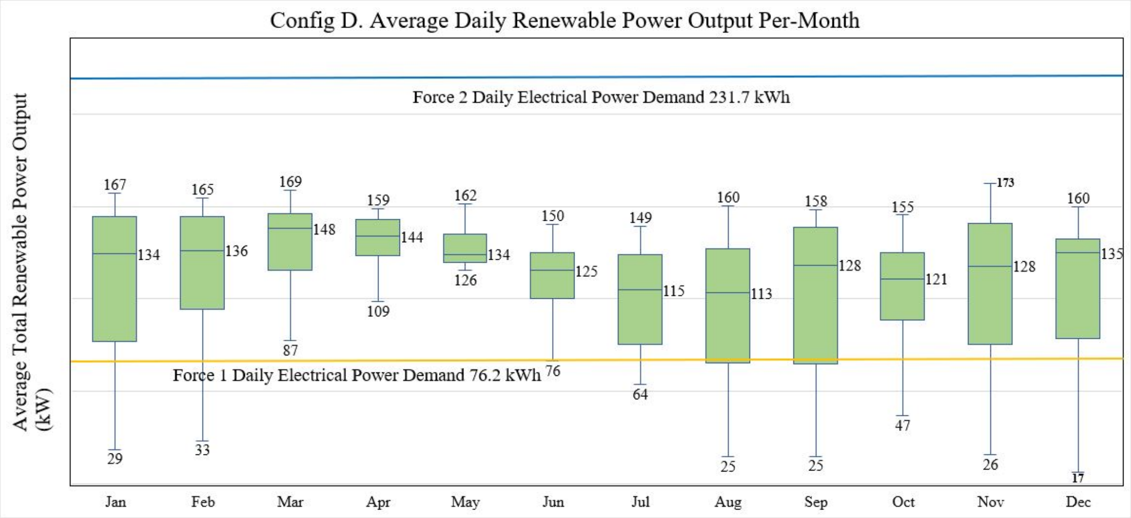


Figure 23. Config D. Average Renewable Output

Configuration D's meets 100% of Force 1's electrical demand; the fuel consumption rate is effectively zero, as displayed in Table 10. Given that 100% of the electrical demand is provided by configuration D, the 200 gallons of pre-positioned fuel should last the deployment duration depending on weather and PV component performance. Force 2 – Configuration D's average fuel burn rate is 1.75 L per hour, resulting in approximately 42 L per day and 15353 L per year, as shown in Table 10. At this rate, a 3000-gallon pre-positioned fuel supply would support operations for approximately 270 days before a fuel resupply would be required.

Table 10. Force 1 and Force 2 – Config D Fuel Consumption

Force Composition	Power Configuration	Avg. Hourly Fuel Consumption (L)	Avg. Daily Fuel Consumption (L)	Annual Fuel Consumption (L)
Force 1	Config D	0	0	0
Force 2	Config D (30kW Generator)	1.75	42.1	15353

1. Force 1 – Configuration D Results

Configuration D renewable energy production, as depicted in Figure 23, exceeds the Force 1 operational energy requirement of 76.2kWh per day by generating an average of 131kWh per day with a maximum average of 173kWh and a minimum average of 17kWh. In addition to producing 131kWh per day, the Tesla Powerpack can store 210kWh of energy in battery backup to compensate for low daily energy production caused by inclement weather and operational power demands during hours of darkness. The energy produced by configuration D not only meets the annual operational power requirements, eliminating the need for tactical diesel generators for Force 1; it also produces an excess of 9,180 kWh of energy annually. This excess energy can be utilized for additional life support, C5ISR Systems, and support peak energy usage during periods of high operational tempo. Although this configuration's power generation capability exceeds the operational energy requirements of Force 1, a 5kW-10kW backup generator should be included as part of the system in case of PV equipment failure or extended periods of inclement weather.

2. Force 2 – Configuration D Results

The Force 2 daily operational energy requirements of 231.8 kWh per day exceed the 131kWh daily average and 173kWh maximum daily average renewable energy production capacity of configuration D, as demonstrated in Figure 23. However, configuration D does provide approximately 56% of the 231.8kWh required daily to power the Force 2 composition. The energy generated coupled with the 210kWh of battery storage available from the Tesla Powerpack 2 substantially offsets reliance on tactical diesel generator power. The remaining 44% of Force 2's energy requirement is met by a 30kW tactical diesel generator that augments this configuration. Force 2 can be powered for over 24 hours on configuration D's renewable and stored energy due to cyclical charging and excess energy storage capacity.

E. FUEL CONSUMPTION COMPARISON

This section analyzes the impact of renewable energy generated and stored by configurations B, C, and D on the Force 1 and Force 2 fuel burn rates. Additionally, each renewable energy configuration's fuel consumption will be compared in order to measure the impact of increased efficiencies on a force composition's ability to operate for longer periods of time without requiring a fuel resupply.

1. Force 1

The fuel consumption savings provided by configuration B is a direct result of the ability to downsize the diesel fuel power generator from 30kW to 10kW, thereby achieving increased fuel efficiency during generator operation. The reduction in the number of hours the diesel fuel power generator is required to run per day due to solar power generation, and battery storage of energy also contributes to substantial fuel savings. As shown in Table 8, the average daily fuel consumption drops by over 100 L per day from 137 L to 26 L, resulting in a lower average annual consumption of 9,475 L. Aside from the considerable operating cost savings from reduced fuel usage, the enhanced fuel economy gained in configuration B by Force 1 has a measurable impact on the unit's refueling requirements. Assuming four 50-gallon diesel fuel drums were pre-positioned at an austere outstation on a remote island, this renewable penetration offset extends the fuel supply from 10 days to 29 days; and significantly eases the logistics requirements to resupply fuel to that location.

Overall, configuration C realizes an additional 47% reduction in fuel consumption compared to configuration B and 81% improvement over configuration A. As seen in Table 8, the SOCOM TOC supported by the MEHPS 10kW system consumes 13.8 L per day, totaling 5045 L of fuel over the course of a year as opposed to the approximately 9475 L consumed by the GREENS 5kW Hybrid configuration. The MEHPS 10kW provides an additional 22% of renewable energy production compared to the GREENS 5kW Hybrid system, accounting for 13,696kWh of the 27,813kWh of power required by the USSOCOM SOF Team TOC annually. As a result, 47% of the annual energy demand is produced by renewable sources; the 200-gallon pre-positioned fuel supply would now only need to be refueled every 55 days as opposed to 28 days in configuration B.

As depicted in Table 8, there is no fuel requirement for Force 1 due to an annual electrical load demand of 27,813kWh, and the configuration D production capacity of 44,040kWh of energy. Due to the excess 13,590kWh per year, there is no requirement for fuel resupply in support of operations in a remote environment. A backup generator, along with prepositioned fuel stores, should be deployed to charge the Tesla powerpacks for configuration D in the event of sustained inclement weather or damage to the PV collection panels.

Even the slightest increase in fuel efficiency can translate into significant operational impacts by extending the utilization timeline for existing fuel supplies, as seen in Table 8. For example, the GREENS 5kW solution only produces 28% of the energy required by Force 1; however, the system extends the refueling window by nineteen days, or 290% enabling the unit to conduct operations for a full month without being re-supplied. MEHPS produces 50% of the required energy annually and improves fuel efficiency by approximately 18% and extends the fuel resupply window from 10 days to 55 days when compared to configuration A, allowing the unit to operate for nearly two months without a fuel resupply. Ultimately, configurations B and C, which are either fielded or in the acquisition process, provide a measurable impact to Force 1's ability to operate without a robust logistics tail. Configuration D, which is a notional design utilizing COTS equipment, has the potential to allow Force 1 to operate indefinitely with minimal backup fuel supplies (Table 10).

Table 11. Force 1 – Force Composition 1 Fuel Consumption

Force Composition 1				
Power Configuration	Avg. Hourly Fuel Consumption (L)	Avg. Daily Fuel Consumption (L)	Annual Fuel Consumption (L)	Fuel Resupply Window (Days)
Config A (30kW)	3.07	73.7	26,896	10
Config B (GREENS 5kw)	1.08	26	9475	29
Config C (MEHPS 15kW)	.57	13.8	5045	55
Config D (COTS)	0	0	0	∞

2. Force 2

The delta between the electrical load requirement for Force 2 and the electrical load served by the renewable energy systems is substantially larger than observed in the configurations supporting Force 1. This is due to the exponentially higher electrical load requirement presented by the C5ISR systems and supporting infrastructure supporting Force 2. Configuration B produces just under 10% of Force 2's requirement; however, this configuration reduces hourly fuel consumption by 35% resulting in an annual fuel savings of 17,631 L. This equates to an average daily fuel burn rate of 88.3 L per day versus 137 L running the generator alone and annual consumption of approximately 32,238 L versus 49,869 L, respectively. The impact of this increased fuel efficiency is realized by an extended refueling window. A 3000-gallon fuel bladder will now provide 128 days of fuel for a site deployed with the GREENS 5kW system, compared to 82 days with the standalone 60kW generator.

Configuration C was not evaluated because none of the MEHPS generator variants were capable of supporting Force 2's power requirements. Theoretically, if MEHPS were paired with a third-party 30kW generator, then configuration C fuel consumption would be reduced from configuration B's 88.3 L per day to 72.1 L per day, realizing an annual fuel savings of 23,239 L. This implementation would impact the Force 2 fuel re-supply window by extending it from 128 days to 157 days, respectively.

Configuration D delivers a considerable reduction in fuel consumption over configurations A and B, as seen in Table 9. The daily average fuel burn rate is just over 42 L per day which represents a reduction of greater than 50% compared to 88 L per day consumed in configuration B. At this rate, when utilizing a 3000-gallon fuel bladder, the resupply window is extended to 270 days, which is a 53% increase over the 128 days of fuel supply with GREENS. Ultimately, configuration D consumes 15,353 L of fuel per year compared to 32,328 L with configuration B and 49,869 L with configuration A. Configuration D reduces Force 2 hourly fuel consumption by 70% saving over 34,500 L of fuel on an annual basis. Configurations B and D both provide a measurable impact on

Table 12. Force Composition 2 Fuel Consumption

Force Composition 2				
Power Configuration	Avg. Hourly Fuel Consumption (L)	Avg. Daily Fuel Consumption (L)	Annual Fuel Consumption (L)	Fuel Resupply Window (Days)
Config A (60kW)	5.69	137	49869	82
Config B (GREENS 5kw)	3.68	88.3	32238	128
Config C (MEHPS 15kW)				
Config D (COTS)	1.75	42.1	15353	270

Force 2's operational capability through extending the fuel supply window by six weeks and 26 weeks, respectively Table 9. As noted in the previous section, configuration D is notional and has not been formally tested, while configuration B is a USMC PoR.

F. COST DATA

While not a primary objective of this research, cost-effectiveness of system acquisition and life cycle management are viable considerations when pursuing new technologies. The total system operating costs for the renewable systems analyzed in this thesis were measured against the baseline total systems operation costs of tactical generators. Although not the focus of our work, there are quantifiable cost factors that U.S. government policymakers and DOD decision-makers must take into consideration when incorporating new systems into military capabilities and mission planning. This section will discuss findings on the costs considerations of each of the modeled systems outlined in Table 13.

Table 13. Annual System Cost Comparison

Force Composition 1						
System	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Configuration A (30kw generator)	$2,165.92	$14,127.97	$87.60	$334,320.22	-$203.84	$350,497.87
Configuration B (10kW generator)	$5,671.23	$7,373.31	$98.74	$117,778.91	-$243.04	$130,679.15
Configuration C (10kW generator)	$7,438.09	$7,335.02	$21.99	$62,703.69	($820.51)	$76,678.27
Configuration D	$17,443.41	$14,415.94	$21.99	$0.00	($1,866.06)	$29,993.30
Force Composition 2						
Configuration A (60kW generator)	$4,728.91	$16,272.19	$137.60	$619,871.78	-$466.88	$640,543.60
Configuration B (30kW generator)	$11,345.87	$13,101.37	$90.14	$398,248.06	($3,587.29)	$419,198.15
Configuration C						
Configuration D (30kW generator)	$34,926.37	$15,303.86	$17.47	$190,837.36	-$1,593.15	$226,255.78

1. Force 1

The cost data for Force 1 is detailed in Table 13; these expenses are annualized over a 10-year period and cover initial capital for systems acquisition, replacement cost, operation and maintenance (O&M), fuel costs, and salvage expense. Configuration A is the baseline that configurations B-D will be measured against and consists of a 30kW tactical generator. Configuration A features the lowest upfront capital costs averaging $2,165 per year; however, the annual fuel costs of $334,320 making it the most expensive system when total life cycle costs are considered. The initial capital outlay of $5,651 to procure configuration B is over twice as much as configuration A; however, replacement costs are almost 50% less, and the fuel costs are 65% less at $117,778 per year resulting in an annual savings of nearly $220,000. Configuration C's acquisition cost averages over $5,200 per year more than configuration A; however, the replacement cost is also 50% less. Configuration C's most aggressive savings over configuration A are realized from reduced fuel costs; configuration C costs over $270k per year less to fuel, resulting in a total annual savings of $273,819. Configuration D is the most expensive annualized acquisition cost at over $17k per year, although it provides 100% of the renewable energy demand to Force 1, eliminating fuel and O&M costs. As a result, configuration D is over $320k less than Configuration A. As seen in Table 13, the total system acquisition cost is progressively reduced as renewable energy penetration offsets fuel consumption, ultimately eliminating fuel cost in configuration D.

2. Force 2

The cost data for Force 2 is detailed in Table 13; these expenses are annualized over a 10-year period and cover initial capital for systems acquisition, replacement cost, operation and maintenance (O&M), fuel costs, and salvage expense. As with Force 1, configuration A is the baseline that configurations B-D will be measured against and consists of a 60kW tactical generator. Configuration A features the lowest upfront capital costs for Force 2, averaging $4,728 per year; however, the annual fuel costs of $619,871 make it the most expensive option over when total life cycle costs are considered. The initial acquisition cost of $11,345 to procure configuration B for Force 2 is over twice the amount of configuration A; however, replacement costs are approximately 20% less, and the fuel costs are 35% less at $398,248 per year resulting in an annual savings of just over $220,000. Configuration C was not evaluated in support of Force 2 due to insufficient generator options. Configuration D has the most expensive annualized acquisition cost at $34,926 per year, and its replacement costs are comparable to configuration A. However, configuration D delivers a 70% fuel cost savings annually for Force 2. As a result, configuration D realizes a total annual cost savings of just over $414,000 compared to Configuration A. As seen in Table 13, the initial acquisition costs for renewable energy solutions are more expensive than tactical diesel generators. However, as the systems increase their renewable penetration, the fuel savings, maintenance, and replacement costs deliver substantial savings to the annualized total operating expenses.

G. SUMMARY

This chapter evaluated four energy production systems: tactical diesel fuel power generators from configuration A, which formed the baseline against which the renewable systems in configurations B through D were measured. The four configurations were evaluated based on the electrical load requirements for two force compositions; the USSOCOM SOF Team sized element was called Force 1, and the USMC Company COC element was Force 2. As a result, eight design points were evaluated in total. Each applicable renewable energy system has proven to effectively offset fuel consumption, ultimately impacting the force composition’s ability to operate for extended periods without requiring a fuel re-supply.

1. Force 1

The electrical load served by each renewable energy production configuration in support of Force 1 is measured against both the annual energy requirements and the tactical diesel fuel power generator (configuration A) annual baseline output. Configuration B meets 28% of Force 1 annual operational power requirements, while configuration C meets 50% of the annual requirement. However, neither configuration B nor C can meet 100% of the annual demand; they both substantially increase the refueling window for Force 1. The energy produced by configuration D not only meets the annual operational power requirements, eliminating the need for tactical diesel generators for Force 1; it also creates an excess of 9,180 kWh of energy. Force 1 and Force 2 can utilize this excess energy for additional life support, C5ISR Systems, and support peak energy usage during periods of high operational tempo. As demonstrated in Table 8, enhanced fuel efficiency translates into significant operational impacts by extending the utilization timeline for existing fuel supplies. For example, the GREENS 5kW solution only produces 28% of the energy required by Force 1; however, the system extends the refueling window by nineteen days, or 290% enabling the unit to conduct operations for an entire month without being re-supplied. MEHPS produces 50% of the required energy annually, improves fuel efficiency by approximately 18%, and extends the fuel re-supply window from 10 days to 55 days compared to configuration A, allowing the unit to operate for nearly two months without a fuel re-supply. Ultimately, configurations B and C, which are either fielded or in the acquisition process, provide a measurable impact to Force 1's ability to operate without a robust logistics tail. Configuration D, which is a conceptual design utilizing COTS equipment, has the potential to allow Force 1 to operate indefinitely with minimal fuel reserves (Table 10).

2. Force 2

The electrical load served by each configuration in support of Force 2's electrical load requirement is measured against both the annual energy requirements and tactical diesel fuel power generator (configuration A) annual baseline output. The delta between electrical load requirement and electrical load served by the renewable energy systems is substantially larger than observed in Figure 33, representing the configurations supporting Force 1. This is due to the exponentially higher electrical load requirement presented by the C5ISR systems and supporting infrastructure supporting Force 2. Configuration B produces just under 10% of Force 2's requirement, however; this configuration reduces hourly fuel consumption by 35% resulting in an annual fuel savings of 17,631 L. Configuration C was not evaluated because none of the MEHPS generator variants were capable of supporting Force 2's power requirements. Theoretically, if MEHPS were paired with a 30kW tactical generator it would provide 15.5% of Force 2's power requirement and realize an annual fuel savings of 23,239 L. Configuration D provides 47% of the energy required for Force 2 and reduces hourly fuel consumption by 70% saving over 34,500 L of fuel on an annual basis. Configuration B and D both provide a measurable impact to Force 2's operational capability through extending the fuel supply window by 6 weeks and 26 weeks respectively Table 9. As noted in the previous section, configuration D is notional and has not been formally tested while configuration B is a USMC PoR.

V. CONCLUSIONS, RECOMMENDATIONS, AND FUTURE WORK

This chapter summarizes our findings and conclusions drawn from the research conducted on three renewable energy configurations measured against a baseline tactical diesel generator configuration. Additionally, in this chapter, we will discuss the quantifiable costs of our modeled systems and the limitations of our research. Lastly, we will discuss our recommendations and identify potential areas for future study.

The primary objective of our research was to measure the effectiveness of current, or near-to-market, COTS/GOTS energy storage and PV charging solutions to augment or replace diesel fuel power generators in support of expeditionary military operations. The authors accomplished this objective by assessing the energy requirements of team to company-sized elements and measuring the ability of renewable energy systems to meet the operational electrical energy demand of those units. The stand-alone and hybrid COTS/GOTS energy storage and charging solutions were modeled and simulated in the HOMER Micropower Optimization Model in the HOMER Pro software program. The secondary objective of this research was to measure the impact of running COTS/GOTS PV solar power and Li-ion battery storage solutions in tandem with tactical diesel generators and demonstrate their effects on the resupply schedule for prepositioned fuel stores supporting remote operations.

Based on these objectives and the results of our analysis, we have identified the optimal renewable energy configuration for each force disposition and the most suitable solution overall. Force 1 is best served by configuration B due to the lower energy demands and smaller footprint. The maxed-out configuration consisting of five sets of panels and batteries cuts the daily fuel requirement for Force 1 by approximately 65% and extended the refueling window by over two weeks. Configuration C is also a good option due to the increased energy storage capacity and fuel efficiencies; however, the logistics required to deploy the system could be excessive. Ideally, configuration B would be scaled to two maxed GREENS kits. One set would power terrestrial RF, ECU, and support components (such as lighting, televisions, coffee pots). The second set would power IT/network infrastructure and satellite communications. Although configuration D is theoretical, it is the most viable solution for the USMC Company sized element. The components are currently used in the commercial sector and could be rapidly prototyped to meet the requirements for military use cases. Configuration B is inadequate and delivers marginal gains compared to configuration D. Table 9 shows that its fuel consumption is 50% more efficient than configuration B and the fuel resupply window is over twice as long. With minor modifications, configuration D could be the most effective option for both Force 1 and Force 2 due to its substantial fuel savings for both force compositions. Force 1 would require a modular dismounted variant capable of being deployed via tactical airdrop or amphibious landing craft.

A. FINDINGS

This thesis assessed the feasibility of employing PV solar collection systems paired with high-density lithium-ion battery packs to complement or replace traditional diesel fuel power generators to meet the power needs of remote expeditionary forces. Our research demonstrated that fielded and near-to-market PoR PV lithium-ion power solutions in a stand-alone configuration are currently incapable of meeting the requirements of USSOCOM SOF Team, and USMC Company sized elements. However, when deployed in a hybrid configuration, the renewable energy solutions significantly extended the operating time between refueling for tactical diesel generators. Furthermore, our research found that a notional COTS system can sustain operations independently via PV solar charging solutions and high capacity battery storage in remote locations for USSOCOM SOF Team sized elements.

The United States Marine Corps Commandant, General David H. Berger, wrote in his December 2021 *A Concept for Stand-in Forces* that,

> Stand-in Forces are small but lethal, low signature, mobile, relatively simple to maintain and sustain forces designed to operate across the competition continuum within a contested area as the leading edge of a maritime defense-in-depth in order to intentionally disrupt the plans of a potential or actual adversary…composed of elements from the Marine Corps, Navy, Coast Guard, special operations forces, interagency, and allies and partners.” (Commandant of the Marine Corps 2021, 4)

We have shown that it is possible for PV solar arrays and commercial-off-the-shelf (COTS) lithium-ion batteries to replace tactical diesel generators as a primary operational energy source for small echelon unit Stand-in Forces (SIF).

How much of a tactical advantage can renewable energy systems provide by reducing the frequency of complex fuel resupply operations to support diesel fuel power generators? General Berger has called for SIF survivability and sustainability to be based upon their ability "to survive inside," and "to achieve logistic sustainability inside a contested area." (Commandant of the Marine Corps 2021, 18; 21). He expounds on this further calling for "demand reduction across the life-cycle of stand-in forces, from their design to their employment…including design features like hybrid-electric or fully electric vehicles [to] reduce future fuel requirements." (Commandant of the Marine Corps 2021, 21). We have demonstrated that all our model systems will help achieve the logistics sustainability inside contested areas that General Berger has identified. We further consider our models' total life cycle and operational costs in the following section and highlight the categories where renewable energy alternatives were demonstrated to be more affordable.

As evidenced in Chapter IV, we demonstrated that currently available and near-to-market COTS/GOTS solutions are sufficiently scalable and customizable to meet the operational energy requirements of deployed team to company-sized elements. Our research modeled a maximum of five GREENS 5kW systems deployed as one set, a single MEHPS, and single custom COTS solution. These systems could be scaled and partitioned to support distinct portions of USSOCOM SOF Team to USMC Company sized element power demands. For example, instead of supporting an entire USSOCOM SOF Team with one MEHPS 10kW, a system could be configured to support RF Communications, IT Infrastructure, and C5ISR systems, and a second system dedicated to life support components. Additionally, these systems could be scaled to enable pre-positioned fuel stores to last the entire duration of an exercise or operation in simulated or real-world contested environments.

This research was limited to existing or near-market PV power generation systems, accompanied by lithium-ion energy storage solutions. The analysis in this thesis focused on systems deployed to remote island environments in the South Pacific. In addition to power distribution capacity, cost, maintenance, and usability were also examined. This thesis remained vendor-agnostic; however, existing capabilities were derived and modeled in HOMER utilizing specifications of current and upcoming products from UEC Electronics limited liability company (LLC), Cummins Incorporated (Inc.), and Tesla Inc.

The results from the modeling and simulation of four distinct design points for the USSOCOM SOF Team TOC and the USMC Company level COC were presented in a case study that demonstrated the simulation and optimization of hybrid energy solutions in HOMER. These simulations' output provided evidentiary support on whether existing PoR, near-to-market PoR, and COTS PV battery storage systems can provide an alternative to tactical diesel generators that currently power SOF and Expeditionary forces in remote environments. The data is organized into four sections; the baseline diesel fuel power generator portion establishes reference data for existing system capital costs, fuel consumption, and fuel costs over a one-year period. This baseline is followed by an evaluation of GREENS, MEHPS, and COTS data for each unit composition.

The results from this research will equip team leaders, company commanders, and higher echelon leadership and decision-makers with the data required to implement hybrid and standalone energy solutions that meet President Biden's Interim National Security Strategy guidance is, to "develop capabilities to better compete and deter gray zone actions," and also "prioritize defense investments in climate resiliency and clean energy" (The White House 2021, 14)

B. RECOMMENDATIONS

Our research demonstrates that PV lithium-ion power solutions deployed in a hybrid configuration may extend the operating capacity of conventional diesel fuel power generators; and ultimately, that such a system can sustain operations independently via PV solar charging solutions in remote locations.

It is very feasible to employ high-density lithium-ion battery banks to complement or replace traditional diesel fuel power generators to meet the operational energy requirements of remote expeditionary forces. PV lithium-ion power solutions deployed in a hybrid configuration will significantly extend the operating capacity of prepositioned fuel supplies that power conventional diesel generators. Ultimately, such a system can sustain certain limited operations independently via PV solar charging solutions in remote locations. Hybrid PV lithium-ion power solutions will increase the operational capability of USMC and USSOCOM expeditionary forces conducting distributed operations in contested and gray zone environments.

PV lithium-ion power solutions deployed in a hybrid configuration will also meet the aim of the DOD energy policy by using renewable energy sources and alternative fuels to enhance operational capability, improve both energy security and resilience, and reduce energy costs (Department of Defense 2018).

C. FUTURE WORK

We recommend exploring how energy management software options could best optimize the hybrid system power production and usage from the solar PV, battery storage, and diesel fuel power generators. We believe that by controlling for the optimal usage rates from the various sources, the overall efficiency of the hybrid system could be increased. We suggest more modeling be considered to provide a more robust analysis on this.

We recommend additional research be done on alternative PV materials, such as fabric or textile-based arrays. Lighter and more flexible fabric or textile arrays could prove to be more operationally feasible and could increase total operational power output with less weight and mass.

Similarly, we also recommend further research into emerging battery technologies. Newer technologies such as lithium-ion silicon, graphene, or iron flow could all prove to be more efficient energy storage systems than the lithium-ion systems we covered in this research.

This research examined COTS/GOTS energy storage and PV charging solutions combined with diesel fuel power generators into hybrid power systems. We recommend further study into how other renewable energy sources such as tidal, geothermal, or wind generation could augment hybrid power systems in support of expeditionary military operations. We also recommend further examination of alternative power generation technologies such as hydrogen and nuclear power options.

The scope of our research looked specifically at a typical location with weather and solar characteristics common for the South Pacific. We recommend further study of how locations in the extreme northern or southern latitudes, traditionally cold weather environments, would differ in their results and what the operational impact would be. This research would be important to consider using hybrid systems to provide operational power for remote outposts in the Arctic or Antarctic.

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