Integration of Renewable Energy in Tactical Military Camps

By

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Abstract

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Modern warfare, as witnessed in Iraq and Afghanistan over the past decade, has reaffirmed the need to safely supply forward-deployed troops. As technology improves the effectiveness of soldiers, our reliance on energy also increases. Transporting fuel both siphons off manpower and offers the enemy an easy target. At one casualty per every 24 fuel convoys, the cost of fuel in lives is too high.

At the tactical level of war, forward-deployed troops are reliant on fossil fuel generators to power their camps. While the military has begun to embrace renewable energy at the operational and strategic levels of war, limited resources have been put towards applying this same technology to the soldier on the front lines. The research presented herein explores whether renewable energy can reduce the fuel dependence of tactical camps while offering the same level of service.

Four energy system scenarios were analyzed using the United States Army Corps of Engineers Infrastructure Component Model (ICM) and Infrastructure Assessment Model (IAM). These models are taught to officers in the U.S. Army's Engineer Corps as a part of their educational curriculum. The ICM modeled what components were needed for the energy system. Then, the IAM modeled how these systems operated in normal conditions and adverse conditions.

The following four scenarios were analyzed using the above models:

- Case 1: Decentralized diesel generators loaded at 30% capacity.
- Case 2: Decentralized diesel generators loaded at 80% capacity.
- Case 3: 100% renewable energy generation.
- Case 4: Hybrid energy system consisting of solar and diesel generation.

When comparing the four cases, the best system for reducing the reliance on fossil fuel was the hybrid system that used both renewable energy and fossil fuel generators. The 100% renewable typography was unfeasible because of the large footprint of generation assets and the enormous weight of required battery systems needed to assure energy reliability. The scenarios also showed that centralizing loads onto fewer generators would decrease fuel reliance.

This research has shown that renewable energy can reduce the fossil fuel dependence of tactical military camps while offering a similar or improved level of service. There are a series of variables that a commander must fully understand when deciding how to power a camp.

Optimizing for one variable, such as reduced fuel consumption, will affect the other variables. Renewable energy will allow units to go further, stay longer, and, one day, free the military from the chains of fossil fuel.

Dedication

This thesis is dedicated to the American military personnel that were injured or made the ultimate sacrifice ensuring that their fellow warfighters were properly supplied.

"And when our work is done,
Our course on Earth is run,
May it be said, "Well done"
Be thou at peace."
-Excerpt from the United States Military Academy at West Point Alma Mater

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Glossary

Area of Operations: The area that a military unit or entity will perform its mission.

Electrical Energy Storage (EES): a device or system used to hold electrical energy until it is needed by the user.

Energy System: a system that takes a fuel source, generates energy, and delivers said energy to the end-user.

Forward Deployed: Troops deployed in an area in or near contact with the enemy.

Infrastructure Assessment Model (IAM): An infrastructure model that analyzes how an infrastructure system operates in normal and adverse conditions.

Infrastructure Component Model (ICM): An infrastructure model that analyzes the various components of a given infrastructure system. The components can be specific physical apparatuses or other infrastructure systems.

Infrastructure Environment Model (IEM): An infrastructure model that analyzes the environmental implications and effects of a proposed or built infrastructure system.

Modified Table of Organization and Equipment (MTOE): A document listing the equipment soldiers that a unit is issued.

Reverse Osmosis Water Purification Unit (ROWPU): The ROWPU is a water purification unit that can turn non-potable water into potable water.

Supply Lines: The logistical route and/or process used to deliver materials to the warfighter.

Tactical Operations Center (TOC): The planning center of a military camp where operations are planned and decisions are made.

Warfighter: A soldier regardless of military branch.

Executive Summary

As witnessed in Iraq and Afghanistan over the past decade, Modern warfare has reaffirmed the need to safely supply forward-deployed troops. While technology improves the effectiveness of soldiers; it also increases our reliance on energy. Transporting fuel both siphons off necessary manpower and offers the enemy an easy target. At one casualty per every 24 fuel convoys, the price of fuel in terms of soldier lives has become too high. In addition, our military's reliance on fossil fuel has reduced our maneuverability and our ability to meet the given objective.

At the tactical level of war, forward-deployed troops are reliant on fossil fuel generators to power their camps. While the military has begun to embrace renewable energy at the operational and strategic levels of war, limited resources have been put towards applying this same technology to the soldier on the front lines. The research presented herein explores whether renewable energy can reduce the fuel dependence of tactical camps without reducing the level of service.

Four energy system scenarios were analyzed using the United States Army Corps of Engineers Infrastructure Component Model (ICM) and Infrastructure Assessment Model (IAM). First, the ICM modeled what components were needed for the energy system. Then, the IAM modeled how these systems operated in normal conditions and adverse conditions.

Case 1 was the baseline case where the camp was powered by decentralized diesel generators loaded at 30% of the generators capacity. This was the common camp configuration found in many tactical military camps. Case 2 was similar to Case 1 except that generators were sized so that they were loaded at 80%. Case 3 was the first case where renewable energy generation was analyzed. This case questioned how a camp powered on 100% renewable energy would operate. Case 4 showcased a hybrid energy system that used both renewable energy generators and diesel generators. The results of the four cases studies are listed below in **Table 1** for the ICM and **Table 2** for the IAM.

Table 1: Modified Infrastructure Component Model Results.

Model Prompt	***Analysis Unit***	***Case 1***	***Case 2***	***Case 3***	***Case 4***
Deployment	Mission Weight (Pounds)	17750	16032	14437	11602
Generation and Fueling	Daily Fuel (Gallons)	79	104	N/A	37
Distribution and Storage	Footprint (Square Feet)	78.6	72.1	7205	2441.3
Use	Daily Actual Load (kWh)	586	586	586	586
Consolidation and Repurposing	Generator Loading	20-25%	50-65%	N/A	40-45%
Coordination	Control System Needed	No	No	Yes	Yes

Table 2: Infrastructure Assessment Model Results

System Conditions	Model Prompt	Analysis Unit	Case 1	Case 2	Case 3	Case 4
Normal	Required	Generation Capability (kW/kW)	552%	200%	172%	287%
	Ready	Generation Capacity (kW)	190	105	90	70
	Organized	Control System Needed	No	No	No	Yes
Adverse	Tough	Required Load Supported	No	No	No	No
	Redundant	Back-Up System Available	No	No	No	Yes
	Prepared	Critical Load Supported	Yes	Yes	No	Yes

Deploying hybrid energy systems that combine renewable generation assets and traditional diesel generators offer the best option for reducing fuel consumption in tactical situations. As **Table 3** notes, each energy system offers commanders the ability to optimize their camp for their given tactical situation.

Table 3: Optimization Variable Results.

Variable	Optimization	Optimal Energy System
Footprint	Minimize	Diesel Generation Properly Loaded (Case 2)
Fuel Consumption	Minimize	Hybrid System (Case 4)
Maintenance	Minimize	Hybrid System (Case 4)
Required Training	Minimize	Diesel Generation Underloaded (Case 1)
Generation Capacity	Maximize	Diesel Generation Underloaded (Case 1)
Fuel Storage Required	Minimize	Hybrid System (Case 4)
Fuel Storage Required	Minimize	Hybrid System (Case 4)
Resupply Frequency	Minimize	Hybrid System (Case 4)

While renewable energy has the ability to reduce the military’s reliance on fossil fuel at tactical military camps, the decision to implement this technology will require strong support from the military at all levels. This hurdle should not be underestimated. The military has two contradictory stances towards energy systems. The prevailing culture at the tactical level is “just add another generator” as evidenced by the gross over-generation at numerous camps. This culture believes that generation capacity must be increased to ensure resilience when in reality the generation capability is often negligible because the actual limiting factor is a lack of fuel. The competing stance is wanting to have a nimble force that can project power farther and for longer periods of time. This culture wants a force that is not weighted down by unnecessary generators and lengthy supply routes. Hybrid energy systems appease both groups. Their lighter weight and energy independence make them ideal for a force that is focused on increased freedom of movement. The ability to add generation assets means the warfighter can rest easy knowing that there is enough generation capacity to meet the needs of their energy systems.

Introduction

A regrettable downside of the United States military's need for fossil fuel has been the unnecessary fuel related deaths of soldiers. During a three-month period in 2010, a Marine was wounded for every 50 fuel convoys (Marine Corps Expeditionary Energy Strategy 2011. Pg. 7). This ratio is even worse for the Army, which calculated that in 2007 every 24 fuel convoys resulted in at least one casualty (Brygider et al. 2014. Pg.9). To put these two ratios in perspective, in 2010, 40 million gallons of fuel were shipped into Afghanistan per month (Brygider et al. 2014. Pg.9).

One source of the military's fuel problem is how tactical military camps are powered. Large camps with populations in the tens of thousands are able to connect to the local grid or have their own microgrids. Small tactical military camps often do not have this luxury and the majority of military camps in conflict areas are small remote outposts that rely on a piecemeal array of military and local generators. Tactical camp fuel consumption is worsened when one takes into consideration the fuel consumed in transporting fuel to these camps. For every gallon of fuel used in these generators, seven gallons of fuel is required to transport said fuel (Vavrin 2010. Slide 7). Ultimately, "moving and protecting [fuel] diverts forces away from combat missions" but "a force that makes better use of fuel will have increased agility, improved resilience against disruption, and more capacity for engaging [our] partners" (Brown et al. 2012. Pg. 1).

Renewable energy could be the solution to the military's dependence on fossil fuel. Renewable energy offers a means to offset a camp's load and thus reduces the amount of fuel that needs to be transported to said camp. Renewable energy also offers the military a tactical edge. Renewable energy both decreases the amount of resources that need to be dedicated to supplying troops and reduces the number of opportunities the enemy has to attack supply lines.

Problem Statement

This thesis will show that integrating renewable energy into tactical military camps will reduce fuel dependency, while offering a similar and potentially superior level of service. As previously noted, numerous injuries and casualties can be linked to supplying the warfighter with fuel. Renewable energy systems will be able to offset or completely handle the energy load of a tactical military camp. In turn, this will reduce the number of fuel resupply missions needed. Beyond the ability to save lives, integrating renewable energy into tactical camps offers the following benefits.

Reliability.

Onsite energy generation using renewable energy only requires initial installation and periodic maintenance compared to the constant resupply needs of fossil fuel generators. Commanders could potentially no longer be constrained by the arrival of fuel resupplies to sustain operations. If fossil fuel powered generators are used in conjunction with renewable energy, the refuel rate is reduced and is less predictable. This means less fuel convoys and less predictable behavior that the enemy can capitalize on.

Critics of renewable energy generation will argue that soldiers will now be reliant on clear weather and perfect conditions for energy generation. While this is true, it is much easier to predict weather patterns than the enemy's patterns. Constant resupply convoys give the enemy numerous opportunities to attack and disrupt operations. As **Table 4** shows, energy generation from fossil fuel and renewable energy require the same infrastructure support systems but less continual inputs.

Table 4: Renewable energy and fossil fuel infrastructure system characteristics.

	Fossil Fuel	***Renewable Energy (Solar and/or Wind)***
System Deployment	Easy	Moderate
Inputs	Continuous Fuel Resupply	None
Maintenance	Moderate	Minimal
System Teardown	Easy	Moderate

Resilience.

Renewable energy increases system resilience compared to fossil fuel energy generation. With fossil fuel energy systems, the enemy has the option to attack the generator itself, the generator's fuel storage, or the fuel supply line. In contrast, renewable energy generation only offers the enemy one potential target.

Environmental Sustainability.

Renewable energy generation emits less direct emissions to the environment and there is no recurring fuel consumed transporting fuel to support the energy system. To determine whether the system as a whole is less environmentally intrusive, a formal life-cycle assessment would need to be conducted.

Scope

This thesis aims to fill the void in research on tactical use of renewable energy. As domestic use of renewable energy has increased in past years, the military has begun to adopt these technologies to power permanent installations in non-combat areas of operations (AO). However, this same technology is not easily transferable to combat AOs because of its fragility. While the private sector has poured significant resources into R&D of renewal assets, the military has yet to invest as heavily into military appropriate renewable energy assets and capabilities. This lack of investment is primarily a result of there being an extensive list of military R&D expenses and relatively limited funding.

The Tactical Level of War.

This research is focused on energy systems used in the tactical level of war. Modern military theory divides war into three levels: tactical, operational, and strategic. Tactical warfare is the achievement of specific military objectives through combat. This level is colloquially referred to as “boots on the ground”. In contrast, the operational level of warfare is the in-theater movement of forces in order to position them to best achieve tactical victories. Operational warfare includes the decision to deploy troops and troop surges such as in Afghanistan in 2009. The strategic level of war is the use of the military to meet national policy such as the decision to invade Afghanistan and ultimately withdraw from Afghanistan (Three Levels of War 1997).

The military’s use of fuel impacts all three levels of warfare. Using Afghanistan as an example, we can see how the miniscule task of fueling multiple small outpost not only affects the immediate AO but can ultimately affect national policy. At the tactical level, a commander decides to implant his forces in a small town to better engage the locals. These troops require a generator to fuel their security lights and recharge the batteries that power their communications equipment, weapons systems, and more. At the operational level, the military must send forces to secure the entire fuel route from Pakistan to the logistics hub and on to the small outpost. Finally at the strategic level, the military must maintain positive relationships and ensure the stability of surrounding countries so that they can ship fuel into landlocked Afghanistan. Thus, fueling small outposts has impacts on all three levels of warfare.

The Department of Defense (DoD) has allocated resources towards integrating renewable energy but these are mainly procurement efforts and not R&D efforts, and procurement is not an approach that will work at the tactical level. At all three levels of the military, renewable energy technology and services have been adopted from the private sector. At the strategic and operational levels, it is an easy process for the DoD to award private sector companies contracts for renewable energy, also known as power purchase agreements. A few examples of this are the 20 renewable energy contracts awarded by the United States Army Corps of Engineers in 2014 and the $7 billion earmarked by the U.S. Army in 2012 (Stolark 2014). However, at the tactical level such a procurement method is not feasible. First, the main private sector market where the military could adopt technology for tactical military camps is the residential renewable energy market. However, residential renewable energy does not have the same rugged equipment needs as combat zones. Secondly, power purchase agreements only work in a connected grid and would be a tremendous endeavor to apply such a model to combat zones. While there are numerous examples of private contractors supplying U.S. troops with various resources including fuel, these contracts can be costly. In terms of renewable energy, the military has been forced to procure technology from a much smaller pool of businesses that specialize in making military energy systems.

It is worth noting that the DoD is the "largest energy consumer in the U.S. government" and as an organization is poised to reap the benefits of renewable energy generation at all levels (Booth et al. 2010. Pg. 2). Currently, the DoD's "energy use patterns impact DoD global operations by constraining freedom of action and self-sufficiency, demanding enormous economic resources, and putting many lives at risk in associated logistics support operations in deployed environments." In fiscal year (FY) 2008, the DoD spent $20 billion on 889 trillion site-delivered British Thermal Unit (BTU) with the majority of energy coming from fossil fuel. To put this figure in perspective, the DoD "accounts for about 1.8% of total U.S. petroleum consumption and 0.4% of the world's consumption" (Booth et al. 2010. Pg. 2).

Permanent and Semi-Permanent Situations.

Tactical situations and temporary structures are a natural pair that arise from the dynamic and constantly changing nature of modern warfare. Semi-permanent standards allow for "systems [to be] selected for moderate energy efficiency" with life expectancies between two and ten years (General Engineering 2015, Pg. 9-7). Understanding that energy efficiency is not worth the investment for temporary structures, integrating renewables allows the military to offset fuel wasted from inefficiencies. By focusing on tactical warfare, this thesis is primarily concerned with semi-permanent structures.

Renewable Energy Generation and Storage.

This thesis primarily explores technologies that have already been used or tested by the military, i.e., photovoltaics and wind turbines. For energy storage, batteries will be the primary focus due to the military's early adoption of battery technology. While energy storage via flywheels and fuel cells has been tested and deployed, no feasible solutions have been generated for tactical conditions. Feasibility of these technologies and others will be covered more thoroughly in the following literature review.

Energy Systems and Microgrids.

Few of the military energy systems analyzed in this research can truly be defined as microgrids. According to the Department of Energy (DOE), a microgrid is "a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid" (Ton and Smith 2012. Pg. 84). Military energy systems fail to meet the majority of this description as noted in **Table 5**. Currently, military energy systems at the tactical level are diesel generators attached to point loads with no control system or interconnection of multiple loads.

Table 5: Characteristics of a microgrid compared to military energy systems at the tactical level.

	Microgrid	Tactical Energy Systems
Interconnected Loads	✓	
Distributed Energy Resources	✓	
Clearly Defined Electrical Bounders	✓	✓
Single Controllable Entity	✓	

Literature Review

To understand whether renewable energy can offset the fuel dependency of tactical military camps, an understanding of the following disciplines is required:

- **Infrastructure Analysis and Planning:** Military camps are infrastructure systems that require various inputs and support from other infrastructure systems to operate. This group of literature focuses on understanding and planning critical infrastructure systems. Critical infrastructure systems are defined as "assets, systems, and networks, whether physical or virtual…so vital…that their incapacitation or destruction would have a debilitating effect on security, national economic security, national public health or safety, or any combination there of" (United States Department of Homeland Security 2017). This portion of the literature review is aimed at answering how tactical military camps should be modeled and analyzed.

- **Energy Resources and Storage:** There are numerous renewable energy resources and storage options. Environmental and user constraints however reduce the number of feasible renewable energy resources and storage options for the military. The renewable energy systems deemed feasible from this section of the literature review will be analyzed using the infrastructure analysis tools from the previous section of the literature review.

- **Military Energy Systems in Practice:** The military has begun experimenting and deploying renewable energy resources in tactical situations. This section of the literature review will document the current status of the military's integration of renewable energy at the tactical level. In addition, this section will guide what case scenarios are analyzed later on in the research.

Infrastructure Analysis and Planning

Infrastructure is a broad term that describes both physical and virtual systems that support society. Characteristics of infrastructure include resource intensive, long lasting, requiring maintenance, and vital to their intended end user. Due to its high cost and long lifetime, planning for infrastructure is as important as the infrastructure itself. Poorly planned infrastructure can waste resources and hinder future progress. Likewise, poorly planned energy systems can hinder future growth and reduce energy dependability.

Critical Infrastructure Guiding Principles

Following 2005's Hurricane Katrina, the American Society of Civil Engineers (ASCE) urged organizations and engineers to "continually evaluate the appropriateness of design criteria, always considering how the performance of individual components affects the overall performance of a system" (ASCE Critical Infrastructure Guidance Task Committee 2009. Pg. 4). ASCE Critical Infrastructure Guidance Task Committee published the *Guiding Principles for the Nations Critical Infrastructure* to help guide planning and maintenance of critical infrastructure. The report argues that the primary infrastructure failure during Hurricane Katrina was that many hurricane-protection components were not integrated into one system but rather numerous self-operating entities. The network was not planned, designed, constructed, nor operated as a system integrated with land use, emergency evacuation, or recovery plans.

To prevent further infrastructure failures, ASCE proposes the following four guiding principles:

- Quantify, communicate, and manage risk
- Employ an integrated systems approach
- Exercise sound leadership, management, and stewardship in the decision-making processes
- Adapt critical infrastructure in response to dynamic conditions and practice

Tactical military camps currently deploy a non-networked system of generators resembling the pre-Katrina infrastructure systems mentioned above. These systems are a prime example of not following the above-mentioned guiding principles. This system of generators is the end user in the fuel supply infrastructure system. Ultimately, the non-networked system of generators puts unnecessary strain on the fuel supply infrastructure system by requiring significant amounts of fuel.

Quantify, Communicate, and Manage Risk. ASCE's first guiding principle aims at truly understanding the need and role of infrastructure prior to implementation. To do this, decision makers and engineers need to clearly communicate the purpose of a project and quantify that vision into project attributes. Additionally, any risks presented during this communication process should be mitigated through project modifications or ancillary systems.

Based on this approach, infrastructure failures such as the 2017 San Fernando Valley blackout that left 140,000 customers without power can be attributed to a lack of communication and risk management. The blackout that lasted for 12 hours was attributed to "excessive energy demands due to [a] heat wave" (Poston and Dakota 2017). Looking through ASCE's framework, one explanation for the avoidable blackout was the lack of communication between the Department of Water and Power, customers, and developers on actual power loads. The three entities also failed to include strategies to mitigate the risk associated with energy demands related to weather.

ASCE makes a strong argument for mitigating risks that arise from the inevitable negotiation process that occurs during planning. They describe this risk as "the gap between the best possible project or program that could be implemented and the actual project" (ASCE Critical Infrastructure Guidance Task Committee 2009. Pg. 15). However, ASCE fails to make the argument of unnegotiable project characteristics, such as the security requirements that military camps are faced with. However, the organization does state that the gap between shareholders increases "the likelihood of compromises to safety, health, and welfare of the project's users" but they do not propose a new solution that would not compromise on such measures. Instead, the organization argues to develop a plan that identifies, analyzes, plans, monitors, and responds to potential risks.

Employ and Integrate Systems Approach. Once a project's goals are quantified, the infrastructure project should be designed to work symbiotically with other infrastructure systems. Instead of designing infrastructure to be an "isolated [project] designed to perform a finite set of functions," infrastructure needs to be developed as a system "with an understanding of all connections, interactions, and interdependencies between system components" (ASCE Critical Infrastructure Guidance Task Committee 2009. Pg. 20). This argument goes against the current tactical renewable energy efforts of the DoD. The DoD has begun to procure renewable generation for certain tactical systems, such as communication equipment, that cannot support other loads. ASCE's approach is easier when a project's life-cycle is understood so that integrations can be planned to fit within the project's life-cycle.

ASCE also notes that life-cycle planning and system integration aids in sustainable development. Sustainable development, defined as "meeting human needs for natural resources…while conserving and protecting environmental quality and the natural resource," requires planners to understand the resources needed to properly maintain a piece of infrastructure and the impacts said infrastructure will have on surrounding systems, both man-made and natural (ASCE Critical Infrastructure Guidance Task Committee 2009. Pg. 20).

ASCE notes that integrating system functions as redundancies can increase infrastructure resiliency. Redundancies are a mitigation strategy that recognize back-up systems that perform the same task as the piece of infrastructure. These systems increase resiliency by offering supporting functions that allow the system to recover quickly after a failure due to unexpected conditions.

Transportation systems are a great example of infrastructure with numerous system integrations, redundancies and resiliency measures. If the road network is the primary transportation infrastructure, typical system integrations include auxiliary routes, parking infrastructure, and public transportation planning. The public transportation network also acts as a redundancy and a resiliency measure because the system can be used as an alternative means of transportation during road maintenance. Energy systems with system integrations, redundancies, and resiliency measures are systems that deploy multiple interconnected generation assets. In a scenario where one generation asset becomes inoperable, say from the unavailability of fuel, other generation assets that do not depend on fuel can meet the unmet load requirement.

Exercise Sound Leadership, Management and Stewardship. ASCE argues that even the best-built structures are vulnerable to improper management. All infrastructure systems require maintenance and these systems begin to falter when there is no leadership to allocate the necessary resources towards maintenance. ASCE notes that there is a difference between leadership and management. Management oversees the administrative aspect of ensuring the right actions are taken to maintain infrastructure while leadership needs to ensure there is proper motivation and eagerness. It is the responsibility of both the leadership and management to foster and instill a sense of stewardship into the organization. Compared to individuals, organizations will have more longevity and the organization will ultimately be responsible for maintaining the infrastructure.

The Interstate Highway network is a prime example of the relationship between leadership, management and stewardship. In 1956, President Dwight D. Eisenhower's leadership led to creation of the Interstate Highway System. Such a large infrastructure endeavor required the management skills housed in the Federal Highway Administration (FHA). President Eisenhower's leadership and the management skills of the FHA have allowed the system to last more than 60 years. Looking at military energy systems, strong leadership would entail championing the tactical use of renewable energy and then creating the supporting management system to deploy the renewable energy systems.

Adapt to Dynamic Conditions and Practice. There is no way to accurately plan how infrastructure will be used during its life-cycle. In terms of the energy grid, there was no way to predict that electricity proliferation would lead to every American having access to electricity regardless of where they live. ASCE urges organizations to consistently view their infrastructure through current conditions. Dynamic conditions such as increasing populations, changes in technology, and the effects of climate change put infrastructure under a series of originally unforeseen stresses.

The above literature shows that the success and failure of infrastructure systems is a result of the planning and leadership of the project. This view is shared by military planners as evidenced by the allotment of resources towards procuring renewable energy. Where the lack of consensus lies is how these principles are applied to tactical military camps. While leadership has prioritized reducing fuel consumption, there has been a lack of metering and data gathering on actual energy requirements. Quantifying energy requirements and communicating the goals of an energy system is crucial to successfully reducing demand. Likewise, there is a consensus that integrating multiple power generation systems will add to system redundancy and resilience. However, the system redundancies of tactical military camps aim at increasing generation capacity and not the actual ability to generate energy. This stems from a lack of coordination between the unit deploying the generators and the supply chain delivering the fuel required for said generators. Organizations that employ energy systems must understand how to be effective stewards of the system and they should encourage leadership and management to be prepared to make difficult decisions. Ultimately, military energy systems, regardless of their life-cycle, face dynamic conditions that will require the infrastructure, users, and the organization to adapt.

Infrastructure Models

As the military began the daunting task of rebuilding Iraq and Afghanistan, individuals with non-engineering backgrounds found themselves making decisions on reconstruction and infrastructure. In response, the U.S. Army's Engineer Research and Development Center-Construction Engineering Research Laboratory (ERDC-CERL) developed *Infrastructure and the Operational Art: A Handbook for Understanding, Visualizing and Describing Infrastructure*. The handbook presents three infrastructure models that quantify, plan, and analyze infrastructure networks.

Infrastructure Environment Model (IEM). IEM roots infrastructure within its surrounding environments. These environments "shape the infrastructure in question by both imposing constraints and providing enabling mechanisms" (Hart et al. 2014. Pg. 46). This infrastructure model fulfills the "Quantify, Communicate, and Manage Risk" guiding principle set forth by ASCE. The model has the following prompts:

- **Needs:** IEM requires that planners identify, quantify, empathize, and appreciate the need for infrastructure. Empathizing and appreciating the need for infrastructure allows an organization to see the infrastructure system from the user point of view which increases the likelihood that the infrastructure will meet its intended need.

- **Social:** Infrastructure is rooted in a social environment in the same manner that it is rooted in the natural environment. Social characteristics such as "standard of living, literacy and education, relationship of culture and technology, employment patterns, and population density and distribution" all effect infrastructure (Hart et al. 2014. Pg. 48-49). Organizations must also be cognizant of how infrastructure will change the above societal characteristics.

- **Political:** Political structures such as "property ownership, regulation, taxation, rule of law, and building codes and their enforcement" will affect how infrastructure projects are implemented and maintained (Hart et al. 2014. Pg. 50).

- **Technical:** Infrastructure systems must employ technology appropriate to the society. Organizations have the option to either build using local practices or build up local practices to meet new technology. In either scenario, the society must be able to "understand, design, build, operate, and maintain the infrastructure technology employed" (Hart et al. 2014. Pg. 50).

- **Financial:** Infrastructure requires capital for both construction, operation and maintenance, and end-of-life. Additionally, users must have a system for "being able to receive the bill, and having a mechanism to pay the bill" (Hart et al. 2014. Pg. 51-52).

- **Organizational:** IEM also notes that organizations are needed to manage and maintain complex infrastructure networks. Such organizations should be able to execute "stakeholder engagement, design, construction, capacity development, and transfer" (Hart et al. 2014. Pg. 52).

- **External:** Infrastructure needs to be designed with external factors and actors in mind. Future users as well as interoperability with adjacent systems are typical external factors.

- **Enemy:** Infrastructure has the potential to be a target and thus security aspects must be incorporated. Organizations need to understand how a potential enemy will either try to use or destroy a piece of infrastructure, as well as how friendly forces can leverage the infrastructure system.

IEM is a great tool for determining what infrastructure needs to be built and how the infrastructure should be built. IEM's primary weakness is the inherent qualitative nature of the model. Without a quantitative aspect, it is difficult for organizations to use the model for planning or execution of infrastructure projects due to the variability of possible answers to the multiple prompts. The IEM will not be used in this research because this research is primarily asking if renewable energy systems can supply energy and meet the constraints placed by a tactical environment.

Infrastructure Component Model (ICM). The six element ICM "provides a basis for identifying, visualizing, and understanding the elements of an infrastructure, the functions they perform, and their relationships to each other" (Hart et al. 2014. Pg. 56). One element of the infrastructure model may require multiple input systems or may be an entirely different infrastructure system.

- **Generation:** This prompt "encompasses all processes necessary to create a final product in bulk." System bounders will dictate whether processes such as "extracting raw materials, converting it to a usable form, and preparing it for bulk transmission" are included (Hart et al. 2014. Pg. 57).

- **Bulk Transmission:** This prompt is the process of moving the final product created during generation long distances. The "long distance" traversed in bulk transmission is in perspective to shorter distances traversed during the Distribution prompt. Bulk transmission systems typically have "limited connection points, and may include reprocessing systems to facilitate distribution" (Hart et al. 2014. Pg. 57).

- **Distribution:** Distribution is the process of moving smaller quantities of finished products shorter distances and, ultimately, to the user.

- **Use:** This is the consumption of the product or service by the user/customer. The user can be another system.

- **Waste Management:** The coordination and use of the final product and byproducts from the entire system. These products are either ignored, disposed, recycled, reused, or repurposed.

- **Coordination:** Coordination is focused on the control measures in place to ensure the "smooth functioning of the infrastructure systems" including but not limited to the "SCADA (Supervisory Control and Data Acquisition) systems, the financial mechanisms for billing customers, maintenance, and regulation" (Hart et al. 2014. Pg. 58).

The authors note that while the ICM can be applied to any infrastructure system, it is best suited for civil infrastructure systems that have a physical backbone or predominately consist of physical elements. Additionally, the model is scalable to nationwide or household systems. For instance, ICM can analyze both the nationwide electrical grid as well as the electrical wiring of a household.

Both a drawback and positive aspect of ICM is its potential to connect multiple infrastructure systems. This is a positive aspect because it gives an organization a greater picture of how one piece of infrastructure fits into a pre-established built environment. However, the model does not offer an organization a way of delineating their specific infrastructure system, thus opening the model up to weak system boundary conditions. In the Methodology section of this research, a modified ICM model will be introduced that better represents the complexity of tactical military camps.

Infrastructure Assessment Model (IAM). IAM is a tool for rapidly assessing and describing "the status of infrastructure components and systems." While comprehensive, the model is "not overly prescriptive or complex" and is "applicable to a variety of infrastructure" systems (Hart et al, 2014. Pg. 60). The components of IAM are assessment questions that consider the aspects of the ICM under normal and adverse conditions.

- **Normal Conditions**: The steady state condition that the infrastructure system is designed to operate in.
  - **Required.** What does the user quantitatively require from the infrastructure system? Organizations need to understand user requirements for an entire series of timesteps and how user needs change over timesteps. This prompt primarily focused on the User aspect of ICM.
  - **Ready.** Does the infrastructure system have the quantitative capacity to meet the needs of the user? This prompt primarily focused on the Generation, Bulk Transmission, and Distribution aspects of ICM.
  - **Organized.** Does the infrastructure system have the proper management and coordination to meet steady state requirements? This prompt is both qualitative and quantitative and primarily focused on the Organized aspect of ICM.
- **Adverse Conditions**: Conditions that put the infrastructure system under unintended strain such as natural or manmade disasters.
  - **Tough.** What is the ability for critical systems to "survive and quickly recover from adverse conditions?" Critical systems "tend to be expensive, hard to replace, and their loss leads to broad delivery disruption" and thus must be able to withstand adverse conditions without being rendered inoperable (Hart et al. 2014. Pg. 62).
  - **Redundant.** What backup or auxiliary systems are available to meet demand if a critical system is inoperable? This prompt "focuses on determining whether the system can withstand the loss of some elements and whether it can be rapidly restored in the event a substantial number of elements are lost or damaged" (Hart et al. 2014. Pg. 63).
  - **Prepared.** Is the user and other infrastructure systems prepared to "survive the inevitable disruption in service provided" by the effected infrastructure (Hart et al. 2014. Pg. 63)? If users and connected infrastructure systems are not prepared to operate without the services of the effected infrastructure system, it could turn a minor disruption into a significant situation.

IAM is a shell of an assessment tool. The authors' goal of making it applicable to numerous infrastructure systems leads many of its prompts too general for in-detail analysis.

Additionally, the mixed qualitative and quantitative nature of the prompts can confuse organizations on whether they are using the tool model properly.

These three ERDC-CERL infrastructure models provide a great starting point for analyzing military energy systems. IEM answers the question of whether a given energy system is appropriate given the needs and organization of the user in addition to the social, political, technical, financial, external, and security situation. However, this thesis is assuming that an energy system is needed and that the only question needing to be answered is which energy system will best meet the user's needs. Thus, the IEM will not be used in this studies case scenarios.

The ICM and IAM will be used to compare different energy system scenarios and to assess their ability to meet user needs. The ICM sheds light on how the energy system will interact with other infrastructure systems. The IAM helps determine if the energy system is suitable in both normal and adverse conditions. While the models are applicable to military energy systems, their generic approach leads many aspects left unanswered and will be modified in the Methodology section of this thesis.

Infrastructure Systems and the Military

A byproduct of the DoD's effort to create net zero energy installations was the *Net Zero Energy Military Installations: A Guide to Assessment and Planning*. This guide focuses on energy used primarily in permanent built structures, not temporary tactical structures, but the guide's framework can be used for planning tactical military energy systems as well.

Key Considerations. DoD installations and facilities have a unique set of planning factors that must be taken into consideration when designing energy systems. These planning factors also guide the implementation of renewable energy in military energy systems.

1. **Mission Capability:** "Mission accomplishment is the top priority for installations" and thus any renewable energy measure that interferes with mission accomplishment is not feasible (Booth et al. 2010. Pg. 3). An example would be a wind-turbine that interferes with runway operations.

2. **Security:** Energy systems cannot interfere with the physical security of the installations. This consideration requires a trade-off analyze between physical security and energy security. For instance, "a bio-mass fueled power system may be unsuited… due to off-site truck traffic required to bring in fuel" but on the other hand, "the ability to meet an installation's critical load using on-site renewable sources… in an islanding mode may greatly enhance energy security" (Booth et al. 2010. Pg. 3).

3. **Economics:** Energy systems economics are based on life-cycle assessments including "technological maturity, fuel availability and cost, energy storage requirements, distribution and interconnection arrangements, financing options, federal/state/local incentives, environmental impacts, and costs for operations, maintenance, repair, and parts replacement" (Booth et al. 2010. Pg. 3).

4. **Agency Goals and Federal Mandates:** The DoD's energy goal is to achieve 25% renewable electrical energy use by 2025. Energy systems must also meet federal mandates on energy efficiency, renewable energy, and potentially carbon emissions.

5. **Site Resources:** Energy systems should take advantage of local environments and siting opportunities including climate, renewable energy resources, and electrical system interconnection opportunities.

6. **Doctrine, Organization, Training, Material, Leadership & Education, Personnel and Facilities (DOTMLPF):** Energy systems and their supporting education material need to evolve with doctrine.

Planning and Assessment Approach. In order to address the above key considerations, the DoD formulated the following planning approach:

1. **Initiate the project:** Energy system projects need to have the support of the installation's leadership, clear project boundaries and timeline, and representation from key stakeholders.

2. **Establish energy and greenhouse gas baselines:** By understanding and recording the installation's current energy requirements, planners have a baseline to compare and measure the effect of renewable energy systems.

3. **Reduce demand through human action:** Before implementing renewable energy systems, planners need to identify ways to minimize wasted energy through behavioral changes "while maintaining or improving the quality of mission execution" (Booth et al. 2010 Pg. 8).

4. **Perform an energy efficiency assessment:** Planners should assess ways to minimize energy inefficiencies on-site which will later on reduce the needed renewable energy generation assets.

5. **Perform a renewable energy and load reduction assessment:** Once the installation is running efficiently, planners can now begin identifying potential on-site renewable energy projects or opportunities to deploy renewable fuels.

6. **Perform a transportation assessment:** The next major source of energy consumption following built structures is transportation. Planners should shift resources to identifying ways to reduce or replace fossil fuel used for transportation.

7. **Perform an electrical systems assessment**: The above improvements will affect the installations electrical systems by adding and removing loads, generation assets and more. Planners need to identify how the above-mentioned projects would impact the installation's current electrical systems. To improve installation resilience, planners should include projects that would "support emergency operations in the event of a public grid outage" (Booth et al. 2010. Pg. 8).

8. **Make energy project recommendations.** Finally, planners can recommend a set of projects that are feasible based on the above assessments and meet external (DoD, DoE, etc.) goals.

Islanding Microgrid Assessment. While military energy systemss do not meet the characteristics of a microgrid, understanding how a standalone grid operates will help understand how military energy systems operate when not connected to the grid. Having an islanded microgrid requires an installation to clearly understand their generation capacity and consumption. It is unlikely that generation will surpass consumption with a satisfactory margin and thus the site “should decide which loads are critical and should be included in the microgrid” (Booth et al. 2010. Pg. 39). These critical loads should behave the same under the microgrid and grid connected scenarios. During a grid failure, the installation would either shed energy available to non-critical systems or enact demand response in order to keep critical systems online. The microgrid should be approached in the following manner:

- Determine the desired microgrid size, critical loads, and area.
- Determine the “most economical electric hybrid system with generators, storage, demand response, and renewable energy sources” (Booth et al. 2010. pg. 39).
- Determine the most appropriate command and control system to manage the energy flow through the microgrid.

The key considerations set forth by the DoD highlight military-specific constraints that make having a renewable energy powered system difficult. Additionally, the framework presented above for designing an energy system or a microgrid is primarily applicable to systems undergoing renovation rather than new construction.

The DoD’s microgrid framework does present an interesting notion of having a layered grid. Their framework calls for critical systems to be put on a microgrid that would exist in conjunction with the actual grid. In the event of grid failure, the installation would island itself, restrict electricity access to non-critical systems and then power critical system from renewable sources and stored energy. However, this layered approach is only feasible if there are multiple generation systems, i.e. a primary system and a backup system. Tactical military camps rarely have backup systems due to the semi-permanent construction standards.

Renewable Energy Resources and Storage

The energy needs of tactical military camps are traditionally met using fossil fuel generators but this research proposes that those energy needs can be met by renewable energy. Renewable energy resources offer the ability to generate energy on-site and, in the process, reduce energy transportation costs and minimize the effects of energy price fluctuations. Additionally, renewable energy is not affected by the constant fluctuation of fossil fuel prices or the associated cost of transporting fossil fuel.

There are numerous renewable energy resources and storage options, each with their own unique characteristics. Tactical constraints however reduce the number of feasible renewable energy resources and storage choices. The following review will look at various energy sources, generators and storage options in terms of feasibility for tactical military camps.

Energy Sources

Energy sources are the raw materials used to generate energy. Energy sources include "nuclear energy, fossil energy – like oil, coal and natural gas – and renewable sources like wind, solar, geothermal and hydropower" (United States Department of Energy 2017). The availability of energy sources varies across the globe but some sources, such as solar and wind, are available globally at some level. Tactical military camps need energy resources with the following characteristics:

- **Availability:** Energy sources need to be available in isolated locations in order to meet on-site generation requirements.

- **Consistency:** Energy sources must be consistent or highly predictable to ensure the availability of energy when needed.

- **Ease of Use:** Energy sources must not require extensive processes to turn the source into electricity. Tactical military camps do not have the facilities, manpower, or resources necessary for extensive energy production processes.

Wind. Wind is the result of temperature and pressure differentiations on Earth. Wind is typically characterized into seven classes according to power density with Class 1 being the lowest and Class 7 the highest. Utility applications require Class 4 or higher which on average is a wind density of 320 to 400 W/m^2 or a wind speed of 5.8m/s (Salameh 2014. Pg. 118). Wind density is the wind velocity raised to the third power. Wind speeds are higher and less variable at higher elevation and thus, wind turbines are typically 30 meters high to take advantage of higher windspeeds (Brown et al. 2011. Pg. 21).

Overall, wind is a viable resource for tactical military camps due to its widespread availability and consistency. However, large wind turbines are not feasibility for security and system deployment constraints. While using micro-scale wind turbines is a possibility, such an endeavor would require studies to determine the wind speed and density at a specific location at various heights. The need for such a study reduces the "ease of use" characteristic needed for tactical military camps.

*Solar***.** Solar energy is light from the sun that can be converted to energy via photovoltaic devices or used to heat a fluid whose steam is used to turn a turbine. While the sun transmits 1.353 kW/m^2 of power (solar constant) to the Earth, Earth's rotation and tilt creates hourly and seasonal fluctuation in the amount of energy that actually reaches the Earth's surface. Additionally, the Earth's atmosphere causes "reflection, adsorption (filtering), refraction, and scattering" of solar radiation.

Solar energy varies throughout the day based on the angle of the sun in relation to a specific location. Solar radiance follows a bell curve where solar radiation is greatest during the middle of the day and less in the morning and afternoon. Weather events such as clouds or storms greatly reduce the amount of solar radiance that reach the Earth's surface.

Solar energy is a viable source of energy for military camps. Solar radiation is available across the globe with the highest potential on and near the equator. While unexpected weather occurrences reduce the consistency of solar energy, solar energies daily and seasonal variation is well understood and forecastable. Furthermore, solar energy technology is well developed increasing the energy source's "ease of use" factor.

Other Energy Sources. There are other renewable energy sources that have the potential to reduce reliance on fossil fuels. However, due to various characteristics, these sources are not feasible for tactical military camps.

- **Tidal:** Tidal energy uses the natural flow and ebb movement of large quantities of water to generate electricity. The two main methods for generating tidal energy are tidal barrages and tidal turbines. Tidal barrages collect water during flood periods and run this water through turbines when the water level recedes. Tidal turbines use tidal currents to generate energy in the same manner hydroelectric power is generated. In contrast to hydroelectric power, tidal turbines operate at low speeds between 2 and 3 m/s (Salameh 2014, Pg. 310). Tidal energy is not feasible for tactical military camps due to the limited availability and the infrastructure required to turn tidal energy into electricity.

- **Wave Power:** Wave power harnesses the energy stored in the velocity and potential energy of a wave. This energy is typically released when a wave reaches the coastline (Salameh 2014. Pg. 318). Similar to tidal energy, wave power's coastal limitation makes it unsuitable for tactical military camps.

- **Geothermal:** Geothermal energy takes advantage of the natural heat of the Earth to heat liquids that then form steam used to generate electricity via turbines. Geothermal energy is not feasible for tactical military camps due to the infrastructure required to drill deep into the Earth to reach the high temperatures needed to create steam.

- **Biomass:** Biomass energy takes various organic inputs such as "wood, agricultural residues,…,municipal waste, [and] manure" and converts them to power (Salameh 2014. Pg. 334-335). This process can be through direct-fired combustion, co-firing, or gasification. Biomass is not feasible for tactical military camps due to the tremendous amount of organic matter needed to generate energy. While the inputs of the energy system are renewable, the method of transporting the biomass to the military camp would most likely require fossil fuel, thus negating the decrease in fossil fuel consumption caused by using renewable energy.

The two feasible renewable energy sources that will be explored are wind and solar sources. The global availability of wind and solar along with their consistent nature make them viable for tactical military camps. The maturity of technology and research in both areas also increases the ease of use and implementation. However, due to the intermittency of these two sources, energy storage needs to be explored. While the other renewable energy sources will not be explored, they may be viable for specific non-military camps. The other renewable energy sources are very location dependent and thus viability would need to be analyzed if the sources are found near a planned camp.

Generation.

Energy generators are the systems and machines used to create electricity from an energy resources. Energy generators also need to fit the characteristics set forth for the renewable energy source. These characteristics applied to generation are:

- **Availability:** The generator must have low ramp-up time. Generators that require renewable inputs that must be transported to the site do not fit this characteristic.

- **Consistency:** The generator must be able to operate consistently when the energy source is available. Generators with long lead or maintenance times do not fit this characteristic.

- **Ease of Use:** The generator must be easy to maintain and require minimal offsite assistance. Generators that cannot be maintained using on-site personnel or resources do not fit this characteristic.

Micro-scale wind turbines and photovoltaic solar panels are two generators that will explored. Large scale wind turbines will not be explored due to the infrastructure and manpower needed to erect and maintain the turbine. Likewise, concentrated solar thermal will not be explored due to the infrastructure and technical expertise needed to operate the energy generator.

Micro-Scale Wind Turbines. Wind turbines are classified based on their rotor diameter as further explained in **Table 6**. Micro-scale turbines typically have a "rotor diameter ranging from 3 m to 10 m and [have] a power capacity of 1.4-20 kW" (Tummala et al. 2016. Pg. 1353). While these turbines "produce more costly electricity than the medium and large-scale wind turbines," they are "handy in some autonomous applications which require a very high level of reliability" and "these small-scale turbines can act as a useful power source" in remote locations such as those locations where tactical military camps are located (Tummala et al. 2016. Pg. 1353).

Table 6: Wind turbine classification is based on the turbine's diameter (Tummala et al, 2016. Pg. 1353).

Classification	Diameter (m^2)	Power Rating (kW)
Large	50-100	1000-3000
Medium	20-50	100-1000
Small	10-20	25-100
Micro/ Household	10-0.5	0.004-16

Micro-scale wind turbines are classified into two categories: vertical axis and horizontal axis. Vertical Axis Wind Turbine's (VAWT) rotor axis is in vertical direction and have an ideal efficiency of 70%. While these turbines do not have the ability to yaw or self-start, their low height of operation makes them easier for maintenance (Tummala et al. 2016. Pg. 1354). Horizontal Axis Wind Turbines (HAWT) in contrast have a rotor axis in the horizontal direction and have the ability to yaw and self-start. Due to their dependence on wind direction, these turbines are operated at higher heights making maintenance more difficult. HAWTs have a typical efficiency of 50-60% (Tummala et al. 2016. Pg. 1354).

Performance. In a 2016 study, Tummala et al. synthesized various research on micro-scale HAWT. Of the eight HAWT designs analyzed, the average power coefficient was .37 with a .098 standard deviation (Tummala et al. 2016. Pg. 1358). The power coefficient of a wind turbine is the actual electrical power produced from the turbine divided by the total amount of wind power.

Tummala et al.'s synthesis of Darrieus VAWT yielded similar results with a mean power coefficient of .36 and a standard deviation of .11 (Tummala et al. 2016. Pg. 1360). Darrieus wind turbines, generating electricity from the lift forces acting upon the blades, are simpler to construct and have lower costs. Savonius VAWT rely on drag to generate electricity and there are numerous model variations. Tummala et al found studies citing .2 to .6 power efficiencies.

Positioning. Wind turbine positioning greatly influences the power output of the turbine. Position factors include wind speed levels, turbulence and aerodynamic noise generated from the turbine (Ledo et al. 2011. Pg 1379-91). Experiments conducted by Sissons et al. on pole mounted turbines found that a minimum of 5 m/s is required to achieve best efficiency (Sissons et al. 2010. 6130-44). Building mounted turbines or turbines located in urban areas should have a height higher than 1.3 times the height of the building because the majority of turbulence occurs between 1-1.3 times the height of the building (Abohela et al. 2013. Pg 1106-18). Additionally, wind flow and turbulence are mainly dependent on the roof shape (Rafailidis et al. 1999. Pg. 333-45).

Conclusion. Micro-scale wind turbines are a viable renewable energy generator for tactical military camps. Studies have shown that at least 5 m/s of wind speed is needed for small scale wind turbines to achieve meaningful efficiency. Micro-scale wind turbines require thorough site analysis to determine wind speeds at turbine height, potential sources of turbulence, and aero acoustics. Extensive site analysis and the importance of positioning reduces small scale wind turbines feasibility as an initial renewable energy generator for new tactical military camp. Turbines are better suited for established camps where proper site analysis can be conducted.

Photovoltaic Panels. Photovoltaic (PV) panels turn energy from the sun's solar rays and converts it into electrical energy. PV panels are collection of solar cells interconnected to increase their voltage and current to usable levels. A series of PV panels is called a solar array. PV systems consist of the array, a form of storage, and an optional inverter depending on whether the load is AC or DC. Battery storage is required due to the variable of solar radiance that powers the system.

Performance. Positioning, location, temperature, and system efficiency are the major factors affecting the performance of PV arrays. In 2014, the average PV array had an efficiency between 11% and 15% (Salameh 2014. Pg. 34). PV systems have the highest output when they are equipped with a tracking system that ensures the sun's rays are perpendicular with the array throughout the entire day. Proper positioning and dynamic systems such as the one described above can increase efficiency of the system up to 20% (Salameh 2014. Pg. 81). System efficiency also varies based on the ambient temperature. Systems perform better in temperate environments than in high heat.

Positioning. PV panels are either roof or standalone mounted. Typically roof-mounted systems are fixed to a rack while ground-mounted systems can either be fixed to a rack or attached to a sun-tracking system. Racked panels are "fixed at an angle of the latitude of the location" (Salameh 2014. Pg. 81). While sun trackers have greater efficiencies, they are much more expensive that static mounting of the array which can be done with cheap local materials such as wood.

Conclusion. PV panels are a very mature renewable energy technology and increased proliferation is driving the cost per kWh lower. From close to $9 per watt in 2008 to less than $3.50 in 2016, the cost of solar electricity is decreasing rapidly (Matasci 2017). Solar systems are easily deployable and can be used to power individual electronics such as laptops to small systems such as exterior lighting. This versatility and decreasing cost makes it a great energy generation source for tactical military camps. The main issue with PV systems is the system footprint and potential difficulty mounting the system. Finding enough suitable land to place ground-mounted panels or constructing mounting structures may be too resource intensive for some tactical military camps.

Both micro-scale wind turbines and PV arrays are feasible renewable energy generators for tactical military camps. Both generators are able to use readily available renewable energy sources and can turn the energy source to electricity on-site. Short ramp up times when wind and solar rays are available means both generators can consistently create electricity. Finally, the maturity of both technologies increases their ease of use. While site studies are needed to increase generation efficiencies, both energy systems can be maintained and operated using minimal on-site personnel and resources.

Storage

Wind and solar energy generation is variable due to environmental factors that prevent constant wind or solar radiation. This variability is called intermittency. Electrical Energy Storage (EES) is needed to maintain "the balance between the supply and demand" of electricity (Du and Lu 2014. Pg. 3). In a perfect scenario, energy would be consumed when renewable energy is available so that there was a direct path from generation to consumption. In reality, energy is consumed throughout the day and renewable energy is only available during certain time periods. This discrepancy is most apparent when renewable energy is the primary energy being used.

EES is needed to store energy generation until it is consumed. As renewable energy generation has increased so have the number of EES technologies. Large-scale EES' that cannot be miniaturized such as pumped hydro storage, compressed to air energy storage, and highly technical EES that require significant maintenance and observation such as superconducting magnetic energy storage, capacitors and supercapacitors will not be explored.

When designing any EES system, designers must take into account the following factors:

- **Energy Density.** Energy density is the ability to store energy per a unit of volume. Typical energy density units are $\frac{Watts-Hours}{Liters}$ or $\frac{Watts-Hours}{Cubed\ Meters}$. Energy density is an important factor when space is a limiting factor.

- **Power Density.** Power density is the ability to output energy per a unit of volume. Typical energy density units are $\frac{Watts}{Liters}$ or $\frac{Watts}{Cubed\ Meters}$. Power density is an important factor when power availability is an important factor.

- **Roundtrip Efficiency.** Roundtrip efficiency is the amount of energy available for output verses the amount of energy input into the system. All EES systems will consume or lose energy during the storage process. High round trip efficiency is critical for systems that have minimal energy availability, such as small scale renewable generation.

- **Response Time.** The response time is the amount of time required for the battery to increase or decrease output based on outside factors. For instance, if a battery is used as backup system, the response time is the amount of time it takes the battery to begin supplying power once the primary system fails.

- **Specific Energy.** Specific energy is the ability to store energy per a unit of weight. A typical specific energy unit is $\frac{Watts-Hours}{Gram}$. Specific energy is an important factor when mission weight is a limiting factor.

- **Specific Power.** Specific power is the ability to output energy per a unit of weight. A typical specific power unit is $\frac{Watts}{Gram}$. Specific power is an important factor when high output is needed, such as when numerous systems are required to come online at the same time.

- **Maintenance.** Some EES systems employ very intricate and high-tech components that make maintenance a significant task. Other systems however, can easily be ruggedized and can operate in austere environments.

- **Technology Maturity.** Technology maturity is closely related to maintenance. Mature technology has often gone through numerous deployments and thus potential maintenance is well understood and can be planned in advance. Experimental technology, on the other hand, provides less information on how the system will operate in real-world conditions.

The military has an extensive use of battery technology and thus this thesis will focus on EES through batteries. Future research should be conducted on the potential use of flywheels and fuel cells as potential EES for tactical military camps.

Batteries. Batteries are a very mature technology with their own set of decision factors listed below. The above EES decision factors are analyzed for batteries in **Table 7.**

Table 7: Batteries' excellent specific power and specific energy make them an ideal EES system for tactical military camps. The following data is based on a lithium-ion battery (Moura 2017).

Energy Density	200-500 Wh/L
Power Density	-
Roundtrip Efficiency	85-98%
Response Time	10-100 milliseconds
Specific Energy	75-200 Wh/kg
Specific Power	150-315 W/kg
Maintenance	"Requires careful management"
Technology Maturity	High

- **Service Rate:** Batteries are either suited for high-rate or low-rate discharge. Watch batteries and memory backup for electronic circuits are examples of long-term drain at a low-rate. Short-term high-rate applications include engine starters and cordless appliances (Salameh 2014. Pg. 208). Military camps require long-term drain at a low-rate if the system is designed to be the primary energy system for the camp.

- **Recharge Rate:** The ratio of time it takes the battery to charge verses its discharge rate is an important factor based on the batteries application. One scenario is "float" applications where the battery spends the majority of its time charged with only a few discharges such as backup battery systems. In contrast, "cyclic" applications are when the battery is used regularly and there is relatively little recharge between uses (Salameh 2014. Pg. 209). Tactical military camps would primarily have float applications of batteries because the battery would be used to maintain energy availability when renewable energy cannot be directly supplied from the renewable energy generator.

- **Temperature:** Battery performance is heavily influenced by temperature. As Salameh states, "if the temperature gets too warm, the chemical reactions within the battery are accelerated and its life may be shortened. If the battery gets too cold, the chemical reactions are slowed down, reducing battery output" (Salameh 2014. Pg. 209). Battery temperature can be properly influenced by placing the battery system in shaded or manually cooled areas.

Storage is an important aspect of renewable energy systems and will greatly affect the adoptability of renewable energy systems. Batteries that can't operate in high temperature such as those in the Middle East could make renewable energy systems unfeasible for the military. However, renewable energy systems can be operated in a way that reduces the need for batteries. If the camp is able to use energy when the renewable energy source generates said energy, then no storage is needed.

Military Energy Systems in Practice

"No plan lasts first contact with the enemy."

This age-old military proverb perfectly describes how laboratory-based predictions do not fully resemble how the system will operate in real-world conditions. In-practice energy systems are affected by both internal and external factors. While these factors can and are planned for, real-world system conditions are rarely homogenous and it is impossible to predict the multiple levels of potential variation. In essence, each system and adjoining system has a level of variability that cannot be predicted in laboratory settings.

Internal factors include actual user behavior and other internal systems that will affect the energy load and energy efficiencies. These systems include additional lighting requirements and building envelopes conditions. External factors include but are not limited to weather and terrain conditions. With this in mind, the following sections will look at actual military energy systems and will identify variabilities that would affect the site.

Military camps dot the globe and can be found in the most austere conditions. While their location may vary, their purpose and characteristics are traditional the same. The U.S. Army Training and Doctrine Command (TRADOC) defines a base camp as, "an evolving military facility that supports the military operations of a deployed unit and provides the necessary support and services for sustained operations." These operations could range from counter terrorism to humanitarian relief. It is important to note that "while base camps are not permanent bases or installations, they develop many of the same functions and facilities the longer they exist." For instance, a base camp could start as a few buildings housing soldiers and their equipment and eventually house landing strips, fast food chains, maintenance shops, and more. All base camps have "a defined perimeter and established access controls and take[s] advantage of natural and man-made features" (Anderson 2011. Slide 3). While camps may have different missions, **Table 8** shows that there are a core set of functions all camps must meet and that military camps have an additional set of function needed to support the warfighter.

Table 8: Camp Functions And Additional Camp Functions Unique To Military Camps.

Generic Camp Functions	Unique Military Camp Functions
Command & Control	Force Protection
Life Support	Power Projection
Communications Support	Fires Support (i.e. artillery and counter-artillery)
Reception, Staging, Onward Movement and Integration (RSOI)	Training Support
Maintenance & Logistics Support	Moral, Welfare, Recreation (MWR)
Transportation Support	
Emergency Services (Medical, Fire, Etc.)	

Laboratory Condition Energy System.

Location and environmental conditions affect the success of a military camp's energy system. Success is defined as the camp closely resembling the initial or master plan. Overall, new construction camps offer greater flexibility for planners to dictate the growth and layout of a camp. New construction camps typically have fewer space restrictions, basic infrastructure can be emplaced prior to buildings, ample space is available for utility corridors, and permanent structures can be erected from the start (Anderson 2011. Slide 22). While captured or repurposed facilities have their own unique benefits, they rarely supersede the benefits associated with new construction. In terms of energy systems, the ability to plan the location of generators so that they can connect to multiple loads greatly influences the systems energy efficiency potential. The type of camp and the camp's importance will dictate what energy system the camp uses.

The military classifies electrical power into the three following categories:

- **Tactical Power:** Power supplied by tactical military generators to units engaged in combat operations. These generators typically range from 5 to 200-kW. This level of power does not require transformers and are typically located at smaller camps. "White generators", small commercial generators purchased off the local economy, are often used in these smaller camps.

- **Prime Power:** Power supplied by non-tactical generators larger than 200kW. Typically located at staging and larger camps since these generators require site preparation including switchgears, transformers, and cabling.

- **Commercial Power:** Power supplied by non-standard systems available from the commercial or local marketplace with outputs ranging from a few kilowatts to several thousand megawatts (Brygider et al. 2014. Pg.15).

Table 9: Generator fuel usage at different loads (Brygider et al. 2014. Pg.21). Improper loading of generators can lead to inefficiencies of up to 17%.

LOAD	Fuel Usage (gal/hr)	Consumption Rate (Gallon/kWh)
25%	21.6	0.0864
30%	24.9*	0.0854*
100%	71.1	0.0711
***INTERPOLATION**		

Tactical power is typically found in hastily built camps or repurposed facilities. Due to the lack of planning and the tactical situation, power generation at this level is highly inefficient. Generator are loaded typically between 20-30%, well under the 80% recommended. (Brygider et al, 2014. Pg.21). Looking at **Table 9**, one sees that generators loaded at 30% are 17% less efficient.

Table 10: Energy system planning rates from various sources (Vavrin, 2010. Slides 3, 5, 21). These rates often fail to resemble real world conditions because tactical situations call of different systems requiring differing loads.

Source	kW/Person	Setting
Army Technical Manual 5-811-1; Air Force Joint Manual 32-1080	3.0	Laboratory (Max)
Camp Atterbury 2009 (Pre-deployment training site)	.5	Real-world Laboratory
"Base in a Box"	1.8	Laboratory
US Army Field Manual 3-34: General Engineering	0.7	Laboratory
CENTCOM Sand Book, 2208	0.7	Laboratory

The military has developed numerous planning power rating which often fail to resemble real world conditions due to the variability of many tactical situations. These consumption rates, listed in **Table 10,** fail to account for the different systems in place at different camps.

Real World Conditions.

While the planning factors presented in **Table 10** set forth consumption rates based on camp population, there are few systems that are population dependent. The majority of camp systems operate without regard to the camp's population. **Table 11** outlines military systems and their associated power class. Systems in bold have a power class that will fluctuate based on a camp's population.

Table 11:Few of a military camp's systems have an energy consumption rate that will fluctuate with the camps population (Stangl, Wertz and Holcomb 2005, pg. 9)

POWER CLASS (KW)	System/ Function
<2	**Battery Charging** Mobile Energy Generation
2	**Mobile Kitchen Units** Combat Support Systems Communications Systems Missile Systems
3, 5, 10	Missile Systems **C4ISR Systems** **Weapon Systems**
10	**Refrigeration Systems**
15	Missile Systems C4ISR Systems Weapon Systems Well Kit
30	Missile Systems C4ISR Systems Weapon Systems ADP Support Systems Water Purification
60	Missile Systems Weapon Systems Aviation Ground Support

Operations and maintenance of military camps is another factor which determines how closely the camp's energy usage resembles the planned loads. Units typically rotate every 9-12 months with a week overlap between one another, which leads to a "large loss of continuity in process, contract oversight, policy, [and] requirements" (Anderson 2011. Slide 24).

Each unit has a different power requirement based on the systems the unit is fielding and thus camps designed for a specific unit may not meet the requirements of future units. Additionally, few units or camps meet their Modified Table of Organization and Equipment (MTOE) requirements which are used for energy system sizing. MTOE's list the number and size of generators that each unit needs to meet their theoretical loads. When units deploy without their full MTOE, they are forced to use local generators that they fail to properly load and/or maintain. To compound this problem, camps often have additional residents that again, fluctuate based on the tactical conditions. With these additional personnel come additional systems and additional loads on current systems. It is also difficult to accurately size the additional load of an individual's personal items such as personal computers, gaming devices, and kitchenware (Vavrin 2010. Slide 6).

Energy solutions at the tactical level are aimed at meeting demand as fast as possible with little regard to efficiency. Due to the "harsh, austere, and hostile environment, and high [operations tempo]" reducing energy consumption is very difficult. In conjunction with the lack of metering across the board, "it is assumed that determining any energy reduction is nearly impossible and probably not worth the effort." (Vavrin 2010. Slide 8). It is known though that the highest energy loads come from HVAC systems at 75%. Furthermore, 50% of energy produced is lost by inefficient structures (Vavrin 2010. Slide 7). Improper management of energy systems leads to gross over generation. **Table 12** highlights two camps that are prime examples of mismanaged generation capacity.

Table 12: These camps had gross energy generation capacity due to improper loading of generators and a lack of understanding their actual energy load (Brygider et al. 2014. Pg. 25-26).

Camp	Issue	Generation	Load
VSSA Delaram (105 personnel)	Excess power generation	1400kW generation from 13 generators	207kW
COP Justice	Excess Power; minimal energy security (grid connected)	1270kW	180kW

This literature shows that the military has indeed made an effort to integrate renewable energy at the tactical level. There is consensus that energy is inefficiently used at the tactical level and that fuel can be reduced by properly operating the current stock of diesel generators. Debate arises when questioning whether renewable energy is needed at all if significant reductions can be made from the proper operation of diesel generators. The following case scenarios will show that integrating renewables will not only reduce fuel consumption, but will provide greater benefits than if just the proper operation of diesel generators was implemented.

Methodology

Tactical military camps are infrastructure systems and as such will be analyzed using the infrastructure models discussed in the *Infrastructure Analysis and Planning* previously discussed. These models will focus on the camp's energy system and the inputs needed to support the energy system.

Four camp energy system scenarios will be analyzed, each with a different energy system or load configuration. The two energy systems in question are the status quo system, diesel generators, and the system of interest, renewable energy generators. Only solar generation will be analyzed due to situational constraints further explored in the *Situation* section of this *Methodology*. The load configurations in question are the status quo configuration, decentralized spot generation, and centralized generation.

The four energy system cases are listed in **Table 13**. Case 1 is the baseline case where the camp is powered by decentralized diesel generators loaded at 30% of the generators capacity. This is the common camp configuration found in many tactical military camps. Case 2 is similar to Case 1 except that generators are properly sized so that they are loaded at 80%. Case 3 is the first case where renewable energy generation will be analyzed. This case will question how a camp powered on 100% renewable energy will operate. Case 4 showcases a hybrid energy system that uses both renewable energy generators and diesel generators.

Table 13: Four cases will be analyzed to determine fuel consumption levels based on different generation assets and energy system typographies.

	PRIMARY ENERGY SYSTEM	LOAD CONFIGURATION
CASE 1	Diesel Generator	Decentralized generation with generators loaded at 30%.
CASE 2	Diesel Generator	Decentralized generation with generators loaded at 80%.
CASE 3	Solar PV Array	Decentralized generation.
CASE 4	Hybrid- Solar PV and Diesel Generators	Centralized generation.

Situation

The tactical and environmental situation will influence how the camp is operated and supported. Each case analysis will be based on the same theoretical camp. This theoretical camp has the following characteristics:

- **Location:** The camp is located in central Afghanistan. This location, as well as the majority of the country, have wind conditions too low to support wind turbines.

- **Population.** The theoretical camp used is sized for a platoon, which consists of 50 soldiers including non-organic support personnel.

- **Loads and Systems.** The camp includes the systems needed to support the population of 50 soldiers listed in **Table 14.** The camp requires approximately 590 kWh of energy daily.

Table 14: This table describes the energy reliant systems deployed in the camp.

SYSTEM	QUANTITY	TOTAL DAILY LOAD (KWH)	DESCRIPTION
HOUSING	1	250	Wood framed tents with minimal climate control systems and assuming that each occupant uses a total of 5kWh daily. For generator sizing purposes, it is assumed the generator will have a peak loading of 25 kW.
KITCHEN	1	36	A mobile tent kitchen (MTK) with 4-kW of generator capacity operating for 9 hours daily.
WATER PURIFICATION	1	60	An Army 600 GPH Reverse Osmosis Water Purification Unit (ROWPU) supported. Assuming each soldier requires 15.6 gallons per day and that the ROWPU creates 600 GPH from seawater, the system needs to operate for approximately 2 hours.
TACTICAL OPERATIONS CENTER (TOC)	1	240	The TOC is where all tactical decisions and communications are held. There is no specific set of equipment for a TOC. The load is generated assuming four computers at .5 kW and two 2-kW radio systems all operating for 24 hours.
Housing: (General Engineering 2015. Pg. 9-6) Kitchen Load: (Kirejczyk And Schleper 200., Pg. 4, 13) Dimensions: (General Engineering 2015. Pg. B-3) Water Purification: (Balling 2009. Slide 10, 13)			

The models that are discussed in the following section look at each case under normal and adverse conditions. Normal conditions include the camp having a stable load between 590 kWh and 730 kWh. The latter value is 125% of the expected load. The camp aims to have eight days worth of storage on site. For the renewable energy cases, there is a daily solar radiance of .61 ± .5 kWh per square meter with the variability stemming from weather patterns. Adverse conditions are an environment where the security situation in the area of operations has severely deteriorated and/or natural weather conditions are disadvantageous to the camp. These conditions result in the camp losing the TOC generation asset and a 50% in fuel supply. For the solar generation assets, there is a 50% reduction in daily solar radiation.

Models

Each case will be analyzed using a modified ICM followed by the IAM. This new ICM is meant to better encapsulate the various components of tactical military camps. The IAM has also been modified to have more easily identifiable prompts. The IAM is used to determine how the energy system will respond to various internal and external conditions.

Modified Infrastructure Component Model.

Hart et al.'s ICM is a great tool for the average user to analyze real-world infrastructure systems. However, its generic nature reduces its effectiveness to capture how an actual infrastructure system operates. In the case of tactical military camps and for the scope of this thesis, the models focus on raw material-to-waste is too broad. To address the discrepancy, a Modified Infrastructure Component Model (MICM) is presented in **Table 15** alongside the original ICM. MICM better addresses the infrastructure systems of a tactical military camp. Following **Table 15**, each prompt is further explained.

Table 15: The original ICM is too broad and poorly encapsulates a tactical military camp.

ICM	MICM
Generation	Deployment
Bulk Transmission	Generation and Fueling (Bulk Transmission of Fuel)
Distribution	Distribution and Storage
Use	Use
Waste Management	Consolidation and Repurposing
Coordination	Coordination

- **Deployment. How is the system set up and prepared for use?** Deployment of the energy system is the movement of all necessary components into a configuration that is ready to meet the energy load of the camp. The analysis unit for this prompt is deployment weight, which is the weight of the primary components of the energy system.

- **Generation and Fueling. How is the electricity generated and what is needed to generate this electricity?** Depending on the energy source, this component is taking a natural energy source (fossil fuel, solar rays, wind, etc.) and generating electricity. This component also includes what is needed to fuel the system including outside inputs and user actions. The analysis unit for this prompt is the daily amount of diesel fuel required to operate the energy system in normal conditions.

- **Distribution and Storage. How does the energy go from the generator to the user?** Once electricity is generated, it must either be stored or distributed to the end user. This component includes the "transportation" of the electricity to the end user whether it be via wires or manual labor. The analysis unit for this prompt is the energy system's footprint. The system's footprint will dictate how the system is planned in the camp's site layout and how much distribution infrastructure is needed.

- **Use. How does the end user use the electricity?** This prompt includes the use of the electricity by the end user including any user actions that need to be taken, energy availability, and energy reliability. The analysis unit for this prompt is energy, measured in daily kilowatt-hours.

- **Consolidation and Repurposing. What happens to the system once it is no longer needed?** Once the camp reaches its end-of-life, the energy system is either discarded or packaged for future use. The analysis unit for this prompt is the generation assets average loading. A generator's loading directly affects the required maintenance. Generators consistently underloaded require greater maintenance and ultimately have shorter life spans.

- **Coordination. How is the system organized and administered?** The energy system must turn energy sources into electricity and then delivery that energy to a load. Some form of coordination is needed to determine the load required and how many energy sources are needed to meet said load. The analysis unit for this prompt is the presence of a control system.

Infrastructure Assessment Model.

The original IAM is used in each case analysis. As a brief reminder, the IAM is as follows:

- **Normal Conditions***:* The steady state condition that the tactical camp will operate in for the majority of its existence.
  - **Required:** what does the platoon quantitatively require from the camp's energy system? The analysis unit for this prompt is generation capacity as a percentage of generation capacity available over the generation capacity needed.
  - **Ready:** Does the camp's energy system have the quantitative capacity to meet the needs of the platoon? The analysis unit for this prompt is generation capacity needed.
  - **Organized:** Does the energy system have the proper management and coordination to meet steady state requirements? The analysis unit for this prompt is whether a control system is needed to properly operate the system.
- **Adverse Conditions***:* Adverse conditions are conditions where the camp's energy system is under unintended strain such as an enemy attack.
  - **Durability:** What is the ability for energy systems to "survive and quickly recover from adverse conditions?" (Hart et al. 2014. Pg. 62). The analysis unit for this prompt is whether the camp's required load is met.
  - **Redundant:** What backup or auxiliary systems are available to meet demand if the energy system is inoperable? The analysis unit for this prompt is whether the energy system had a back-up system that can provide power when the main system is inoperable.
  - **Prepared:** Are the platoon and the camp's other systems prepared to "survive the inevitable disruption in service provided" by the affected infrastructure (Hart et al.

2014. Pg. 63)? The analysis unit for this prompt is whether the energy system can meet the camp's critical load, which includes the TOC, water purification system, and the kitchen.

Findings and Results

As noted previously, four cases with unique generation sources and system layouts were explored using the ICM and IAM. These four cases are detailed in **Table 10.**

Case 1: Decentralized Diesel Generators Underloaded.

Case 1 is the baseline case that resembles current military practices. In this case, the camp is powered by decentralized diesel generators loaded at 30% of the generators capacity. From these conditions, it was found that the generators in **Table 16** were needed. Supporting calculations can be found in **Appendix A** and product specification documents for the generation assets can be found in **Appendix B.**

Table 16: Case 1 requires three 60-kW generators and one 10-kW generator to meet the camp's required load when these generators are loaded at 30%.

System	Generation Required at 30% Load and 125% Generation	Generator Size (kW)	Hourly Fuel Consumption (Gal/hr)	Daily Fuel Required (Gallons)
Tent	43.4	60	1.44	34.56
Kitchen	8.3	10	0.2	4.4
ROWPU*	50.0	60	1.8	9.0
TOC	41.7	60	1.44	34.56

*Platoon sized units typically will not have generation assets larger than 60-kW. In order to load the ROWPU's generator to 30%, the ROWPU's operational hours were increased from two hours to five hours.

Modified Infrastructure Component Model.

Deployment. Case 1 deploys the following generators: one 10-kW generator and three 60-kW generators. This scenario has a deployment weight of 18,000 pounds of equipment. (Marine Corps Systems Command 2011). The system requires 82 gallons of diesel daily. The energy system's typography requires little need for energy system planning or management because the generators are placed with their loads.

Generation and Fueling. Case 2 has a 552% generation potential over the required load; that is 190-kW of generation capacity to 34-kW of generation needed. This 552% generation is a factor of each generator operating independently and being loaded to only 30%. Each generator will operate independently and a straight forward fueling plan could meet the generators fueling needs due to their predictable use. This fueling plan will move the 82 gallons of diesel required by the system daily from the centralized fueling point to the various generators. In addition to this daily fueling plan, each generator will have emergency fuel, typically a 5-gallon fuel container, located with the generator. As noted before, the camp will have eight days' worth of fuel on site, which is 660 gallons of diesel.

Distribution and Storage. Fuel will be stored in above-ground tanks and then be hand-delivered to individual generators. The four generators have a total footprint of 79 square feet and will be spread amongst the camp. The fueling plan will most likely require one to two soldiers to deliver fuel to each generator. Delivering fuel to the platoon will be covered in the *Interpretation and Discussion of Results* section of this research.

Use. The camp uses 590 kWh of energy daily. Due to the minimal loading of each generator, individual users will not have to worry about fuel levels. The soldier in charge of fueling each generator will monitor fuel levels and the unit as a whole will be responsible for maintenance. When generators are taken offline for maintenance, there is so much over-over generation that loads can be redistributed depending on proximity to other generators.

Consolidation and Repurposing. Consolidating and repurposing this system will ultimately depend on how well maintenance was completed on the generators. These generators will require additional maintenance as a result of their minimal loading. If the generators are properly maintained and worth salvaging, the unit will only have to disconnect the loads from the generator, drain the generators in preparation for storage, and finally store the equipment. Other system components such as the fuel storage tank and small fuel containers are highly reusable and require minimal maintenance.

Coordination. The energy system does not require an automated control system. Minimal coordination is required to operate the system. Scheduled bi-weekly fuel resupplies will keep the cam properly under normal and increased fuel consumption. On site, maintaining the generators will be an assigned responsibility to a soldier trained in generator maintenance. Refueling the generators will be a task assigned to a soldier.

Infrastructure Assessment Model.

Normal Conditions. Normal conditions for this Case are a daily load between 590 and 730 kWh and eight days' worth of fuel stored on-site.

Required. The camp has a daily energy load of 590 kWh. The camp has a daily generation capacity of 550% over its required energy.

Ready. The camp has a generation capacity of 190 kW while camp's hourly energy requirement is roughly 34 kW.

Organized. The energy system requires no control system. The over-generation and amble fuel available means the system can operate with no coordination and still meet user needs. For instance, there is so much generation capacity that if a generator is improperly maintained and becomes inoperable, there is enough over-generation to meet the system's needs.

Adverse Conditions. Adverse conditions for the camp are losing the TOC generator, which removes 60-kW of generation capacity, and a 50% decrease in fuel supply, which is 41 gallons of diesel daily, or 330 gallons weekly.

Tough. Between losing the TOC's 60-kW generator and the 50% reduction of fuel, the energy systems limiting factor is fuel, as noted in **Table 17.** When the camp consolidates their loads onto one 60-kW generator, an additional 14 gallons of fuel over what is available is needed to meet the camp's load.

Table 17: The limiting factor for Case 1 is the availability of fuel.

	Normal Requirement	Critical Load Requirement	Available
Generation Capacity (kW)	20-34	6-24	130
Diesel Fuel (Gallons)	60	46	41

Redundant. The camp's energy redundancy comes from its high generation capacity. As noted, even under adverse conditions, the camp has enough generator capacity to meet its required load. However, this redundancy is irrelevant since there is not enough fuel to power the one generator needed. The camp's best course of action would be to shed non-critical loads and be very cognizant of fuel levels.

Prepared. Even after shedding non-critical loads, the camp does not have enough fuel to power its critical system.

Synopsis.

While inefficient, Case 1 is the easiest to obtain for a military unwilling to devote time to properly managing energy systems. Fuel availability is the limiting factor in adverse situations, not the availability of generation potential. Case 1 does give the camp the largest room to grow if their load increases.

Case 2: Decentralized Diesel Generators Properly Loaded.

Case 2 is very similar to Case 1 except for the generator loading and thus the generation assets required. In this case, the camp is powered by decentralized diesel generators loaded at 80% of the generators capacity. From these conditions, it was found that the generators in **Table 18** were needed. Supporting calculations can be found in **Appendix A** and product specification documents for the generation assets can be found in **Appendix B.**

Table 18: Case 1 requires two 20-kW generators, one 60-kW generator and one 5-kW generator to meet the camp's required load when these generators are loaded at 80%.

System	Generation Required at 80% Generator Load and 125% Generation	Generator Size (kW)	Hourly Fuel Consumption (Gal/hr)	Daily Fuel Required (Gal)
Tent	16.3	20	1.8	43.2
Kitchen	3.1	5	0.42	7.6
ROWPU	46.9	60	3.44	10.32
TOC	15.6	20	1.8	43.2

Modified Infrastructure Component Model.

Deployment. Case 2's layout calls for four total generators: one 5-kW generator, two 20-kW generators, and one 60-kW generator. These four generators total a mission weight of 16,000 pounds of equipment and site footprint of 72 square feet (Marine Corps Systems Command 2011). Since the generators will be placed with their load, there is no need for additional energy system planning. Considerations such as specific generator and fuel storage placement will be dictated by the security situation.

Generation and Fueling. The camp has a generation capacity of 105 kW to meet its 52 kW load. The system requires 101 gallons of fuel daily to generate the 730 kWh required (United States Engineer Corps 2001. Pg. 24). Thus, the camp will need 830 gallons of fuel on site to meet an 8-day stock objective (General Engineering 2015. Pg. B-5). The loading requirement of the ROWPU leads to Case 2 having a higher fuel requirement than Case 1 despite the more efficient loading of the generator.

Distribution and Storage. The four generators have a footprint of 72 square feet. Fuel will be stored in above ground tanks and then hand delivered to individual generators. This prompt closely resembles the distribution and storage needed for Case 1.

Use. As in Case 1, each generator is operated independently. Due to the moderate loading of each generator, individual users will not have to worry about fuel levels. The soldier in charge of fueling each generator will monitor fuel levels and the unit as a whole will be responsible for maintenance. When generators are taken offline for maintenance, non-critical users will have to go without power based on fuel availability and not generation capacity. Generators used for non-critical loads will be shifted to critical loads during maintenance.

Consolidation and Repurposing. Consolidating and repurposing this system will ultimately depend on how well maintenance was completed on the generators, which will be easier since the generators are more properly loaded. Consolidating and repurposing the system is the same as Case 1 once necessary maintenance is completed.

Coordination. Minimal coordination is required to operate the system and no control system is needed. Scheduled bi-weekly fuel resupplies will keep the platoon fueled if they have their typical energy load and even if they have over consumption, the platoon has eight days' worth of additional fuel on hand.

Infrastructure Assessment Model.

Normal Conditions. Normal conditions are a daily load between 590 and 730 kWh, and eight days' worth of fuel stored on site.

Required. The camp has a daily energy load of 590 kWh. The camp has a daily generation capacity of 200% over its required energy.

Ready. The camp has a generation capacity of 105 kW while the camp's hourly energy requirement is roughly 52 kW. The difference in required energy between Case 1 and 2 is from how the ROWPU is powered in the two cases. In Case 1, the ROWPU is underpowered for five hours so that its supporting 60-kW generator can be loaded at 30%. In contrast, Case 2's ROWPU is powered for the two hours needed to supply the camp with enough water while loading the generator at 50%. The generator is not loaded to 80% because the ROWPU has an issued 60-kW generator and the only changeable variable is how long the ROWPU is operating.

Organized. The energy system requires little organization and no control system. The over-generation and amble fuel available means the system can operate with no coordination and still meet user needs. For instance, if a generator is improperly maintained and becomes inoperable, there is enough over-generation to meet the system's needs.

Adverse Conditions. Adverse conditions for the camp are losing the TOC generator, which removes 20-kW of generation capacity, and a 50% decrease in fuel supply, which is 50 gallons of diesel daily, or 403 gallons weekly.

Tough. Between the loss of the 20-kW generator and the 50% reduction in fuel resupply, the limiting factor on the camp's ability to generate energy is the loss of fuel as noted in **Table 19**. After losing the 20-kW generator, the camp still has enough kilowattage to meet its hourly

Table 19: Available fuel is the limiting factor for Case 2 under adverse conditions.

	Normal Requirement	Critical Load Requirement	Available
Generation Capacity (kW)	20-52	6-24	85
Diesel Fuel (Gallons)	60	46	52

demand. If the camp consolidates its loads onto one generator, they will have their best fuel efficiency but will still need an additional 8 gallons of fuel.

Redundant. The camp's energy redundancy comes from its high generation capacity. With one generator inoperable, the camp still has enough generation capacity. However, this redundancy is irrelevant since there is not enough fuel to power the one generator needed to operate the camp.

Prepared. With less generation potential and less fuel, the camp will have to shed non-critical loads. The energy system would be able to support the camp's critical load.

Synopsis.

This case is the easiest to obtain with minimal investment. It calls for camps to continue their current practice of spot generation but with generators being properly sized to their potential load. This would call for greater load-awareness and potentially not using generators organic to the unit or camp. In adverse conditions, Case 2 fairs well. The planned over-generation of 125% became 200% from the inefficiency of spot generation. However, this over-generation allows the camp to operate with less planned fuel when needed.

Case 3: 100% Renewable Energy

Case 3 is a basecamp fully powered by renewable energy from photovoltaic panels. Wind energy was initially considered, but the majority of central Afghanistan has poor wind resource potential according to a study from USAID and NREL (United States Agency for International Development; National Renewable Energy Laboratory 2007). The average daily solar radiance over a year for Kabul, Afghanistan is 5.5 kWh per square meter. The 18-kW Sundial solar system listed in **Table 20** used in this model is an actual system currently deployed for research purposes by the military. No specific energy storage system is used due to the lack of currently available military energy storage systems with the storage capacity needed. Instead, real world power densities are used to plan mission weights. Refer to **Appendix A** for detailed calculations used to generate **Table 20** and **Appendix B** for product information on the generators featured.

Table 20: Case 3 is a camp powered by 100% renewable energy. The energy system used in the model is Sundial's 18-kW system.

System	Generation Required at 125% Generation (kWh)	18-kW SunDial Solar Array	Daily Generation (kWh)
Tent	313	2	324
Kitchen ROWPU	32	1	162
TOC	300	2	324

Modified Infrastructure Component Model.

Deployment. This Case requires 342 commercial solar panels, which are typically sized at 21 square feet. At an average of 37 pounds per panel, the system would weigh 14,400 pounds for the PV array and 150-kW of energy storage.

In addition to the solar panels, the system will also need energy storage. The camp could decide to deploy enough energy storage to hold all unused energy storage, approximately 220 kWh. This is very unrealistic due to the weight of current energy storage systems. A more realistic option is to have enough energy storage to store a fourth of their daily load, approximately 150 kWh. If the unit is able to deploy flywheel technology, at 12 pounds per kWh, the system would weigh 1,800 pounds (Moura 2017, Slide 9). More likely, the camp will have lithium ion battery storage. At 18 pounds per kWh, the system would weigh 2,700 pounds (Beckett Energy Systems 2017).

Generation and Fueling. Afghanistan has an average daily solar radiance of 5.5 kWh per square meter over a year (USAID & NREL 2007). Assuming nine hours of sunlight, the previous solar radiance becomes .61 kWh per square meter per day (TimeandDate 2017). At 22% efficiency, the system would generate 810 kWh, 170% of the camp's load. Being completely powered by PVs, it is assumed the camp would require little to no fuel resupply. With 342 panels however, the camp would need to properly clean and maintain the panels to maintain their generation capacity.

Distribution and Storage. The solar array would need to allot 7,172 square feet of space for the system (Matasci 2017).[1] Due to the area requirement of the solar array, spot generation is solely a reference to the generation asset and load relationship, and not the physical location of the generation asset. The solar array will need to be placed in any available open space that has adequate solar radiance. To further explain this point, look at the barrack's tent system. The barrack tent system has an area of 2,002 square feet while the two supporting solar arrays are 2,885 square feet. The 150 kWh of battery storage would be distributed between the tent system and the TOC because they are the only two loads with 24-hour operational hours.

Use. The camp still has a daily energy requirement of 590 kWh. Due to the characteristics of solar generation, the camp would need to be cognizant of when they are operating certain system. The ROWPU and kitchen, which share an 18-kW solar array and has no battery storage and would need to be operated during peak solar radiance. The tent system and TOC should aim to conduct energy intensive activities during peak solar radiance but their battery storage offers these two systems more flexibility.

Consolidation and Repurposing. The solar panels and storage systems are reusable. Consolidating 342 solar panels is a daunting task, especially in austere environments, which is compounded by the fragility of the PV's surface. The modular rectangular design of the panels makes them easy to transport however. The lithium ion battery storage has a cycle life of 3,650 cycles and a storage life of 18-months (Beckett Energy Systems 2017). The battery's life will also be affected by discharge utilization which is ideally 88% of the batteries capacity. The ability to reuse the energy storage system is directly correlated with how many cycles the battery system will experience.

Coordination. Case 3 would require an automated control system to control when the solar panels versus the battery are discharged. A soldier would need to be responsible for monitoring energy levels and switching solar arrays between storage options. If the system were interconnected, meaning that all PV arrays were connected to all storage devices, the soldier would only need to monitor energy levels in order to request additional energy resources to prevent shortages.

Infrastructure Assessment Model.

Normal Conditions. Case 3 normal conditions are a daily solar radiance of .61 ± .5 kWh per square meter with the variability stemming from weather patterns.

Required. As in Case 1 and 2, Case 3 requires 590 kWh, or 730 kWh when factoring in planned overgeneration of 125%.

Ready. At a solar radiance of .61 ± .5 kWh per square meter, the camp has a generation potential between 740 and 870 kWh daily, which is 101% to 120% above the required energy.

[1] For comparison, a standard NBA basketball court is 4,700 square feet.

Organized. Case 3 requires significantly more organization than Case 1 or 2. Due to the size of the solar array, significant planning must be put towards site planning to ensure that each panel receives adequate solar radiance through the day.

Adverse Conditions. In Case 1 and 2, adverse conditions were the loss of the TOC's generator and a reduction of 50% fuel resupply. In this scenario, adverse conditions include losing one of the systems 18-kW solar arrays and a 50% reduction in solar radiation.

Tough. By losing one 18-kW array, the camp losses 162 kWh of generation capacity. As noted in **Table 21**, the 50% reduction in solar radiation, which could be caused by severe weather, results in a system wide output of 405 kWh, 190 kWh shy of the camp's actual load requirement.

Table 21: Available solar radiance is the limiting factor for Case 2 under adverse conditions.

	Normal Requirement	Critical Load Requirement	Available
Generation Capacity (kW)	20-52	42	72
Solar Radiance (kWh)	590	340	405

Redundant. The camp has no redundancies that could support operations in the case of decreased solar radiance.

Prepared. The energy system could support the camp's critical load.

Synopsis.

Case 3 is highly vulnerable to uncontrollable environmental conditions. While in normal conditions the camp would be energy self-sufficient, the camp would be crippled by bad weather patterns. Additionally, it's unlikely a camp would be able to support the number of solar panels required due to space limitations. Essentially, more panels means more land that needs to be secured and held by the unit. Lastly, so many solar panels present the enemy with numerous easy targets.

Case 4: Hybrid System

Case 4's energy system is a centralized hybrid power system consisting of PV solar panels and diesel generators. The systems will work as one centralized energy system with solar energy being dispatched first. By dispatching the solar energy first, there is no need for energy storage. The generators will work in tandem and share the load equally. The energy system's components are listed in **Table 22**. The 30-kW solar system is the military's prototype Mobile Electric Hybrid Power Source which acts as a centralized node for multiple energy systems. Refer to **Appendix A** for detailed calculations used to generate Table 19 and **Appendix B** for product information on the generators featured.

Table 22: Case 4 has one 30-kW solar array supported by two 20-kW generators.

System	kWh Required Daily	Generation Required at 80% Load and 125% Generation	Generator Size (kW)	Daily Fuel Required (Gallons)
Generator 1	158	10.3	20	18.72
Generator 2	158	10.3	20	18.7
Solar	270	-	30	-

Modified Infrastructure Component Model.

Deployment. The energy system has a mission weight of approximately 12,000 pounds. The 114 PV panel's required weigh 4,200 pounds and have a flat footprint of 2,368 square feet. The two 20-kW generators are an additional 5,900 pounds and require 38 gallons of diesel daily, or 300 gallons to meet 8-day stocking requirements.

As a whole, the system's components would be spaced amongst the camp in order to reduce the potential threat from enemy attack. The entire system, meaning loads and generation assets, would need to plug into a central control node that would manage the dispatching of the two generators based on the output of the PV array.

Generation and Fueling. The solar array would operate continuously, outputting approximately 270 kWh daily, which is 37% of the camp's required generation. The remaining 460 kWh would come from the two 20-kW generators. The generators would run throughout the day and output an average of 10 kWh hourly while consuming two gallons of diesel hourly.

Distribution and Storage. The system has a total footprint of 2,433 square feet. The solar array would be distributed amongst the camp in locations where the panels would receive the most solar radiation. To support the generators, the camp would have 300 gallons worth of fuel storage on site. One 25-gallon container would be needed to fuel each generator and would take one soldier less than an hour to complete.

Use. Case 3 uses 590 kWh of energy daily. The camp could operate without devoting too much time on monitoring the energy system but would need a control system to operate the system. Overcast weather would affect the solar array, but at 90% loading, the two 20-kW generators could supply the entire camp. In that scenario, the camp would need to be very cognizant of their fuel supply.

Consolidation and Repurposing. The entire system is reusable. The solar panels need to be cleaned and properly stored once removed from the camp. While not ideal for the generators, operating at 50% is better than operating at 30% and will require less maintenance. Thus, there is a higher probability that the two generators will be in a state worthy of salvaging.

Coordination. While a control system is needed, minimal manpower hours are required to operate the system. The minimal fuel requirement of the two generators means that less manpower needs to be devoted to maintaining the generator fuel levels. There should be an individual who understands how the PV array and control system operates in case of any failures.

Infrastructure Assessment Model.

Normal Conditions. Normal conditions include a daily solar radiance of .61 ± .5 kWh per square meter with the variability stemming from weather patterns.

Required. As in the previous cases, the camp has a required energy load of 590 kWh, or 730 kWh when factoring in planned overgeneration of 125%.

Ready. The camp has 70-kW of generation and the ability to produce 1270 kWh daily, with the majority of that generation coming from the two 20-kW generators. At 170% generation, the camp has the capability to meet its load.

Organized. Case 4 heavily relies on the ability for the control system to regulate the use of the two generators. If the generators are used secondarily to the solar system, then they will require minimal fueling and maintenance.

Adverse Conditions. In Case 1 and 2, adverse conditions included the loss of the TOC's generator. Since there is no spot generation in this scenario, adverse conditions are the loss of one 20-kW generator as well as a 50% reduction in fuel resupply. There is no reduction in solar radiance because it is less likely that both sources of energy will be impacted at the same time. Such a scenario would be penalizing Case 4 for having two types of generation.

Table 23: Available solar radiance is the limiting factor for Case 2 under adverse conditions.

	Needed Requirement	Critical Load Requirement	Available
Generation Capacity (kW)	20-52	10-12	50
Fuel Required (Gallons)	35	17	19

Tough. As shown in **Table 23**, the system is unable to meet the camp's required capacity nor has enough fuel to meet the required load. The loss of fuel means the system can only generate 500 kWh, 86 kWh short of the camp's actual requirements.

Redundant. The system redundancies are found in the two types of generation: solar energy from the photovoltaic panels and diesel energy from the generators. While possible, it is less likely that both generation assets will be affected at the same time. Regardless of the redundant systems, the loss of fuel prevents the system from meeting the camps load under adverse conditions.

Prepared. The camp's critical load can be met even after losing one 20-kW generator and a 50% reduction in available fuel. The camp would need to need to shed non-critical loads by 17% to operate all loads using just the solar system and one generator. In the event of a catastrophic failure, the majority of the camp's critical load can be supported by one generation asset.

Synopsis.

By not being heavily reliant on one source of generation, Case 4 offers the best resilience in the face of adverse conditions. Like Case 3, significant site planning will need to be conducted to ensure that the solar array receives adequate solar radiance. The presence of the solar array as well as centralization of the system makes the camp much less reliant on fuel resupply.

Interpretation and Discussion of Results

Case Comparison

The four cases presented focused on the energy systems of a small military camp home to 50 soldiers in central Afghanistan. Case 1 and 2 had energy systems solely based on diesel generators. Case 3 looked at the opposite extreme of having a camp run on 100% renewable energy. Lastly, Case 4 was a camp run on a hybrid energy system of renewable solar energy and diesel generators.

Modified Infrastructure Component Model.

Table 24: Case 4 offers the least dependence on fossil fuel. While Case 3 requires no fossil fuel, the Case's footprint is too large to be tactically feasible.

Model Prompt	***Analysis Unit***	***Case 1***	***Case 2***	***Case 3***	***Case 4***
Deployment	Mission Weight (Pounds)	17750	16032	14437	**11602**
Generation and Fueling	Daily Fuel (Gallons)	79	104	N/A	**37**
Distribution and Storage	Footprint (Square Feet)	78.6	**72.1**	7205	2441.3
Use	Daily Actual Load (kWh)	586	586	586	586
Consolidation and Repurposing	Generator Loading	20-25%	**50-65%**	N/A	40-45%
Coordination	Control System Needed	No	No	**Yes**	**Yes**

If optimizing for minimal fuel consumption and tactical feasibility, Case 4's hybrid energy system is ideal as noted in **Table 24**. However, there is no superior case since such a ranking would be determined based on the given optimization variable. Optimizing for a certain variable would be based on what a commander prioritizes, which would change based on the tactical situation. The following bullet points describe the best prompt based on the optimization of the given prompt.

- **Deployment.** Case 4 has the lowest mission weight by approximately 3,000 pounds. This would be important to a commander of an airborne commander who needs to fit all his soldier and equipment into a C-130 aircraft.[2] In contrast, mission weight is not an issue to a mechanized unit with amble towing capacity.

- **Generation and Fueling.** Case 4 also has the lowest amount of daily fuel required. All commanders could benefit from being less dependent on resupply from logistics hubs. Case 4 also shows that renewable can offset dependence on fossil fuel at the tactical level.

- **Distribution and Storage.** In Case 3 and 4, energy is distributed to the PV array via solar radiance and thus the required footprint is very important because it directly affects the

[2] Airborne units have the capability to deploy into the area of operation via aircraft.

energy systems output capability. Case 1 and 2 are the best for commanders looking to minimize their camp's footprint. Units operating in urban areas with limited space and dense buildings cannot deploy a solar array that is approximately half the size of an NBA basketball court as in Case 4.

- **Use.** Each camp requires the same energy daily but each case does not have the same generation requirements. This interesting phenomenon is due to differing operational hours for the ROWPU which can either be operated at high power for a short amount of time, or at lower power for an extended period of time.

  Usage is closely linked to the energy system configuration. Spot generation, where the generator is directly connected to one load, ultimately leads to gross over generation. In contrast, when loads and generators are pooled into a centralized system, generators can be sized to better meet demand.

- **Consolidation and Repurposing.** Case 2 has the best possibility that its generators will be salvageable for later use. Underloading of generators increases required maintenance and decreases the life of the generator. While Case 3 is 100% renewable and thus has no generators, the size and fragility of the array means the system will easily be damaged through contact with the enemy.

- **Coordination.** Case 1 and 2 only require monitoring and refueling of their generators. Case 3 and 4 require additional training to properly coordinate the system and the system's themselves require an internal control system to regulate dispatching of the system's assets. While additional training would be required to properly operate Case 3 and 4 energy system, there are numerous examples of units purchasing generators off the local enemy that they do not know how to properly operate. Training on how to operate solar panels could reduce the purchase and waste of money on local generators.

Infrastructure Assessment Model.

Table 25: Generation capacity does not equate to energy resilience. As all the case scenarios have shown, when faced with the loss of generation capacity verses fuel availability, fuel availability is always the limiting factor.

System Conditions	Model Prompt	Analysis Unit	Case 1	Case 2	Case 3	Case 4
Normal	Required	Generation Capability (kW/kW)	552%	200%	172%	167%
	Ready	Generation Capacity (kW)	190	105	90	70
	Organized	Control System Needed	No	No	No	Yes
Adverse	Tough	Required Load Supported	No	No	No	No
	Redundant	Back-Up System Available	No	No	No	Yes
	Prepared	Critical Load Supported	No	Yes	Yes	Yes

The IAM answers the question of how the system will respond when tactical and environmental characteristics change against the camp's favor. Tactical situations constantly change and thus all commanders must be cognizant of how their energy system will operate in normal conditions and in adverse conditions. **Table 25** presents how each case operated under normal and adverse conditions.

- **Required.** Each case aimed to have generation capacity of 125% over its required energy as a means of ensuring energy availability. Due to system topography and the available size of generation assets, that goal of 125% is always overshot. Over generation at a certain point doesn't benefit a camp. Over-generation does allow for the camp to rapidly expand but any additional units will undoubtedly bring their own generation assets. Case 4's generation capacity is closest to the goal generation of 162% which is possible because of the load and generation centralization.

- **Ready.** The generation capacity of camp is always greater than the needed generation capacity due to the available sizes of generators and solar arrays.

- **Organized.** Case 3 and 4 requires a control system to regulate the use of the various energy systems. Case 1 and 2 only use one type of generation system and thus no control system is required.

- **Tough.** None of the Cases are able to meet the camp's load under adverse conditions. While not ideal, the camp has non-critical loads that can be shed during adverse conditions.

- **Redundant.** Only Case 4 has system redundancy. By having energy generation from solar and diesel fuel, there is decreased chance that the system will be as susceptible to adverse conditions that affect both systems in contrast to Case 1 and 2 where there is only one fuel source.

- **Prepared.** Case 3 is the only case that could not support the camp's critical load under adverse conditions. The camp's critical load is comprised of the camp's TOC, water purification system, and kitchen.

Transportation Fuel

Reducing the amount of fuel consumed at tactical military camps will naturally reduce the amount of fuel consumed transporting fuel to tactical military camps. It is difficult to accurately estimate transportation fuel savings for two reasons. First, no accurate assumption of fueling distance can be made. While fuel must travel from a logistics hub to the remote camp, fuel resupply may take different routes to reduce the chance of attack. Additionally, there is no way to know what resources will be deployed for the fuel resupply. Secondly, fuel resupply missions often deliver other mission critical resources such as food, water and munitions. Since there are multiple resources supplied during a resupply mission, it is impossible to know which resource is the primary reason for the resupply.

While the exact amount of transportation fuel for each case cannot be estimated, a ratio can be estimated based on the fuel consumption of each camp. Using Case 1 as the base scenario, only Case 4 has reduced fuel consumption, which is 36% of the fuel that Case 1 consumes. Surprisingly, Case 2 consumes more fuel despite using smaller generators and having those generators properly loaded.

There are two potential refuel scenarios which influence how much transportation fuel will be consumed. The first scenario is that every camp has the same fuel storage capacity of 800-gallons and that each camp is resupplied when the fuel bladder is at or below 50%. Case 1 would require fuel resupply every 5 days while Case 4 only requires resupply 11 days. This means Case 4 would lead to 55% less fuel related casualties over a year as compared to Case 1.

The second scenario is that each case has a fuel bladder sized for its specific 8-day fuel stock. Under this scenario, each camp would require the same frequency of refuel missions but the size of each refuel mission would be smaller. Assuming both camps were resupplied every 5th day, Case 1 would have a resupply weight of 2,800 pounds while Case 4 would only require 1,300 pounds.

Implementation

Renewable energy has had limited but promising implementation in combat situations. The majority of these instances have been after the fact modifications by hired contractors or specific renewable energy systems used for a sole tactical purpose. This thesis shows that it is possible to have renewable energy at a larger scale. The following are recommendations and action items that need to be executed to go from the research to deployment phase of renewable energy.

Training

Adopting new energy systems will require a new set of skills for soldiers. Currently, the military has Tactical Power Generation Specialists who are "responsible for supervising and performing maintenance and overhaul of power-generation equipment, internal combustion engines and associated equipment in mobile and stationary power plants” (U.S. Army 2017). The military needs to educate these soldiers on the major principles of renewable energy. Concepts such as energy availability, energy storage, and renewable resource characteristics would give these soldiers the necessary knowledge to understand how renewable energy can support their mission.

Additionally, immediate gains can be made by training units on how to properly load generators. By understand the load of their systems and how much load a generator can handle, units can centralize loads onto less generators and in the process, decrease fuel consumption.

Technology

The military needs to adopt a rugged renewable energy generator. Standardized photovoltaic panel and distribution systems would improve the accuracy of planning and logistics. To support these renewable systems, light weight energy storage needs to be researched and developed. To bring these two systems together, control systems such as those found in the MEHPS products needs to be made readily available to deploying units.

The military has begun this process by procuring and developing a series of systems that are aimed at offsetting a camp’s energy demand. In 2010, a Marine Company (approximately 120 soldiers) “trained on and deployed to Afghanistan with a suite of renewable energy-efficient technologies” and was able to operate “two patrol bases entirely on renewable energy and reduced fuel consumption at a third base by 90%” (Vavrin 2014. Pg. 13). The following are a few of the technologies the Marines used to offset their energy demand.

- **Solar Portable Alternative Communication Energy System (SPACES):** a flexible solar panel used for smaller items like radios and batteries and can be carried by a single soldier.

- **PowerShade (Shades):** a larger solar tarp that fit over a standard Marine Corps tent and powers the tent’s lighting system.

- **Ground Renewable Expeditionary Energy System (GREENS):** a solar panel array capable of providing a platoon-sized Combat Operations Center (COC), or approximately 4 computers.

- **ZeroBase Regenerator:** six outsized solar panels funneling energy into a battery that can power 20 lighting systems and 15 computers.

- **Mobile Electric Hybrid Power System (MEHPS):** MEHPS combines batteries, solar, and smart controls with traditional diesel generators and has demonstrated up to 50% fuel savings and up to 80% reduced generator operational time (Marine Corps Expeditionary Energy Office 2016). The system has 3, 10, 60, and 300-kW variants.

In a separate effort conducted by the U.S. Army between 2012 and 2014, Operational Energy (OE) Advisors visited 57 various military camps in Afghanistan and deployed numerous renewable energy systems. These systems are listed in **Table 26**.

Table 26: Power systems deployed by the U.S. Army between 2012 and 2014.

Power Class (kW)	**Renewable Energy System**	**System Deployments**
<2	Soldier Power Hybrid System WASP (.06-kW)	1
	Hybrid Energy System Patrol Pak (.36-kW)	6
2	Hybrid Power System FORGE 440 (2.4-kW)	4
3	Hybrid Power System FORGE 510 (3.6-kW)	6
	Hybrid Energy System Solar Stik 360 (3-kW)	11
5	Hybrid Energy System Solar Stik 400 (5-kW)	9
	Hybrid Energy System T-Series 910 Model (5-kW)	1
10	Hybrid Energy System T-Series 910 Model (10-kW)	-
15	18 kW SunDial	4

Power Classes: Stangl, Wertz and Holcomb 2005, Pg. 9
Energy Systems: Brygider et al, 2014. Pg.51-57

Military Doctrine

A camp's energy system can be optimized for a wide variety of variables. Which variable to optimize is based the commander's intent which will be based on the mission and tactical environment. Ultimately, every military camp is different and every commander's priority will be different. As **Table 27** illustrates, there is a different optimal energy system based on which variable is optimized.

Table 27: While the hybrid energy system had the least fuel consumption, the case is not optimal for all tactical situations.

Variable	**Optimization**	**Optimal Energy System**
Footprint	Minimize	Diesel Generation Properly Loaded (Case 2)
Fuel Consumption	Minimize	Hybrid System (Case 4)
Maintenance	Minimize	Hybrid System (Case 4)
Required Training	Minimize	Diesel Generation Underloaded (Case 1)
Generation Capacity	Maximize	Diesel Generation Underloaded (Case 1)
Fuel Storage Required	Minimize	Hybrid System (Case 4)
Resupply Frequency	Minimize	Hybrid System (Case 4)

Conclusions and Recommendations

This thesis shows that renewable energy from photovoltaic solar panels has the potential to reduce the military's reliance on fossil fuels while maintaining the same level of service as traditional diesel generators. Hybrid systems that combine PV panels and diesel generators can reduce camp dependence on fuel resupply while providing additional energy redundancy. These hybrid systems are less vulnerable to changing weather patterns and still offer camps the ability to operate at a level of self-reliance. The system's reduced dependence on fossil fuel and less generators reduce the mission weight of the entire system and puts less soldiers in harm's way when delivering fuel. However, this reduced weight may be negated if EES systems are required. EES systems may not be required if the renewable generation of the hybrid system is dispatched when the generator is able to generate energy. The primary drawbacks of these hybrid systems are their increased footprint and the increased level of training needed to operate the system.

Prior to this thesis, the majority of research in this field looked at tactical fossil fuel and renewable energy systems via two different lenses. One group of research attempted to reduce fuel consumption by improving the efficiency of diesel generators while another group of research attempted to answer the feasibility of renewable energy in tactical situations. Unlike prior research, the research presented in this thesis compared both systems under the same tactical situation. Another unique aspect of this research is how it looked at the life-cycle of the energy systems, from deployment to end-of-life. Lastly, little prior research focused exclusively on the application of these energy systems in tactical situations.

It is currently infeasible to have a camp run on 100% renewable energy. Firstly, the solar array footprint increases the camp's size to the point where additional resources need to be devoted to securing such a large area and these additional resources may not equate to the forces required to deliver fuel. A 100% renewable energy camp is also only feasible in swathes of empty land with no adjacent structures that could shade the array. The required structures would provide a large and easy target for the enemy. Secondly, a 100% renewable energy camp would require a sizeable energy storage system that with today's technology is not feasible because of the system's potential weight. Deploying such a system would be costly in terms of fuel spent and vehicles required.

Currently, the "lowest hanging fruit" for military camps to reduce fuel dependence would be the centralization of loads and generators. Energy is wasted on generators when they are improperly sized and under loaded. Centralization of loads on less generators will increase the loading percentage on generators, decrease the number of generators needed, and reduce the required maintenance of generators.

While the research conducted for this thesis was focused on energy systems of tactical military camps, there are other examples of renewable energy systems being deployed and reducing a camp's fuel dependence. A few of these examples are listed in **Table 28**.

Table 28: These camps were able to reduce their fuel consumption by consolidating and eliminating unnecessary generators (Brygider et al, 2014. Pg.45-47).

CAMP	ACTION ITEM	RESULT
Belembai, Oda	"Removed excess power generation."	"Fuel Savings from removing generator."
Black	"Combined loads to reduce fuel."	"Reduced fuel by 43 gallons per day."
Daman Dc	Combine generators; "Removed excess power generation."	"Saved 58 gallons per day."
Khenjakak	"Removed excess power generation."	"Combined two 60-kW loads onto one 60-kW to remove one 60-kW and save 43 gallons per day."
Moscall (Muskal)	"Excess power generation"	"Removed 150-kW and 10-kW offline to save 404 gallons per day."

Research Limitations.

The above research is comprised of a serious of assumptions that would need to be validated before the recommendations and case studies presented could be used to influence policy. Those assumptions are as follows:

- Cost is an important planning factor that was negated in this research. Along with cost, a life-cycle assessment primarily focused on the energy system's longevity would have greatly improved the ability to base planning decisions off of this research. These topics were omitted so that the research could focus on the primary question of whether renewable energy could reduce dependence on fossil fuel while offering the same level of service.

- The technology used and analyzed for the four case studies is not organic to one specific branch of the military. Instead, the best technologies from multiple branches and from the private sector were combined in the case studies. For the energy storage portions of the case studies, private sector technology was used when there was no public information on similar military technologies.

- Military operations occur globally in a variety of environments. While the majority of U.S. military operations in the past decade have occurred in the Middle East, solutions to our military's fossil fuel dependence must be appropriate for numerous environments. With that in mind, renewable energy availability would need to be researched for each area of operations.

- Renewable energy generation using wind resources was not explored in this paper due to the lack of wind resources in central Afghanistan. Wind may be a feasible source of renewable energy in other areas of operation.

- Generators are not issued to units based on their projected tactical energy load. Rather, generators are issued to units based on the energy reliant systems the unit operates, regardless if said systems are actually used. This paper sized generators based on the unit's load and not the unit's issued generators.

- Fuel consumption was based on standard diesel fuel generators at specific loads rather than actual military generators. Additionally, fuel consumption rates were linearly interpolated from few data points which decreased the accuracy of said values.

- The required loads of camps vary with the logistical and tactical situation of the area of operations. Some camps will have food and water delivered from logistics hubs, reducing their energy load while increasing the weight and frequency of resupply missions.

The research presented does not apply to situations where a tactical camp can source its energy from the local grid. In such a situation, the camp is no longer reliant on fuel to power their generators and thus consumption rates no longer are directly tied to the unit's ability to execute their mission. However, this research would be applicable if the camp wanted a backup energy system in case the main grid fails.

Sensitivity and Uncertainty Analysis.

The inputs of the four energy system models were designed to reduce the chance of uncertainty propagated through each model and into the model's output. The following inputs and their uncertainty are worth noting:

- **Camp Population.** The camp population for the four models was based on the average size of a military platoon. The platoon is the smallest whole maneuver unit. The size of a platoon varies based on unit type, injuries, and allotted troop levels. The average infantry platoon has approximately 40 soldiers organic to the unit. Also, the unit will be augmented with specific soldiers such as medics, forward observers, and interpreters. A population of 50 soldiers was chosen as an upper limit. Fewer soldiers would require the same energy systems as noted above. Additional soldier may require more energy system but it is unlikely a platoon would operate with more soldiers or that these soldiers would require significantly more energy.

- **Energy Systems.** The four energy reliant systems are an oversimplification of the systems the camp would require. However, there is no way to know exactly what systems the camp and its soldiers will need to accomplish their mission. The tent system's load would include both climate control systems as well as any personal energy the unit might need. Depending on the tactical situation, the unit may not deploy with a water purification system or a kitchen system. Instead, the unit would get resupplied with bottled water and Meals Ready to Eat (MRE). The camp's TOC would house a variety of energy reliant systems, such as battery recharging stations, computers, and communications equipment. There is no standardization of what electronics are included in a TOC since each mission requires different systems.

- **Solar Radiance.** Solar radiance data was derived from the daily solar radiance over a year in Afghanistan. This value did not take into account weather or seasonal fluctuations. In order to negate the sensitivity of this data, a ±.5 solar radiance range was used. Additionally, the adverse conditions analysis used a solar radiance of half the average daily solar radiance.

- **Adverse Conditions.** Adverse conditions could range from natural weather disasters to an attack by the enemy. The adverse conditions presented in the four cases studies resembled tactical situations where the camp would be expected to operate without external support. More drastic adverse conditions would warrant the support of large installations and units.

Related Applications.

The research presented is applicable to non-military camps as well. Disaster relief and refugee camps could reduce their fuel dependence by using renewable energy. The primary difference between military camps and other camps are the available resources, energy loads, and external threats placed on the camp.

Concluding Remarks

The military has two contradictory stances when it comes energy systems. The prevailing culture at the tactical level is “just add another generator.” This culture believes that generation capability is critical to the reliability of an energy system. However, a lack of fuel is often the limiting factor for an energy system, not the energy system’s generation capability. The competing culture is encapsulated in the phrase “we want to go further and stay longer.” This culture wants a nimble force that is not weighted down by unnecessary generators and lengthy supply lines. This thesis shows that with renewable energy it is possible to have both a nimble fighting force and a reliable energy system, that is not constrained by fossil fuel.

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Appendix A: Calculations

Generator Information

Table 29: Information on diesel generators came from their accompanying product specifications. Information on solar assets was calculated and can be found in the respective case study.

Generator Weight and Size		
Generator	Weight (lbs)	Area (ft^2)
5-kW	888	11.1
10-kW	1242	13.8
20-kW	2655	19.5
60-kW	4042	21.6
18-kW Solar[1]	2527	1440.9
30-kW Solar[2]	4218	2405.1

1. Refer to Case 3 for weight and area calculations.
2. Refer to Case 3 for weight and area calculations.

Table 30: Bolded consumption rates are data points based on the average diesel generator. All other consumption rates were linearly interpolated from the bolded data points.

Load	**Consumption (Gal/hr)**			
	5-kW[1]	10-kW	20-kW	60-kW
0%	0	0.00	0.00	0.00
20%	-	0.19	-	1.44
25%	**-**	**0.24**	**0.60**	**1.80**
30%	-	0.29	-	2.02
40%	-	0.39	0.78	2.46
50%	**-**	**0.49**	**0.90**	**2.90**
60%	0.42	0.58	1.50	3.26
65%	-	0.63	1.80	3.44
75%	**0.42**	**0.73**	**2.40**	**3.80**
80%	0.42	0.78	2.50	4.00
90%	-	0.87	2.70	4.40
100%	**0.42**	**0.97**	**2.90**	**4.80**

1. Only one consumption rate was available for the 5-kW generator. This data point was for loads between 60-100%.

Table 31: Afghanistan receives an average of 5.5 kWh of solar radiation per square meter daily. From this value, the daily solar radiation given 9 hours of sunlight can be calculated.

Afghanistan Solar Characteristics	
Solar Radiation (kWh/m^2/day)	5.5
Hours of Sunlight (hr)	9
Daily Solar Radiation (kW/ m^2) [1]	0.61
Sensitivity Lower Parameter (kW/ m^2) [2]	0.56
Sensitivity Upper Parameter (kW/ m^2) [3]	0.66
Adverse Conditions (kW/ m^2) [4]	0.31

1. $\text{Daily Solar Radiation}\left[\frac{kW}{\text{m}^2}\right] = \text{Solar Radiation}\left[\frac{\frac{\text{kWh}}{\text{m2}}}{\text{day}}\right] * \text{Hours of Sunlight [hr]}$

2. $\text{Daily Solar Radiation\_Lower Parameter}\left[\frac{kW}{\text{m}^2}\right] = \text{Daily Solar Radiation}\left[\frac{kW}{\text{m}^2}\right] - .05[\frac{kW}{\text{m}^2}]$

3. $\text{Daily Solar Radiation\_pper Parameter}\left[\frac{kW}{\text{m}^2}\right] = \text{Daily Solar Radiation}\left[\frac{kW}{\text{m}^2}\right] + .05[\frac{kW}{\text{m}^2}]$

4. $\text{Daily Solar Radiation\_Adverse Conditions}\left[\frac{kW}{\text{m}^2}\right] = \text{Daily Solar Radiation}\left[\frac{kW}{\text{m}^2}\right]/2$

Table 32: The photovoltaic system was analyzed under four conditions: normal conditions, normal conditions with an upper limit, normal conditions with a lower limit, and adverse conditions.

Photovoltaic System	
Panel Efficiency	22%
Panel Size (m^2/Panel)	1.96
Panel Weight (lbs/Panel)	37
Normal Conditions	
Panel Output (kW/Panel) [1]	0.26
Panel Output Daily (kWh/Panel/Day) [2]	2.37
Lower Panel Output (kW/Panel) [3]	0.24
Lower Panel Output Daily (kWh/Panel/Day) [4]	2.17
Upper Panel Output (kW/Panel) [5]	0.28
Upper Panel Output Daily (kWh/Panel/Day) [6]	2.56
Adverse Conditions	
Panel Output (kW/Panel) [7]	0.13
Panel Output Daily (kWh/Panel/Day) [8]	1.19

1. $\text{Panel Output}\left[\frac{\text{kW}}{\text{Panel}}\right] = \text{Panel Size}\left(\frac{\text{m}^2}{\text{Panel}}\right) * \text{Panel Efficiency[\%]} * \text{Daily Solar Radiation}\left[\frac{kW}{\text{m}^2}\right]$

2. $\text{Panel Output Daily}\left[\frac{\frac{\text{kWh}}{\text{Panel}}}{Day}\right] = \text{Panel Output}\left[\frac{\text{kW}}{\text{Panel}}\right] * \text{Hours of Sunlight}\left[\frac{\text{hr}}{\text{day}}\right]$

3. Calculations 3-8 were completed using the same equations as calculations 1 and 2 but with the respective Daily Solar Radiation.

Case 1: Decentralized Diesel Generators Underloaded.

Table 33: Generators were sized based on 125% of the power required to power a given system at if the generator was operated at 30% load.

System	Operational Hours[1]	Energy Required Daily (kWh)[2]	Power Required Hourly (kW)[3]	Power Required Hourly @125% Capacity (kW)[4]	Power Required at 30% Loading and 125% Capacity (kW)[5]	Generator Size (kW)[6]
Tent	24	250	10.4	13.0	43.4	60
Kitchen	18	36	2.0	2.5	8.3	10
ROWPU	5	60	12.0	15	50.0	60
TOC	24	240	10.0	12.5	41.7	60

1. The number of hours the system requires energy. Operational hours were drawn from tactical experience, user manuals and military reports.

2. The energy each system would require daily was drawn from user manuals, military reports and tactical experience for situational energy requirements such as the tents load.

3. $\text{Power Required Hourly [kW]} = \frac{\text{Energy Required Daily [kWh]}}{\text{Operational Hours [hr]}}$

4. Military doctrine recommends having enough generation capacity to meet 125% of the camp's predicted load.
$\text{Power Required Hourly @125\% Capacity [kW]} = \text{Power Required Hourly [kW]} * 125\%$

5. Case 1 models generators loaded at 30% because site visits and generator metering have found this to be the average loading of military generators. $\text{Power Required at 30\% Loading and 125\% Capacity [kW]} = \frac{\text{Power Required Hourly @125\% Capacity [kW]}}{\mathbf{30}\%}$

6. There are a set number of generator sizes available to military units, which can be found in Appendix B. Based on the "Power Required at 30% Loading and 125% Capacity (kW)," the next largest available generator was chosen.

Table 34: Once generators were sized, the actual loading of the generator needed to be calculated in order to find the generator's fuel consumption rate.

System	Generator Size (kW)	Actual Loading[1,2]	Hourly Fuel Consumption (Gal/hr)	Daily Fuel Required (Gallons)[3]
Tent	60	17-22%	1.4	34.6
Kitchen	10	20-25%	0.2	4.4
ROWPU	60	20-25%	1.8	5.4
TOC	60	17-21%	1.4	34.6

1. There are two methods for generator sizing. Option 1 is to set generation capacity so that each generator is loaded at 30% of its load capacity, which requires combining multiple loads on one generator. This option would narrow the gap between the actual generator load and the intended load and thus would be prioritizing modeling the generator at 30%. Option 2, which is the option used in this thesis, is to size the generator based on the specific load the generator is to support. This option prioritizes modeling the camp's energy system typography.

2. The range for "Actual Load" is the actual load placed on the generator and 125% of the actual load. The 125% load was used for to calculate the "Hourly Fuel Consumption" because this value was closer to 30%, allowing the research to rebalance the topography prioritization from earlier.

$$\text{Actual Loading}_{\text{upper value}} = \frac{\text{Power Required Hourly [kW]}}{\text{Generator Size } [kW]}, \quad \text{Actual Loading}_{\text{lower value}} = \frac{\text{Power Required Hourly @125\% Capacity [kW]}}{\text{Generator Size } [kW]}$$

3. $\text{Daily Fuel Required [Gallons]} = \text{Hourly Fuel Consumption } [\frac{\text{Gal}}{\text{hr}}] * \text{Operational Hours [hr]}$

Table 35: Under adverse conditions, load would be centralized onto one generator to reduce fuel consumption.

60-kW Generator[1]	**Load Evenly Distributed Throughout 24-Hours**[2]	**Specific Time-steps**		
		Peak Load[3]	**Load 2**[4]	**Load 3**[5]
Operational Hours	24	5	13	6
Load (kW)	24.4	34.4	22.4	20.4
Loading	41%	57%	37%	34%
Fuel Consumption Rate (Gal/hr)	2.5	3.3	2.5	2.0
Daily Fuel Consumption (Gal)	59.0	16.3	32.0	12.1
Total	59.0	60.4		

1. In an adverse condition where generation capacity and available fuel were both reduced, the camp would consolidate loads onto one generator to reduce fuel consumption. The 60-kW generator is the smallest generator that can support the camp's peak load of 34 kW.

2. Evenly distributing the camp's load is an inaccurate but easy method for modeling a generators use. This method is used to compare how accurate the value is to the actual loading of the generator looking at various timesteps. While the total fuel consumed are close to one another, using this method could lead an individual to choose a 30-kW generator because the average load required for the generator is 24 kW.

3. Peak load is only 5 hours during the day when all energy reliant systems are operating.

4. Load 2 is once the ROWPU stops operating and only the tent system, the kitchen, and the TOC require energy.

5. Load 3 is once the ROWPU and kitchen stop operating and only the tent system and TOC require energy.

Table 36: Once the camp realizes that it cannot support their normal load under adverse conditions, non-critical loads will be shed to reduce the camp's load. However, even after this step is taken, the camp does not have enough fuel to meet its critical load.

60-kW Generator	**Load Evenly Distributed Throughout 24-Hours**	**Specific Time-steps**		
		Peak Load	**Load 2**	**Load 3**
Operational Hours	24.0	5.0	13.0	6.0
Load (kW)	14.0	24.0	12.0	10.0
Loading	0.2	0.4	0.2	0.2
Fuel Consumption Rate (Gal/hr)	1.8	3.8	1.4	1.4
Daily Fuel Consumption (Gal)	43.2	19.0	18.7	8.6
Total	43.2	46.4		

Case 2: Decentralized Diesel Generators Properly Loaded.

Table 37: Case 2 requires smaller generators since they are properly sized to meet the required load.

System	Operational Hours	Energy Required Daily (kWh)	Power Required Hourly (kW)	Power Required Hourly @125% Capacity (kW)	Power Required at 30% Loading and 125% Capacity (kW)	Generator Size (kW)
Tent	24	250	10.4	13.0	16.3	20
Kitchen	18	36	2.0	2.5	3.1	5
ROWPU	2	60	30.0	37.5	46.9	60
TOC	24	240	10.0	12.5	15.6	20

Table 38: While the generators in this case are better loaded, the ROWPU can now operate at a peak performance. The ROWPU thus operates at a higher energy load for a shorter amount of time but also requires more fuel.

System	Generator Size (kW)	Actual Loading	Hourly Fuel Consumption (Gal/hr)	Daily Fuel Required (Gallons)
Tent	20	52-65%	480	1.8
Kitchen	5	40-50%	90	0.42
ROWPU	60	50-63%	120	3.44
TOC	20	50-63%	480	1.8

Table 39: Under adverse conditions, Case 1 and Case 2 operate similarly.

60-kW Generator	**Load Evenly Distributed Throughout 24-Hours**	**Specific Time-steps**		
		Peak Load	**Load 2**	**Load 3**
Operational Hours	24	2	16	6
Load (kW)	24.4	52.4	22.4	20.4
Loading	41%	87%	37%	34%
Fuel Consumption Rate (Gal/hr)	2.5	4.4	2.46	2.02
Daily Fuel Consumption (Gal)	59.0	9	39	12
Total	59.0	60.3		

Table 40: Unlike Case 1, Case 2 is able to handle its critical load under adverse conditions due to the additional fuel required to properly power the ROWPU.

60-kW Generator	**Load Evenly Distributed Throughout 24-Hours**	**Specific Time-steps**		
		Peak Load	**Load 2**	**Load 3**
Operational Hours	24.0	5.0	13.0	6.0
Load (kW)	14.0	24.0	12.0	10.0
Loading	0.2	0.4	0.2	0.2
Fuel Consumption Rate (Gal/hr)	1.8	3.8	1.4	1.4
Daily Fuel Consumption (Gal)	43.2	19.0	18.7	8.6
Total	43.2	46.4		

Case 3: 100% Renewable Energy

Table 41: A camp powered by 100% renewable is highly dependent on weather patterns.

Required 18-kW Systems[1]	5
Total System Power (kW)	90
Panels Required[2]	342
System Output (kWh/day)[3]	810/742.2/874.8/405

1. The number of 18-kW Systems required was determined using the following process:

    a. Daily energy output of each 18-kW System.

    b. Number of systems required to meet each energy reliant systems load. However, the ROWPU and kitchen loads were combined. Case Keeping the same system layouts discussed in Cases 1 and 2 requires.

2. $\text{Panels Required} = \frac{\text{Total System Power [kW]}}{Panel\ Output\ \left[\frac{kW}{panel}\right]}$

3. The four values listed are the system outputs under normal conditions, normal conditions-upper limit, normal conditions-lower limit, and adverse conditions.

    $\text{System Ouput } \left[\frac{\text{kWh}}{\text{day}}\right] = \text{Panels Required} * \text{Panel Output Daily } \left[\frac{\frac{\text{kWh}}{\text{Panel}}}{\text{Day}}\right]$

Case 4: Hybrid System

Table 42: The renewable portion of the hybrid energy system will be a 30-kW solar array comprised of 114 panels.

Required 30-kW Systems	1
System kW	30
Panels Required	114
System Output (kWh/day)[1]	270/247/292/135

1. The four system output are the output under normal conditions, normal conditions-lower limit, normal conditions-upper limit, and adverse conditions respectively.

Table 43: Since energy from the solar array will be dispatched first, the two generators will need to split the remaining load.

System	Operational Hours	Energy Required Daily (kWh)	Power Required Hourly (kW)	Power Required Hourly @125% Capacity (kW)	Power Required at 30% Loading and 125% Capacity (kW)	Generator Size (kW)
Generator 1	24	158	6.6	8.2	10.3	20
Generator 2	24	158	6.6	8.2	10.3	20

Table 44: The generators are underloaded since the requirement on both generators is so low compared to the available generator sizes.

System	Generator Size (kW)	Actual Loading	Hourly Fuel Consumption (Gal/hr)	Daily Fuel Required (Gallons)
Generator 1	20	33-41%	0.8	18.7
Generator 2	20	33-41%	0.8	18.7

Table 45: Under adverse conditions, the camp's one 20-kW generator does not have enough capacity to support the camp.

20-kW Generator	Specific Time-steps		
	Peak Load	Load 2	Load 3
Operational Hours	2	16	6
Load (kW)[1]	22.4	22.4	20.4
Loading	112%	112%	112%
Fuel Consumption Rate (Gal/hr)	-	-	-
Daily Fuel Consumption (Gal)	-	-	-
Total	-		

1. This load is the camp's load minus the 30-kW of solar generation that is unaffected during adverse conditions.

Table 46: Under adverse conditions, the camp is able to support its critical load using just the solar array and the one diesel generator.

20-kW Generator	Specific Time-steps		
	Peak Load	Load 2	Load 3
Operational Hours	2	16	6
Load (kW)	12.0	12.0	10.0
Loading	60%	60%	50%
Fuel Consumption Rate (Gal/hr)	1.5	1.5	0.9
Daily Fuel Consumption (Gal)	3	9	5
Total	17.4		

Appendix B: Product Specifications

Mobile Electric Power Systems (Program Manager Expeditionary Power Systems 2010, Pg. 2)

MOBILE ELECTRIC POWER (MEP)

The Marine Corps Systems Command (MCSC) is the USMC fielding agent for the Joint Service Program for Mobile Electric Power (MEP). MCSC continues to field the family of Tactical Quiet Generators (TQGs) and will manage legacy systems until they are completely removed from the fleet.

GENERATOR SET, MEP-531A
2kW, 60Hz, DIESEL ENGINE
B0980 6115-01-435-1565
120 Volts, 1 Phase
No USMC Items replaced

GENERATOR SET, MEP-831A
3kW, 60 Hz, DIESEL ENGINE
B0730 6115-01-285-3012
120/240 Volts, 1 Phase
Replaced MEP-016 Series

BATTERY CHARGING APU
3.5 kW, DIESEL ENGINE
28VDC, I phase, 3600 RPM
Supports the LVS / MK48 Power Unit
No USMC Items replaced

GENERATOR SET, MEP-802A
5kW, 50/60Hz, DIESEL ENGINE
B0077 6115-01-274-7387
120/208/240 Volts, 1 and 3 Phase
No USMC Items replaced

GENERATOR SET, MEP-803A
10kW, 60Hz, DIESEL ENGINE
B0891 6115-01-275-5061
120/208/240 Volts, 1 and 3 Phase
Replaced MEP-003A

GENERATOR SET, MEP-813A
10kW, 400Hz, DIESEL ENGINE
B0921 6115-01-274-7392
120/208/240 Volts, 1 and 3 Phase
Replaced MEP-112A

GENERATOR SET, MMG 25
20kW, 60Hz, DIESEL ENGINE
B0930 6115-01-531-0571
120/208 Volts, 3 Phase
No USMC Items replaced

SYNCHRONIZER BOX, MSB25
20kW, 60Hz
No TAMCN
NSN 6110-01-559-0584
120/208 Volts, 3 Phase
No USMC Items replaced
For use with MMG 25 B0930

GENERATOR SET, MEP-805B
30kW, 60Hz, DIESEL ENGINE
B0953 6115-01-461-9335
120/208/240/416 Volts, 3 Phase
Replaced MEP-805A

GENERATOR SET, MEP-805A
30kW, 60Hz, DIESEL ENGINE
B0953 6115-01-274-7389
120/208/240/416 Volts, 3 Phase
Replaced MEP-005A

GENERATOR SET, MEP-815B
30kW, 400Hz, DIESEL ENGINE
B0971 6115-01-462-0290
120/208/240/416 Volts, 3 Phase
Replaced MEP-815A

GENERATOR SET, MEP-815A
30kW, 400Hz, DIESEL ENGINE
B0971 6115-01-274-7394
120/208/240/416 Volts, 3 Phase
Replaced MEP-114A

GENERATOR SET, MEP-816B
60kW, 400Hz, DIESEL ENGINE
B1016 6115-01-462-0292
120/208/240/416 Volts, 3 Phase
Replaced MEP-816A

GENERATOR SET, MEP-816A
60kW, 400Hz, DIESEL ENGINE
B1016 6115-01-274-7395
120/208/240/416 Volts, 3 Phase
Replaced MEP-115A

GENERATOR SET, MEP-806B
60kW, 60Hz, DIESEL ENGINE
B1021 6115-01-462-0291
120/208/240/416 Volts, 3 Phase
Replaced MEP-806A

GENERATOR SET, MEP-806A
60kW, 60Hz, DIESEL ENGINE
B1021 6115-01-274-7390
120/208/240/416 Volts, 3 Phase
Replaced MEP-006A

GENERATOR SET, MEP-807A
100kW, 60Hz, DIESEL ENGINE
B1045 6115-01-296-1463
120/208/240/416 Volts, 3 Phase
Replaced MEP-007A/B/C

GENERATOR SET, MEP-809A
200kW, 60Hz, DIESEL ENGINE
B0083 6115-01-296-1462
120/208/240/416 Volts, 3 Phase
Replaced MEP-009A

5-kW Diesel Generator (Marine Corps Systems Command 2011)

TM 12359A-OD

GENERATOR SET, DIESEL ENGINE, 5kW, 60Hz

TAMCN: B0077

ID: 09292A

NSN: 6115-01-274-7387

Functional Description

The 5kW TQG Generator Set, MEP-802A, is a self contained, skid mounted, portable unit. It is equipped with controls, instruments and accessories necessary for operation. The generator set consists of a diesel engine, brushless generator, excitation system, speed governing system, fuel system, 24VDC starting system, control system and fault system. The generator set is designed to be used with any equipment requiring a small source of AC power and operates in a "Hot and Basic" climatic condition range of -25°F to +120°F. This generator set is mobile and requires forklift support.

Technical Description

Generator Set		**Fuel**	
Manufacturer:	Fermont	Fuel Capacity (Gal):	5
Model:	MEP-802A	Fuel Consumption (GPH):	.57
Voltage (Volts):	120/208/240	Fuel Requirement:	Diesel/JP-8
Frequency (Hz):	60		
Speed (RPM):	1800	**Dimensions**	
Phase:	1 and 3	Length (in):	50.4
		Width (in):	31.8
		Height (in):	36.2
Engine		Weight (lbs):	
Manufacturer:	Onan	Dry:	800
Model:	DN2M	Wet (coolant & POLs):	888
Type:	2 Cycle	Volume (ft^3):	34
Cylinders:	2		
Displacement:	57 in^3 (0.9L)	**Aural Signature**	
		Audio Rating:	70dBA @ 7 meters

Replaced Items No USMC items replaced.

Transportability LTT-MCC Trailer.

EXTRACT FROM TM 12359A-OD DATED 2011

6-7

10-kW Diesel Generator (Marine Corps Systems Command 2011)

TM 12359A-OD

GENERATOR SET, DIESEL ENGINE, 10kW, 60Hz

TAMCN: B0891

ID: 09247A

NSN: 6115-01-275-5061

Functional Description

The 10kW TQG Generator Set, MEP-803A, is a fully enclosed, self-contained, skid-mounted, portable unit. It is equipped with controls, instruments and accessories necessary for operation. The generator set consists of a diesel engine, brushless generator, excitation system, speed governing system, fuel system, 24VDC starting system, control system and fault system. The generator set is designed to be used with any equipment requiring a small source of AC power and operates in a "Hot and Basic" climatic condition range of -25°F to +120°F. This generator set is mobile and requires forklift support.

Technical Description

Generator Set

Manufacturer:	Fermont
Model:	MEP-803A
Voltage (Volts):	120/208/240
Frequency (Hz):	50/60
Speed (RPM):	1800
Phase:	1 and 3

Engine

Manufacturer:	Onan
Model:	DN4M
Type:	Cycle
Cylinders:	4
Displacement:	114 in^3 (1.9L)

Fuel

Fuel Capacity (Gal):	9
Fuel Consumption (GPH):	0.99
Fuel Requirement:	Diesel/JP-8

Dimensions

Length (in):	62
Width (in):	32
Height (in):	37
Weight (lbs):	
Dry:	1140
Wet (coolant & POLs):	1242
Volume (ft^3):	41

Aural Signature

Audio Rating:	70dBA @ 7 meters

Replaced Items MEP-003A.

Transportability All variants of the USMC M116 trailer and the LTT-MCC trailer.

EXTRACT FROM TM 12359A-OD DATED 2011

6-13

20-kW Diesel Generator (Marine Corps Systems Command 2011)

TM 12359A-OD

GENERATOR SET, DIESEL ENGINE, 20kW, 60Hz

TAMCN: B0930

ID: 11125A

NSN: 6115-01-531-0571

Functional Description

The 20kW Generator Set, MMG 25, is a fully enclosed, self-contained, skid-mounted, portable unit. It is equipped with controls, instruments, and accessories necessary for operation as a single unit. The generator set consists of a diesel engine, brushless generator, fuel system, 12VDC starting system, control system, and automatic safety shutdown system. The generator set is designed to be used with any piece of equipment requiring a medium source of AC power. This generator set is mobile and requires forklift support.

Technical Description

Generator Set

Manufacturer:	Magnum
Model:	MMG 25
Voltage (Volts):	120/208
Frequency (Hz):	60
Speed (RPM):	1800
Phase:	3

Engine

Manufacturer:	Isuzu
Model:	4LE1 PV-05 Tier II 4LE1 NYGV-01 Tier IV
Type:	4 Cycle
Cylinders:	4
Displacement:	133 in^3 (2.179L)

Fuel

Fuel Capacity (Gal):	46
Fuel Consumption (GPH):	2.1
Fuel Requirement:	Diesel/JP-8

Dimensions

Length (in):	77.5
Width (in):	36.25
Height (in):	51.61
Weight (lbs):	
Dry:	2345 w/adapter
Wet (coolant & POLs):	2655 w/adapter
Volume (ft^3):	79

Aural Signature

Audio Rating:	65dBA @ 23 feet

Replaced Items No USMC items replaced.

Transportability All variants of the USMC M116 trailer and the LTT-MCC trailer.

EXTRACT FROM TM 12359A-OD DATED 2011

60-kW Diesel Generator (Marine Corps Systems Command 2011)

TM 12359A-OD

GENERATOR SET, DIESEL ENGINE, 60kW, 400Hz

TAMCN: B1016

ID: 09245A

NSN: 6115-01-274-7395

Functional Description

The 60kW TQG Generator Set, MEP-816A, is a fully enclosed, self-contained, skid-mounted, portable unit. It is equipped with controls, instruments, and accessories necessary for operation as a single unit or in parallel with another unit of the same class and mode. The generator set consists of a diesel engine, brushless generator, excitation system, speed governing system, fuel system, 24VDC starting system, control system, and fault system. The generator set is designed to be used with any piece of equipment requiring a medium source of AC power and operates in a "Hot and Basic" climatic condition range of -25°F to +120°F. This generator set is mobile and requires forklift support.

Technical Description

Generator Set

Manufacturer:	Libby / Fermont
Model:	MEP-816A
Voltage (Volts):	120/208/240/416
Frequency (Hz):	400
Speed (RPM):	2000
Phase:	3

Engine

Manufacturer:	John Deere
Model:	6059T
Type:	4 Cycle
Cylinders:	6
Displacement:	359 in^3 (5.9L)

Fuel

Fuel Capacity (Gal):	43
Fuel Consumption (GPH):	5.37
Fuel Requirement:	Diesel/JP-8

Dimensions

Length (in):	87
Width (in):	35.7
Height (in):	59
Weight (lbs):	
Dry:	3606
Wet (coolant & POLs):	4042
Volume (ft^3):	103

Aural Signature

Audio Rating:	72dBA @ 7 meters

Replaced Items MEP-115.

Transportability All variants of the USMC M353 trailer.

NOTES: Libby Models serial numbers start with "RZH" & Fermont Models start with "FZ"

EXTRACT FROM TM 12359A-OD DATED 2011

6-25

600 GPH ROWPU (Balling 2009, Slide 12-13)

RDECOM

600 GPH Reverse Osmosis Water Purification Unit (ROWPU)

TARDEC

- Produce potable water that meets Tri-Service Standards from any available source
- System produces 600 gallons per hour on seawater (35,000 ppm) and 900 gallons per hour on freshwater
- Raw water intake system – strainer and raw water pump
- Clarification system – multi-media filter, cartridge filter, chemical injection pumps
- Purification system – high pressure pump, 8 6-inch reverse osmosis elements
- NBC decontamination system – activated carbon, mixed-bed ion exchange
- Disinfection by Chlorination

TECHNOLOGY DRIVEN. WARFIGHTER FOCUSED.

Unclassified/FOUO

RDECOM

600 GPH ROWPU Characteristics

TARDEC

- 30 kW Generator (Army only) 2850 lb
- 5 ton Trailer (Army only) 5595 lb
- Skid mounted (USMC and AF)
  - 9.5 L x 7 W x 5.7 H ft
  - 7300 lb
- Trailer Mounted with 30Kw generator
  - 19 L x 8 W x 8 H ft
  - 16,975 lb
- Three - 3K onion tanks packed w/ROWPU
- GAC, IX and chlorination post treatment for NBC removal
- Chlorination to 2 ppm

- Feed flow – 30 gpm
- Multi-media filtration
  6-7 gal/min/sq. ft
- 5um cartridge filtration
  8 ea - 2.5 inch dia x 40 inch long filters
  String wound, polypropylene
- Reverse osmosis
  8 ea – 6 inch dia. X 40 inch long polyamide RO elements
  Avg salt rejection – 99.4%
  All elements in series
  50% recovery on freshwater and 33% on seawater

TECHNOLOGY DRIVEN. WARFIGHTER FOCUSED.

Unclassified/FOUO

Lithium Battery Specifications (Beckett Energy Systems 2017)

24Vdc Lithium Ion Battery

- Product Overview
- Specifications
- Literature

TECHNICAL SPECIFICATION	VALUE
Nominal Voltage	24Vdc
Maximum Energy Storage Capacity (100% DOD)	1.1kWh / 42.4Ah
Available Energy Storage Capacity (88% DOD)	950Wh / 37.3Ah
Gravimetric Energy Density – finished module	135Wh/kg
Volumetric Energy Density – finished module	153Wh/l
Voltage Range	21.0 – 28.7Vdc
Continuous Discharge Current	25.0Adc recommended 50.0Adc maximum
Maximum Continuous Charge Current	21.2Adc
Fuse Protection	100A internal
Cell Balancing	Passive resistive – automatic
Dimensions(W X D X H)	8.25 X 23.65 X 2.19 in 210 X 600 X 56 mm

Weight	17.5 lb 8.0 kg
Cycle Life (25 C and 80% DOD)	>3,650 (0.5C Charge and 0.5C Discharge Recommended)
Operating Temperature	-20 to +60 degrees C charge -40 to +60 degrees C discharge
Storage Temperature	-40 to +60 degrees C
Storage Life @25 degrees C	18 months from 50%SOC to 25%SOC
Communication Ports	CAN 2.0b to BMS
Communication Message Sets	State of Charge (SOC) Condition Status and Alarms Sleep / Wake Up Commands Serial Identification
Compliance Standards	Cell: UL1642, UN38.3, IEC 62133 Module: UN38.3, CE marked
Shipping	UN 3480

On 21 November 2017, it was discovered that the manufacturer of the 18-kW SunDial system went out of business and thus no product information is available for this system.