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Optimized Off-Grid Energy Systems Using Climate-Based Energy Demand for Soft-Walled Facilities

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OPTIMIZED OFF-GRID ENERGY SYSTEMS USING CLIMATE-BASED ENERGY DEMAND FOR SOFT-WALLED FACILITIES

THESIS

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Abstract

Remote contingency military operations often require the use of temporary facilities powered by inefficient diesel generators that are expensive to operate and maintain. Site planners can reduce operating costs by augmenting generators with hybrid energy systems, but they must select the optimal design configuration based on the region's climate to meet the power demand at the lowest cost. To assist planners, this paper proposes two innovative, climate-optimized, hybrid energy system selection models. The first model is capable of selecting the facility insulation type, solar array size, and battery backup system to minimize the annual operating cost. The Hybrid Energy Renewable Delivery System (HERDS) model builds on this model by minimizing the entire system's net present cost, and accounts for the transportation costs of airlifting the system to an operational site. To demonstrate the first model's capability in various climates, model performance was evaluated for applications in southwest Asia and the Caribbean. An additional case study was performed on Clark Air Base, Philippines to highlight the HERDS model's capabilities. The capability of both models is expected to support planners of remote sites in their ongoing effort to minimize fuel requirements, lower annual operating costs and increase site resiliency.

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Jay F. Pearson

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OPTIMIZED OFF-GRID ENERGY SYSTEMS USING CLIMATE-BASED ENERGY DEMAND FOR SOFT WALLED FACILITES

I. Introduction

Background

General Robert H. Barrow, USMC, noted in 1980 that “Amateurs talk about tactics, but professionals study logistics.” This phrase is as relevant in today’s military as it was back then. Logistic success has been a dominant component of any military campaign throughout history, and coupled with the need to project military power leads to a complex and expensive logistic network [1]. For the United States (US) Department of Defense (DoD), this means being able to support and sustain a multitude of forward operating bases (FOB) that have become characteristic of U.S. contingency operations.

In 2010, there were nearly 400 FOBs in Afghanistan and almost 300 in Iraq; these numerous remote sites required frequent resupply for fuel and water. For instance, a 600 personnel FOB required 22 trucks per day to both bring in supplies and to discard wastewater and refuse [2]. The supply lines supporting all the different FOBs represent a significant operational vulnerability and have been the source of many casualties during the conflict. In 2007 alone, there were 170 US Army casualties in Iraq and Afghanistan associated with convoys [3]. As a result of the massive amount of logistics needed to support these FOBs, efforts to create more sustainable options have been pushed for, particularly methods to reduce fuel consumption in an operational location.

In a contingency environment, a steady supply of fuel ensures the projection of military power. It allows convoys to run, air operations to be carried out, and generators to produce a constant supply of fossil-fueled energy across the area of responsibility. This energy is the lifeblood of the mission, and without it, the modern-day Air Force would grind to a halt. To ensure this does not occur, the Air Force must look to alternative sources of energy to support its warfighting network of FOBs. By diversifying its energy generation assets and looking into ways to more efficiently utilize available fuel, bases can reduce the cost of resupply missions, in both the dollars and lives, needed to sustain a base.

Problem Statement

The 2017 US Air Force Energy Plan is a document born out of necessity. As the DoD's largest energy user, 48% overall, the service must be deliberate and scrutinize the way it consumes energy [4]. The report defines three goals for its energy future (1) improve resiliency, (2) optimize demand, and (3) assure supply.

At both enduring locations within the United States and contingency locations worldwide, all three goals may be attainable with hybrid energy systems (HES). Hybrid energy systems can be defined as any system that combines different energy generation technologies to create a more diversified and robust power infrastructure. These systems typically consist of photovoltaic panels, an energy storage system, and either a generator or a connection to a primary power source such as a local electric grid [5].

The goal of improving resiliency includes identifying vulnerabilities to energy supplies, mitigating impacts for disruptions, and advancing physical infrastructure to protect critical mission systems [4]. In a contingency setting, this goal translates to improving the independent energy capabilities of our forward-deployed locations and reducing the resupply requirements needed for the base to ensure mission success. Supplementing generator-produced power with renewable energy and battery backup systems, creates a more robust energy generation system and vastly improves the base's resiliency.

HESs also contribute to the goal of optimizing the demand from bases by increasing the rate of energy produced per gallon of fuel consumed. Traditionally, generators in contingency environments have been oversized due to using factors of safety and standard base planning factors [6] [7]. The energy storage capability of these systems allows for generators, when run, to operate closer to their optimal capacity, thus increasing the energy efficiency of the fuel used, by not wasting any of excess energy being produced by the generator. Technologies like the PowerShade system also help to optimize the electrical demand in deployed locations by providing extra sun protection to temporary facilities and utilizing PV cells to level out the tents demand during the peak heat of the day [8].

An assured supply of energy is also guaranteed by a functioning HES. This goal refers to integrating alternative sources of energy and diversifying drop-in energy components. HESs are the clear answer to accomplishing this goal. By combining energy sources such as solar photovoltaics, wind turbines, energy storage, and other site-specific resources, they allow for energy to be produced in almost all circumstances and locations.

To meet Air Force and broad Department of Defense goals of reducing fuel consumption and increasing energy efficiency, several departments have been tasked with exploring and testing new technologies. The US Army Corps of Engineers, Engineer Research and Development Center (ERDC), has analyzed different methods to mitigate energy consumption. ERDC has analyzed the energy and heat flow patterns of different temporary structures and further explored the effects of integrating different insulating materials into the structures [9] [10]. Additionally, the Air Force Research Laboratory and U.S. Army Natick Soldier Research, Development and Engineering Center have both evaluated integrating solar panels to offset the demand of generators powering soft-walled shelters [11] [12].

Model creation has also been a prevalent research topic to demonstrate the potential benefits of integrating HESs into existing power infrastructure. These models have evaluated different technologies, ranging from coupling a battery system to a diesel generator, to a simulation relating the cost and benefits of adding a photovoltaic array and battery backup system to a 1,100 person base [13] [14]. Several civilian applications of HESs have also been simulated to quantify economic returns and in terms of cost and fuel savings [5] [15] [16]. This thesis seeks to build on the previous research in order to inform base planners and demonstrate the advantages of utilizing HESs to augment power production in a contingency environment.

Research Objectives

The overall research theme for this thesis is to demonstrate expeditionary energy assurance using hybrid energy systems. This theme can be broken down into several objective statements:

1. Analyze the characteristics and predict the power loads of temporary fabric shelters.

2. Optimize the HES size and component types using location-specific climate data.

3. Demonstrate cost and mission benefits from the implementation of HESs in forward-deployed locations.

Thesis Organization

This thesis follows a scholarly article format in which chapters 3 and 4 will be stand-alone articles intended for academic publications. In Chapter 2, the topics covered within this thesis will be discussed at length. This will include a description of fuel's role in contingency operations, previous research and demonstrations detailing the DoD's efforts to mitigate the energy consumption at isolated bases, optimization models used to size HESs, and how those models have been applied to soft-walled shelters.

Chapter 3, "Meeting temporary facility energy demand with climate-optimized off-grid energy systems," presents an in-depth analysis of a single temporary facility and the energy demands of the attached environmental control unit. The paper proposes an innovative, climate-optimized, hybrid energy system selection model capable of selecting the facility insulation type, solar array size, and battery backup system to minimize the annual operating cost. The paper evaluates model performance using case studies in two distinct climates, Southwest Asia, and the Caribbean, in order to demonstrate to site planners the cost benefits of minimizing fuel supply requirements. This journal paper was submitted for publication in the Institute of Electrical and Electronics Engineers' Power and Energy Journal.

Chapter 4, "Cost analysis of optimized islanded energy systems in a dispersed air base conflict," builds on the work of Chapter 3 by presenting the Hybrid Energy Renewable Delivery System (HERDS) model, which integrates the climate-based energy demand function to predict the energy demands of a base, optimizes an HES system for its overall net present cost using HOMER software, and analyzes the transportation cost associated with airlifting the selected HES. A case study was performed using Clark Air Base, Philippines, as the target site to demonstrate the model's unique capabilities and potential use for future military operations in the area. This journal paper is intended for submission to the Annals of Operational Research. Finally, Chapter 5 details concluding thoughts and suggested follow-on research.

II. Literature Review

Chapter Overview

This chapter will cover the overarching themes of the thesis and describe the previous research related to those topics. The first section describes the integral role of fuel and part it plays in contingency operations. The next section will cover technology and equipment that have been developed to save energy and fuel. The results and findings of military-sponsored demonstrations showcasing this kind of equipment will also be discussed. The next section will discuss the simulations of hybrid energy systems (HES) for both military and civilian applications and then specifically focus on the research into the modeling of soft-walled shelters.

Previous Research

The Department of Defense (DoD) invests $1.6B per year in energy research, development, testing, and evaluation in order to assure a steady supply of mission-essential energy for its future [17]. This substantial investment reflects the great importance of energy to the DoD and how it relates to every service's mission. Energy is a combat enabler, and without it, operational missions cannot continue. This reality of war has been demonstrated most recently in Operation Iraqi Freedom when a tank-led march to Baghdad was stopped to allow fuel trucks time to convene with the advancing forces.

The Role of Fuel

Until the wars in Afghanistan and Iraq, the DoD only considered fuel logistics as a periphery priority in a war campaign. War games and strategies demonstrated that incorporating fuel logistics was of little importance. Leaders assumed that the supply of fuel was free and invulnerable to disruption [3]. If fuel was modeled in war games, it was assumed to be purchased in bulk and at the standard rate of $0.95 per liter ($3.60 per gallon) from the Defense Logistics Agency (DLA) [18].

This standard cost did not account for the logistical tail of fuel delivery in a war zone. For the fuel to reach its destination, in many cases, a remote forward operating base (FOB), it would have to be transported by truck in an armored convoy. These convoys made for attractive targets to adversaries and consistently faced IED attacks and ambushes. In fiscal year 2007, casualties associated with convoy activities amounted to 12% of the total US losses in Iraq and 35% in Afghanistan [3]. To account for the resources and effort being put forth to protect these fuel supply routes, in 2007, the DoD started to use a fully burdened cost of fuel (FBCF) model. This model incorporates all of the costs associated with delivering the fuel to the base including the additional transportation and security measures. This cost ranged from $2 – 12 per liter ($9-45 per gallon) [18] [19]. Using the FBCF model, the daily cost of fuel required to sustain operations increases quickly. At the height of the Afghanistan and Iraq War, fuel consumption was estimated to be 46 liters per soldier per day. At a typical 300 person FOB, this number equates to annual fuel consumption levels of five million liters and costs of nearly $20 million per year.

Expeditionary Technology

With such a considerable expense dedicated to delivering fuel and sustaining combat operations, it was no surprise that the DoD started to implement research programs to investigate different technologies that would reduce the amount of energy used in expeditionary operations. These investigations evaluated equipment ranging from different tent structures to energy-efficient lights to use within a shelter.

In order to reduce the amount of fuel used at a FOB, researchers first had to identify the pieces of equipment had the highest demand for energy. The US Marine Corps conducted a study to meter tents, ECUs, communications equipment and other additional loads from a FOB in Afghanistan. They found that a large portion of the electrical demand was coming from heating and cooling the soft-walled facilities [7]. This finding was consistent with other reports stating that environmental control units (ECUs) account for as much as 75% to 80% of the electric load at a FOB [20]. Another iteration of the ECU was developed to reduce its energy consumption. The Improved Environmental Control Unit (IECU) was able to provide increased heating and cooling capacities and has a soft start feature that dramatically reduces the inrush current, allowing it to be operated with a smaller generator and use less energy overall [8]. Economic simulations identified an annual theater-wide cost savings potential of $2.4 – $6.7 million achievable by increasing the ECU's electrical efficiency by 10 – 30% [21].

As the essential building block of a contingency base, tent structures were evaluated from different manufactures by the US Army Corps of Engineers, Engineering Research and Development Center (ERDC). They compared several different temporary facility types throughout the two studies and quantified how well they resisted heat flow in different conditions [9] [22]. Figure 1 pictures two of the shelters that were analyzed in the study. By measuring the heat flow passing through the surface's of the shelter, researchers were able to measure how well the tent retains heat in the winter and how well the tents resist incoming heat flow in the summer. Researchers were able to determine how much energy each tent design could potentially save in different environments.

Figure 1. Utilis shelter (left) and HDT AirBeam shelter (right) [9].

A structure's level of thermal insulation also plays a significant role in determining potential energy savings from the ECU. ERDC has thoroughly investigated different types of insulation for both soft-walled shelters as well as enhanced temporary shelters, also known as B-huts [22] [10]. In arid climates such as Ali Al Salem, Kuwait, using a combination of radiant and Thinsulate insulation created ECU power savings up to 13%, while in colder climates like Fort Devens, Massachusetts, a Thinsulate liner rendered energy savings up to 27%. Aerogel and fiberglass matting were analyzed for use within contingency shelters with mixed success. Fiberglass liners are cheaper to manufacture but have a lower thermal resistive rate per inch of the material than other liners. Aerogel, in contrast, has a much higher thermal resistance rating but is much more expensive to manufacture [10] [23]. As an alternative to internal insulation layers, some enduring locations used spray-on polyurethane foam applied to temporary facilities. While this practice did reduce the energy intensity of the tent structures, it also presented an extreme fire hazard to individuals inside the shelter. In October of 2009, a safety notice was issued to all deployed commanders that mitigated the use of spray-on insulation [24].

As a potential energy savings measure, tent lighting was investigated. The baseline lighting systems for tents are normally fluorescent tubes hung along the interior beams of the structure. Alternative solutions are shown in Figure 2 and included light-emitting diodes (LED) and Electroluminescence panels. LED lights performed better overall and were preferred by the soldiers at the testing site, but did not exhibit a dramatic reduction in energy savings, so the study concluded that a shift away from fluorescent tubes was not yet justified [23]. Recently, more efficient LED models have emerged, demonstrating up to a 45% reduction in power consumption [24]. These new models have been tested and installed at multiple bases in Southwest Asia.

Figure 2. Various light sources for tents. LED (top), fluorescent tubes (left), Electroluminescence (right) [23].

Ultimately, the path to reduce the fossil fuel dependence of contingency sites is through the use of alternative energy generation. One report cited nuclear energy as the solution for all future expeditionary base energy needs [1]. The use of small modular reactors (SMR) is a promising technology because of their energy density and a semi-annual resupply requirement. The Army is currently considering this emerging technology and is advocating for rapid prototyping and fielding in order to take advantage of this potentially disruptive energy source [25]. Meanwhile, renewable energy generation has matured to a point where the DoD can begin implementing solar panels, wind turbines, and other green sources of energy. The readiness to adapt these technologies is made evident by the numerous demonstrations hosted by the military to integrate these systems into their expeditionary camps.

Contingency Demonstrations

Demonstrations hosted by U.S. Army Natick Soldier Research, Development, and Engineering Center all included a large number of technologies that could save energy at contingency sites. The first large-scale demonstration was at the National Training Center at Fort Irwin, California, starting in FY 2008 [24]. The demonstration, named Net Zero Plus, involved different shelters and technologies from the Army, Marines, and Air Force and operated until March 2011. Figure 3 shows the multitude of different technologies that were studied to find the most significant reductions in energy demand. Some of the key findings showed that shading systems in the summer months reduced power consumption by up to 30% and that the insulation provided an ECU power reduction of up to 30% during winter months [14]. When combined, flexible photovoltaics and shading systems demonstrated a reduced the peak demand of 35% [26].

Figure 3. Net Zero Plus demonstration site [14].

Natick hosted another demonstration at Fort Devens, Massachusetts, investigating technologies that could be implemented at smaller FOBs hosting approximately 50 personnel [12]. Among the exhibited equipment there was a self-contained microgrid and a system that allowed for tactical vehicles to supply power to the camp grid. The Renewable Energy for Distributed Under-supplied Command Environments (REDUCE), pictured in Figure 4, initially provided power for the on-site operations center but failed after nine days. The stress from switching between generator power and solar power caused the power coupling to break. This incident highlighted some of the challenges associated with microgrid controls with multiple power sources. The Onboard Vehicle Power/Tactical Vehicle-to-Grid Module (OBVP/TV2GM) was able to provide a fuel consumption savings of 47.4% by coupling with a 30 kW tactical quiet generator (TQG) and demonstrated the ability of a tactical vehicle to be integrated into the grid if needed.

Figure 4. REDUCE trailer (left) OBVP/TV2GM (right)

Fort Leonard Wood hosted an additional demonstration of a 1000-person camp. Some of the notable technologies included a PowerShade system that has photovoltaic (PV) cells built-in to both diminish radiative heat loads to a tent and provide power, and a microgrid control software, and a hybrid power trailer that combines an 80 kWh li-ion battery with a 15 kW TQG. All of these technologies were succesfully integrated into the camp's grid and reduced the amount of fuel needed to operate [8].

HES Simulations

As an alternative to hosting live demonstrations or building a physical microgrid, there has been a considerable amount of research dedicated to the optimization of HESs. This simulation approach to HES design applies to both military and civilian research streams, both motivated by lowering the cost of available energy.

The military postgraduate schools, the Air Force Institute of Technology and the Naval Postgraduate School (NPS), have conducted the majority of the simulation work for the military. One such study from NPS evaluated integrating a PV-battery system with different sized generators to provide fuel savings to a 150 person camp. The model was able to generate a 12% fuel savings annually [27]. Another study focused on using simulated wind forecasts to predict the performance of a wind turbine and diesel generator microgrid [28]. Other military studies have focused on cost savings through optimal sizing of HESs. These studies compare economic benefits of renewable energy systems against the FBCF included in operating a generator [29] [13] [30]. Another study performed a similar comparison, but instead of considering economic factors, the reduction in casualties from resupply convoys was considered [31]. A Marine Corps study took a different approach to optimization by modifying the HOMER software to account for existing energy systems in the service's inventory and allow base planers to better account for their expected energy use [32].

On the civilian side of HES optimizations, many different approaches exist. Multiple studies explore integrating a HES within rural and isolated communities to replace fossil fuel systems [33] [5] [15]. Other studies use residential or urban center locations to optimize renewable systems [34] [35]. Predominantly, these systems combine PV and diesel generators, with wind turbine inclusion being dependent on location. Other case studies use a host of other optimization techniques. Most commonly, studies used the Hybrid Optimization Model for Multiple Energy Resources (HOMER) software to perform HES optimizations [33] [34] [36]. Other techniques included using Genetic Algorithms, the Strength Pareto Evolutionary Algorithm, and other techniques developed by using high-level programming languages such as MATLAB-Simulink [15] [35]. These studies all focused on permanent facilities with consistent and routine daily electric loading. When simulating the load profile of soft-walled shelters, additional considerations must be accounted for.

Soft-Wall Shelter Modeling

The electric load of a tent is highly dependent on both human factors and the environment around it. The load dedicated to internal heating and cooling makes up a large portion of the electric load. Therefore, measuring the heat flow through the different surfaces of the tent provides a good indication of how much thermal energy needs to be exchanged by the attached ECU. Attempting to model the thermal properties of a tent is not a new venture. In 1979, Natick developed mathematical models to predict the heat loss from a tent structure [37]. Modern-day modeling has since progressed to allow for computer-based models to better predict the heat flow in and out of the exterior walls, roof, and floor of the tent [9]. The computer-based models utilize a combination of the real-world observed data, such as Figure 5 and Figure 6, and adjust established equations to model the thermal interactions accurately.

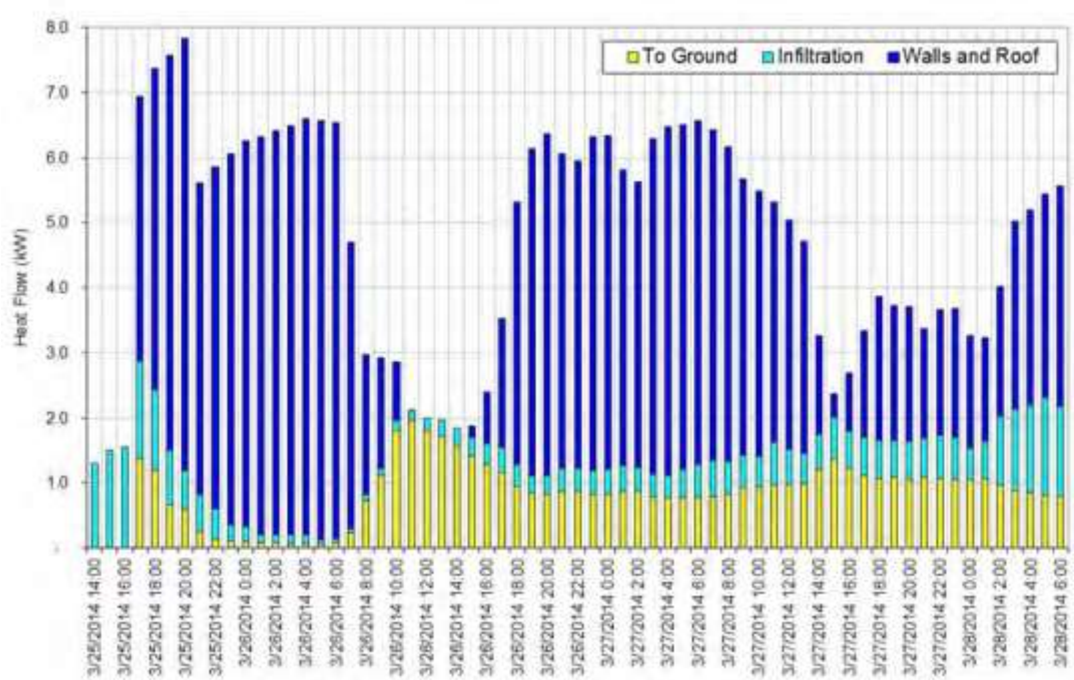

Figure 5. AirBeam tent winter heat flows by surface and type [9].

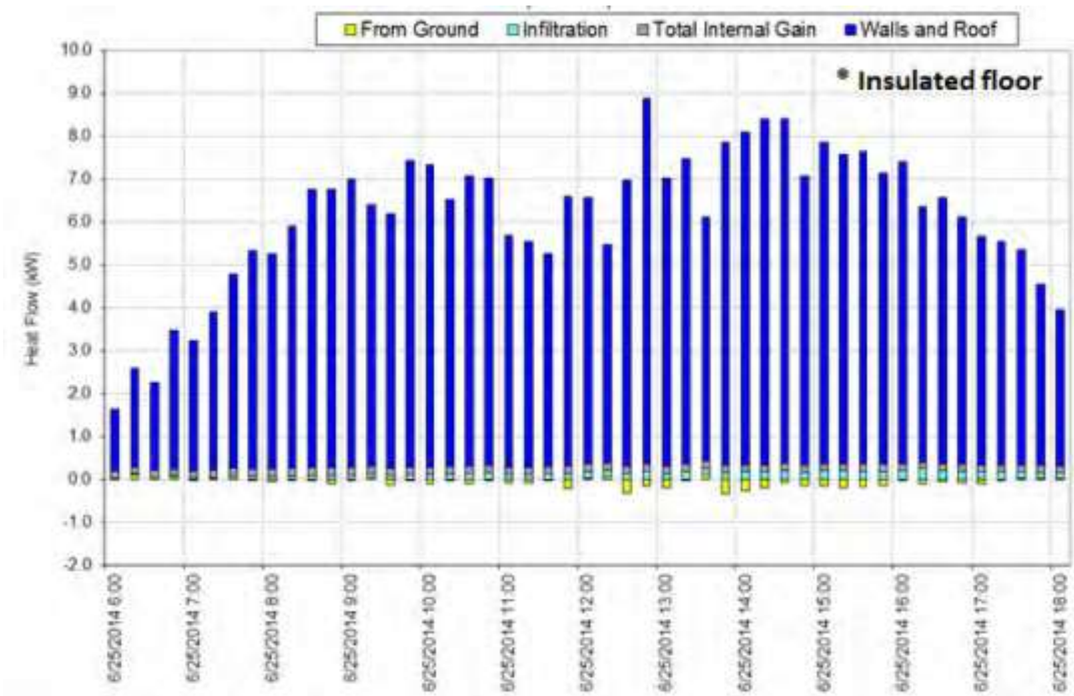

Figure 6. AirBeam tent summer heat flows by surface and type [9].

From Figure 5 andFigure 6, it is clear that the exposed walls and roof of the tent are the controlling element for heat flow. Similar patterns were observed from the Net Zero Plus studies, between the ambient air temperature and the power required by the ECU to maintain the temperature within the tent [23] [38]. The metering data taken from a FOB in Afghanistan also provides additional insight into the human factors of the electric loads [7]. Studies using refugee tents as a basis for an electrical load also contribute to a better understanding of the load profile for soft-walled shelters [39] [40].

Summary

This chapter covered previous relevant research on hybrid energy systems from both the military and civilian perspectives. The integral role of fuel was discussed, as well as the technological advances that have been made to reduce energy consumption in the field. Previous military demonstration and their results were also investigated. Additionally, HES research done through simulation software was also considered, in particular when those simulations were modeling tents. The models presented in Chapters 3 and 4 build upon the findings and results of the research presented in this chapter.

III. Scholarly Article 1: Meeting Temporary Facility Energy Demand with Climate-Optimized Off-Grid Energy Systems

Jay Pearson, Torrey Wagner Ph.D., Justin Delorit Ph.D., P.E., and

Steven Schuldt Ph.D., P.E.

Abstract

Remote and contingency operations, including military and disaster-relief activities, often require the use of temporary facilities powered by inefficient diesel generators that are expensive to operate and maintain. Site planners can reduce operating costs by increasing shelter insulation and augmenting generators with photovoltaic-battery hybrid energy systems, but they must select the optimal design configuration based on the region's climate to meet the power demand at the lowest cost. To assist planners, this paper proposes an innovative, climate-optimized, hybrid energy system selection model capable of selecting the facility insulation type, solar array size, and battery backup system to minimize the annual operating cost. To demonstrate the model's capability in various climates, model performance was evaluated for applications in southwest Asia and the Caribbean. For a facility in Southwest Asia, the model reduced fuel consumption by 93% and saved $271 thousand compared to operating a diesel generator. The simulated facility in the Caribbean resulted in more significant savings, decreasing fuel consumption by 92% and saving $291 thousand. This capability is expected to support planners of remote sites in their ongoing effort to minimize fuel supply requirements and annual operating costs of temporary facilities.

Introduction

For military or disaster relief operations, the creation of isolated bases in remote locations are often required. These bases typically have little to no access to an established power grid and are required to generate energy for any of the base's power requirements [41]. In order to provide sustained power for the base, fuel resupply convoys are required to make frequent trips from a fuel depot to the remote location. The fuel from these convoys is then used to run multiple generator units spread throughout the base. During the Iraq and Afghan Wars, the U.S. military sustained its remote sites with daily deliveries of more than seven and a half million liters of fuel. This method of power production is extremely resource-intensive; costs not only include the purchase price of the fuel but also in transportation, and security factors. This leads to a Fully Burdened Cost of Fuel (FBCF) that ranges from three to nearly 12 dollars per liter [3]. This leads to a significant cost when considering that diesel generators are typically run 24 hours per day, every day of the year. Using a FBCF of $4/L, the annual operational cost of the baseline generator case was $357K.

To reduce the high annual operating cost of generators, base planners have begun to incorporate the use of Hybrid Energy Systems (HES). These systems combine different energy generation technologies resulting in a more robust energy generation system. Predominantly, these systems consist of photovoltaic (PV) panels, a battery backup system, and a diesel generator [5]. Both field testing and simulation-based modeling have been used to verify the effectiveness of these systems. Field testing has proven that these technologies can be integrated into both existing power grid-connected systems and island systems [11] [38] [12]. Models have also been developed to optimize the system performance or the cost of a HES [5] [15] [29] [23] [13].

This paper is structured as follows: Section II provides a background for integrating HES systems into isolated bases as well as a background of efforts to model these interactions. Section III defines the parameters used to create the energy requirement model, while Section IV details the results of shelter analysis to minimize system component and operations cost. Section V provides a summary of the study and concluding thoughts.

Literature Search

Providing fuel to geographically isolated bases is an essential element for the operation of the camp. This has become such an accepted notion that when military planners participated in wargames up until 2007, the United States Department of Defense assumed its fuel logistics were free and invulnerable [3]. Planners now include fuel logistics to include the FBCF when developing future camps. This inclusion has driven the requirement to develop technology to reduce the demand for fuel at remote bases. The response included various field tests that integrated existing products directly into shelter systems. One of the more comprehensive tests performed included evaluating different shelter insulations and thin-film PV technologies to directly offset the power demand of the shelter [11] [14]. Another demonstration explored the possibility of integrating a self-contained HES, consisting of PV panels, lead-acid batteries, and a diesel generator, into a camp with moderate success [12].

To further reduce the fuel consumed at a remote base, studies sought to improve the efficiency of the Environmental Control Unit (ECU) that is commonly used to maintain interior temperatures within shelters. One study reported that as much as 80% of the energy consumed at a remote base is due to heating and cooling loads [20]. By improving an ECU's energy efficiency by 10%, one study showed that the savings in fuel costs of a large base could be as high as $2.42 million per year [21].

In addition to live demonstrations, many studies have focused on optimizing output, cost, and size of HES systems. These models range from electrifying rural areas in Algeria [15] to sizing a HES system to provide power to an Indonesian island [5]. Additionally, models have also been applied to military bases in order to increase energy resilience and cost [29], as well as evaluating the economic payback of investing in energy-saving technologies, such as LED lighting, different shelter systems, and different insulation methods [9].

Despite the significant contributions of the aforementioned research studies and demonstrations, there is no reported research that focused on: (1) analyzing the performance of single shelters; (2) computing system energy requirements based on local weather data; (3) integrating the insulative value of a structure directly into the energy requirement; (4) accounting for the insulative material's impact on cost and performance; and (5) minimizing annual operating cost by computing the optimal tradeoff between PV array size, lithium-ion energy storage capacity, diesel generator use. Accordingly, this paper demonstrates a novel model that addresses the aforementioned limitations.

Method and Modeling

The present model analyzes an Alaska Small Shelter System because it is representative of the temporary facilities most frequently utilized in military and disaster-relief operations. The Alaska Small Shelter System consists of hollow aluminum segments held together by rack and pin, as shown in Figure 7. The system is placed directly on the ground with a fabric liner used as a floor. The exterior shell is made of a polyvinyl chloride-coated material 1.6mm thick [26]. All insulation for the system is placed on the interior and connected to the structural members of the shelter. The final dimensions of the tent are 9.91m x 6.10m x 3.05m (L x W x H), with an exterior fabric surface area of 124.04 m^2

Figure 7. The exterior and interior view of the modeled Alaska Small Shelter System [42].

With the intent of reducing the ECU energy requirement for a shelter system, a loading profile was chosen to simulate field conditions. The load profiles are directly related to the type of ECU used and the insulation properties of the liner used. For this model, the specifications from an HDT 60K Improved Environmental Control Unit (IECU) were used [43]. The effects of insulation are easily observed and are demonstrated in Figure

8. The uninsulated tent on the right has a higher exterior temperature, indicating an increased rate of heat loss from the shelter.

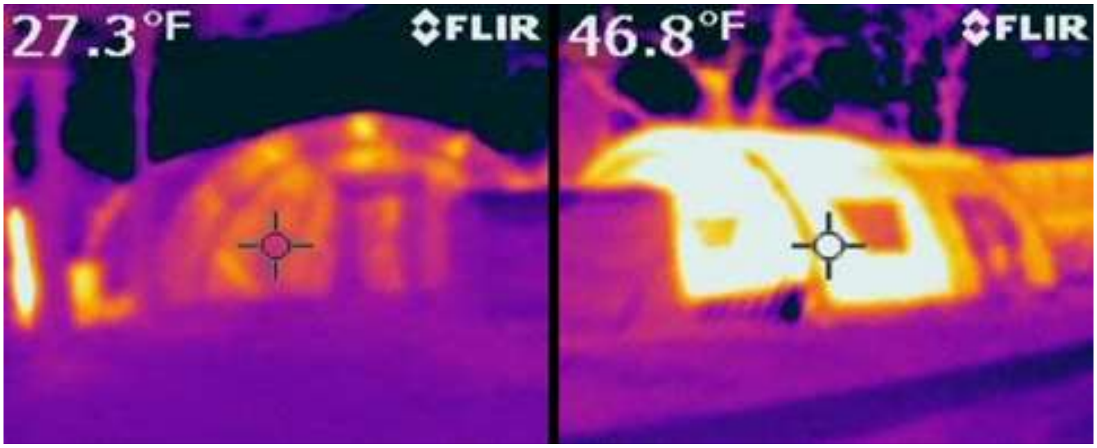

Figure 8. The thermal profile of an insulated tent (left) against an uninsulated tent (right) [23].

In order to directly compare the insulation properties of the different materials in this study, insulation is modeled as one-inch thick layer placed on the interior tent surface. Their corresponding insulation values are listed in Table 1. These values are used in conjunction with thermal resistivity values for exterior and interior air films as well as the shelter's exterior material.

Once the loading profiles have been determined, to include an estimated peak demand and average kWh usage, the HES can then be sized. The case study models the use of a single islanded microgrid serving all loads, as shown in Figure 9. Power is primarily generated through the photovoltaic solar array and is passed through an inverter to supply the alternating current primary load. Excess power generated from the solar array is stored in a lithium-ion battery. When the solar array is not able to meet the primary load, electricity is passed from the battery through the inverter to the load until fully discharged.

If the battery is fully discharged and the solar array is not producing sufficient power, the diesel generator turns on in order to supply the necessary load.

Table 1. Model Input Parameters

Component	Parameter
PV system loss (Power Factor)	20% [29]
PV system efficiency	15% [29]
PV capacity per m^2	106.6 W [29]
Li-ion Battery Allowable Depth of Discharge	80% [44]
30 kW Generator avg fuel consumption rate	10.2 L/hour [12]
ECU Peak Cooling Capacity	12.3 kW [43]
ECU Peak Heating Capacity	8.8 kW [43]
ECU Energy Efficiency Ratio $[W_{heat/cool}/W_{elec}]$	1.69 [43]
Tent Material R-value $[m^2\ °C/W]$	0.0084 [26]
Fiberglass liner R-value $[m^2\ °C/W]$	0.60 [10]
Thinsulate liner R-value $[m^2\ °C/W]$	0.83 [13]
Aerogel liner R-value $[m^2\ °C/W]$	1.62 [13]
Outside Air Film R-value $[m^2\ °C/W]$	0.030 [45]
Interior Air Gap R-value $[m^2\ °C/W]$	0.12 [45]

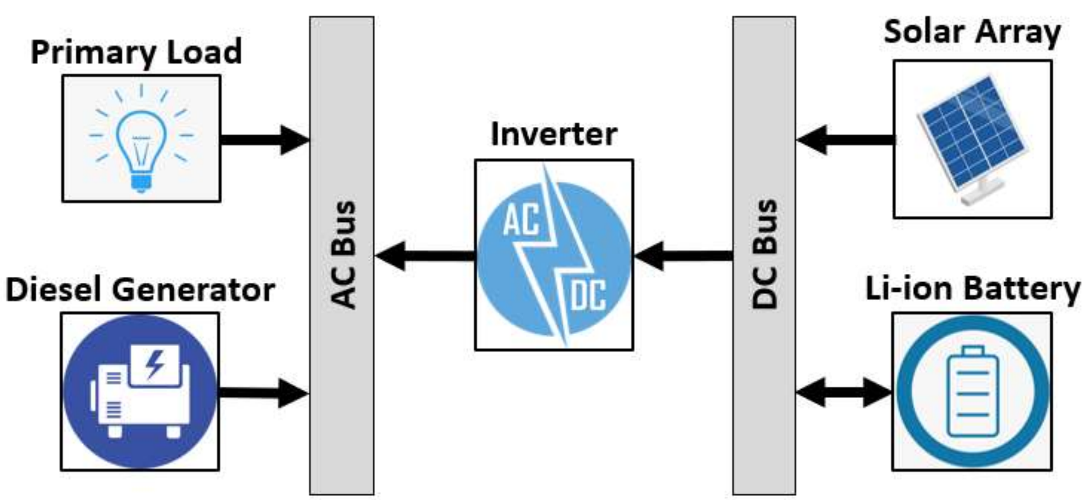

Figure 9. Systems block definition diagram model of the simulated microgrid.

The objective of the hybrid energy system optimization model is to minimize the annual operating cost of the system. The model calculates the optimal balance between the size of the solar array, the size of the battery, the type of insulation used, and the cost associated with purchasing these components. This cost is then compared to the system's annual savings in terms of fuel cost saved.

The solar potential that can be harnessed from the system was determined using NASA's global weather data [46] [47]. 2018 Weather data, in one-hour interval periods, was used from two locations, Kabul, Afghanistan, and San Juan, Puerto Rico. These two locations were chosen to demonstrate the model's applicability in determining HES for both military applications as well as disaster relief operations. These two locations have distinctly different climates and highlight the range of solutions generated from the model. Figure 10 and Figure 11 show the differences in the two climates in terms of their observed temperature and solar insolation levels.

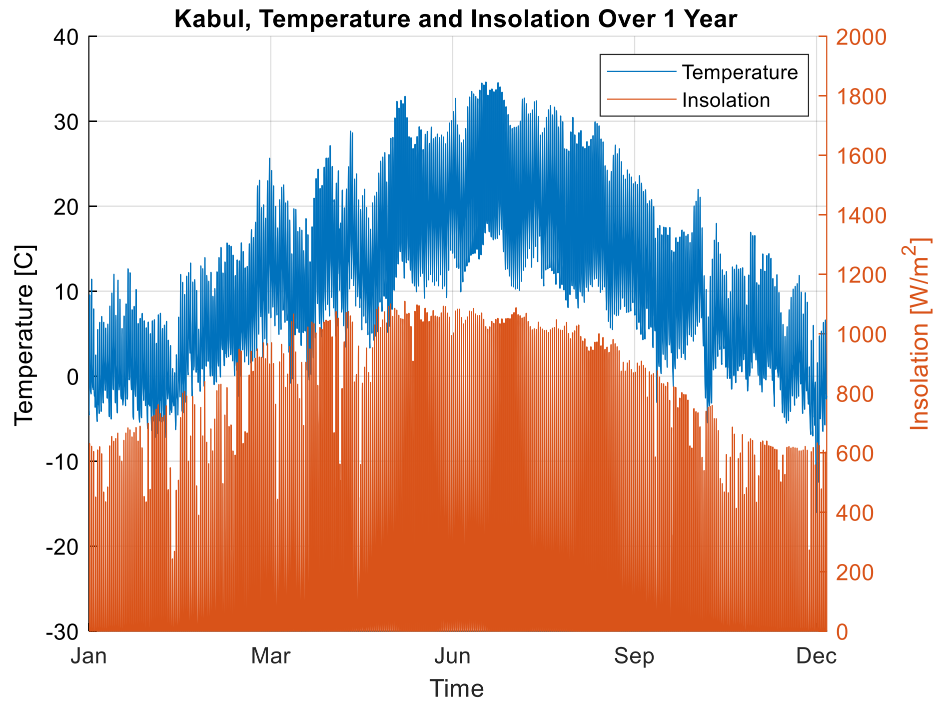

Figure 10. Temperature (blue) and insolation (red) data from Kabul, Afghanistan, over the course of 2018.

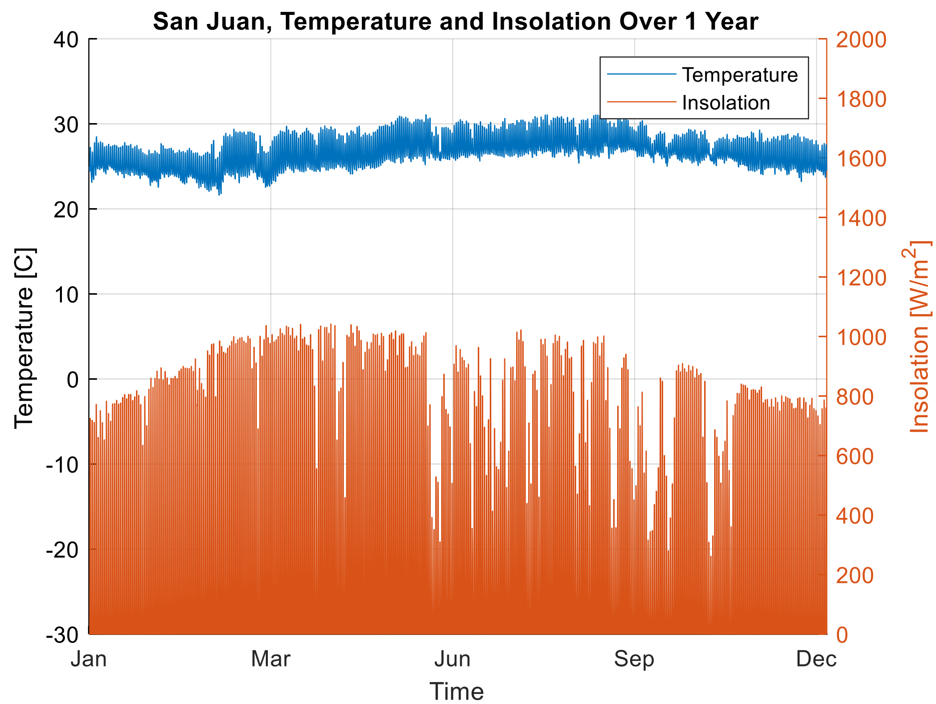

Figure 11. Temperature (blue) and insolation (red) data from San Juan, Puerto Rico, over the course of 2018.

Utilizing Kabul, Afghanistan, as a test case, a two-day period in late July is used to demonstrate the model's ability to predict the energy usage when there is an abundance of incoming solar radiation and large outside air temperature change. This time period demonstrates the model's behavior under peak ECU loads and provides a visual feasibility check in relation to different model variables.

The cost data utilized in the optimization model are displayed in Table 2. They account for the initial cost of a PV array, the battery storage system, the cost of insulation, and the fuel costs associated with running a backup generator. The insulation costs are based on the unit cost of the material plus a historical markup factor for producing a product that is compatible with the shelter system. The table also refers to the FBCF in dollars per gallon. This term refers to the commodity price plus the total life-cycle cost of all personnel, assets, and infrastructure required to move and protect fuel from the point of sale to the end-user [5].

Table 2. Cost Input Parameters

Component	Parameter
PV array price per area [per m^2]	\$245 [29]
Lithium-ion battery system [per kWh]	\$400 [29]
Fiberglass liners [per tent]	\$5,000 [10]
Thinsulate liners [per tent]	\$6,400 [10]
Aerogel liners [per tent]	\$64,000 [10]
Fully Burdened Cost of Fuel (FBCF)	\$4/L [29]

Analysis

The temperature and incoming solar radiation data from Kabul, Afghanistan, during the week of 23 July 2018, is plotted in Figure 12. It shows the large temperature swings experienced in the area, ranging from 11 to 39 degrees Celsius.

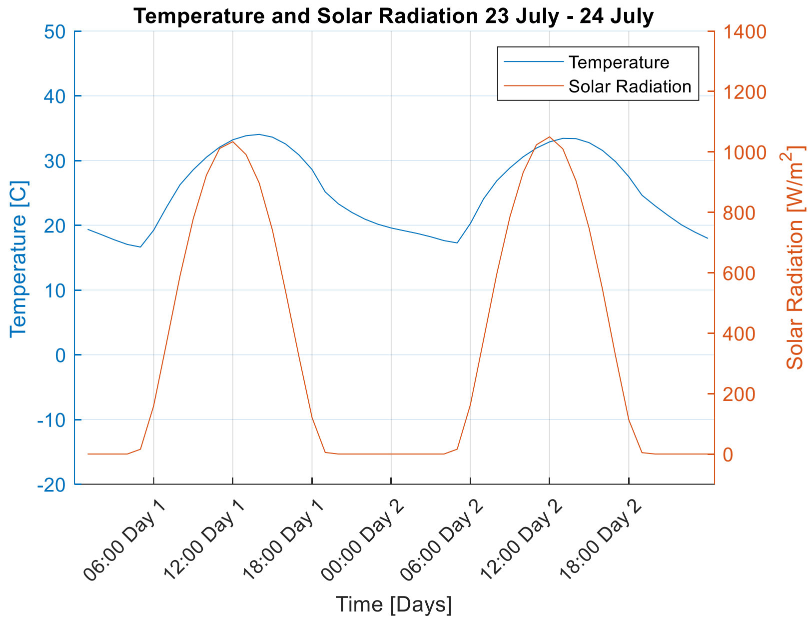

Figure 12. Temperature and incoming solar radiation profiles of Kabul, Afghanistan on 23 July 2018 – 26 July 2018 [46] [47].

From the data presented in the Net Zero Plus Joint Capability Technology Demonstration study and the specification sheet for the ECU, a piecewise linear relationship was generated empirically from comparing the outside air temperature to the power draw of the ECU at any given time [38] [43]. Using the outside temperature as an input for each iteration, an initial power draw for the ECU can be calculated using Equation (1). This equation is used when the unit is not operating at peak capacity (Equation 2) for either heating or cooling.

$$P_i\ [kW] = \frac{3 \times A_t \times |T_o - 21℃|}{\sum R_i \times \eta_{ECU} \times 1000} + 2\ kW \quad (1)$$

Equation 1. Initial ECU power draw equation. η_{ECU} represents the energy efficiency ratio of the ECU, $A_t\ [m^2]$ is the exposed surface area of the tent, T_o [℃] is the outside air temperature, R $[m^2 \cdot ℃/W]$ is the summation of thermal resistances by the air films, tent material and insulation [37] [10]. 2 kW is added as a base load requirement to run the ventilation fan. The 3 is a constant to account for additional heat transfer through convection, radiation, and air infiltration [11] [38].

$$P_{ECU}[kW] = \begin{cases} 8.8 & \textbf{if } T_o < 21℃ \textbf{ and } P_i > 8.8\ kW \\ P_i & \textbf{if } T_o < 21℃ \textbf{ and } P_i < 8.8\ kW \\ P_i & \textbf{if } T_o > 21℃ \textbf{ and } P_i < 12.3\ kW \\ 12.3 & \textbf{if } T_o > 21℃ \textbf{ and } P_i > 12.3\ kW \end{cases} \quad (2)$$

Equation 2. ECU heating and cooling capacity equation [43]**.**

A conduction heat transfer model was used to account for the thermal resistive effects of the different layers between the exterior and the interior environment of the shelter. The model sums the resistive elements between the ambient temperature (T_o) and the interior temperature (T_i) to account for the changes in the heat flow of the different materials, accounting for their thickness and thermal conductive properties. Figure 13 shows the different resistive layers that are accounted for within the model.

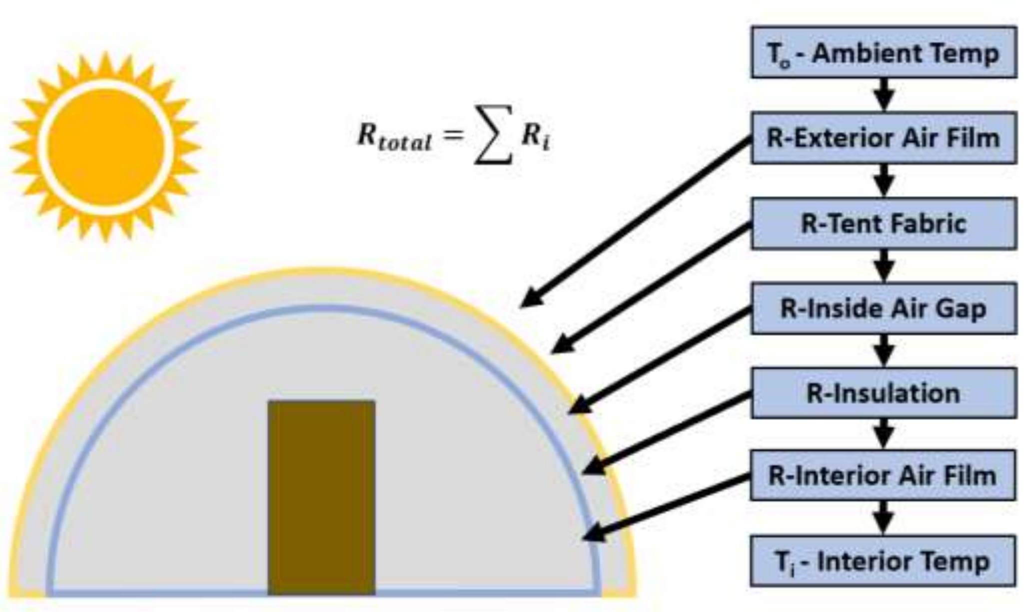

Figure 13. Thermal resistances affecting the heat flow from the shelter when $T_o > T_i$. When $T_o < T_i$ the heat flow (represented by the arrows) changes directions.

In Figure 14, Equation 2 is plotted for the values of insulation used in this analysis. It is apparent that the minimal amount of power is required when the outside temperature equals the inside temperature set point of 21℃. As the outside temperature increases or decreases away from this set point, the power required to maintain the indoor air temperature increases until it reaches the peak heating or cooling capacity of the ECU. As the figure demonstrates, the change in temperature rapidly brings an ECU connected to an uninsulated shelter to peak performance. Conversely, tents with insulative layers require a much larger temperature swing needed to bring their respective ECUs to peak heating/cooling. [38] [37].

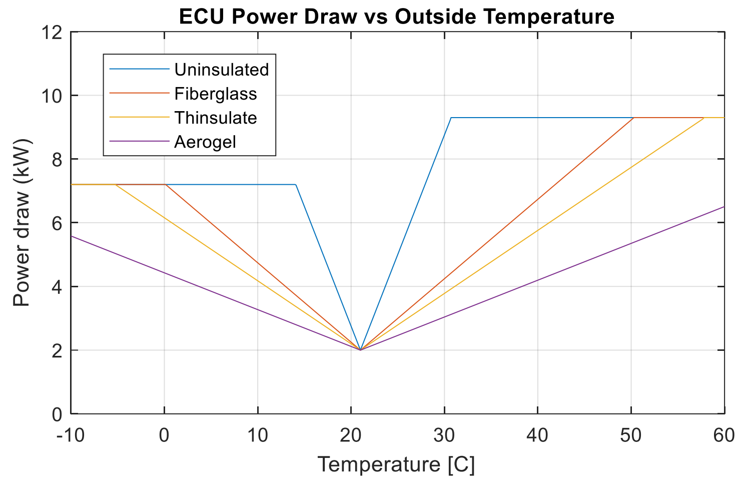

Figure 14. ECU power draw vs. outside air temperature for various levels of insulation based on an inside air set point of 21 ℃.

Figure 15 shows the resulting ECU power draw for two days of weather data when calculating the power draw from Equation 2. The figure shows there are two peak power draw times: one during the hottest time of day and the other during the coldest part of the night.

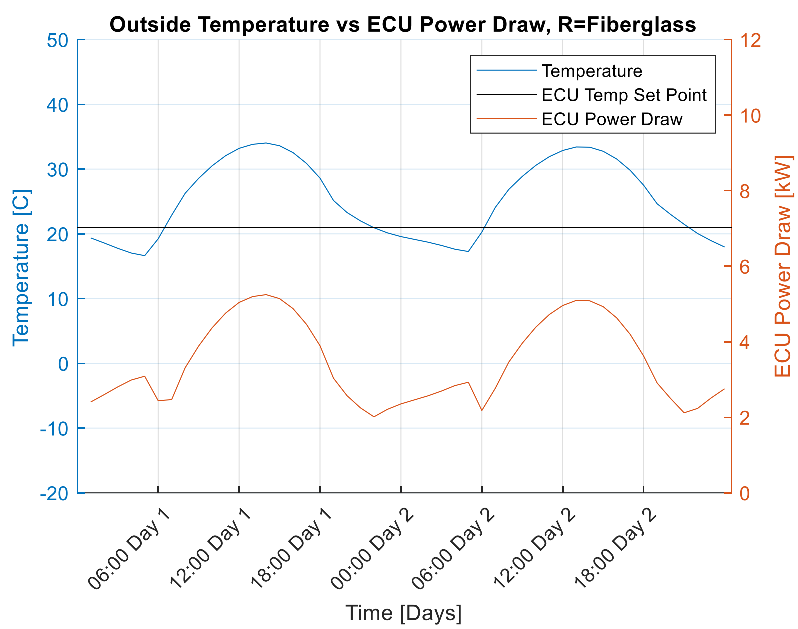

Figure 15. Outside air temperature (blue) and the resulting ECU power draw (red) based on an inside air set point of 21 ℃ (black).

After factoring in the incoming solar radiation and converting it to useable power, then subtracting the ECU load, a load profile is generated for the net power of the system as described in (3).

$$Net\ Power\ [kW] = \left\lfloor \frac{E_e \times A_a \times \eta_{PV} \times PF}{1000} \right\rfloor - P_{ECU} \qquad (2)$$

Equation 3. Net Power as a function of Insolation - E_e [W/m^2], Area of the Array - A_a [m^2], PV efficiency– η_{PV} [%], Power factor, representing the system electrical losses - PF [%] and the Power draw from the ECU - P_{ECU} [kW].

Net power quantifies the ability of the solar array to meet ECU demand, which is shown in Figure 16.

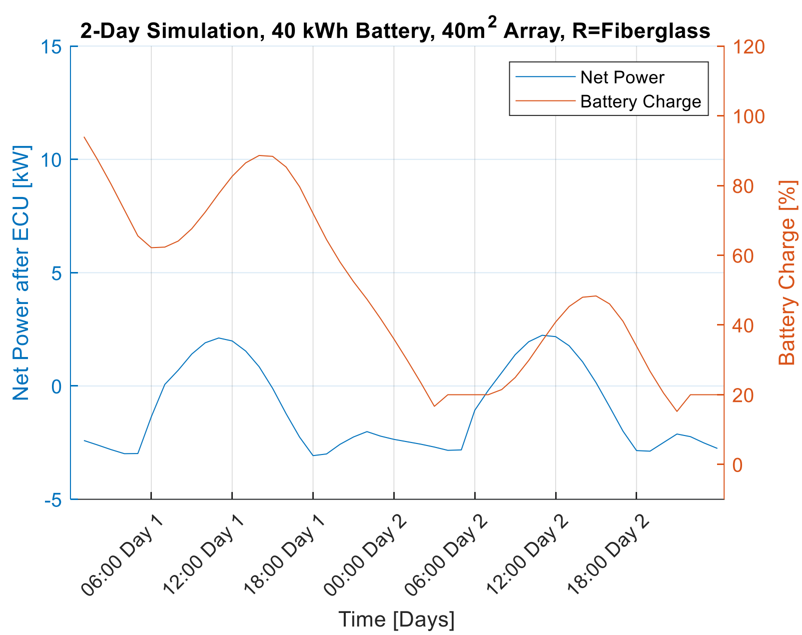

Figure 16. Resulting net power from a 40 m^2 solar array (blue) and the 40 kWh battery state of charge (red).

When the net power is negative, the system drains the attached battery. The theoretical battery used in this instance has a capacity of 40 kWh and starts with a full charge. When paired with a 40 m^2 solar array, the battery charge is quickly depleted, and by the end of the first night, it is discharged to the allowed 80% depth of discharge (DOD). The DOD limitation is used to protect the battery and increase its service life when compared to utilizing 100% DOD [44]. To contrast this example, Figure 17 shows the same input conditions, but with a 100 m^2 solar array to gather solar radiation.

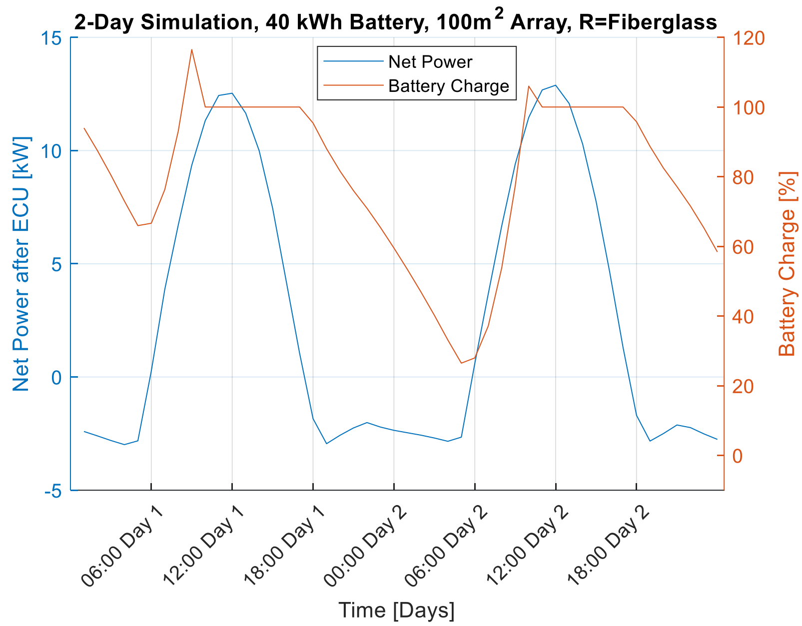

Figure 17. Resulting net power from a 100 m^2 solar array (blue) and the 40 kWh battery state of charge (red).

Figure 17 illustrates that the 100 m^2 solar array generates more energy than can be stored by the battery. This excess energy can be quantified and used as a factor to determine a more appropriate solar array size. Another factor to consider when sizing the array is minimizing the amount of time that the battery is fully discharged. These two considerations are plotted in Figure 18 for various insulation levels.

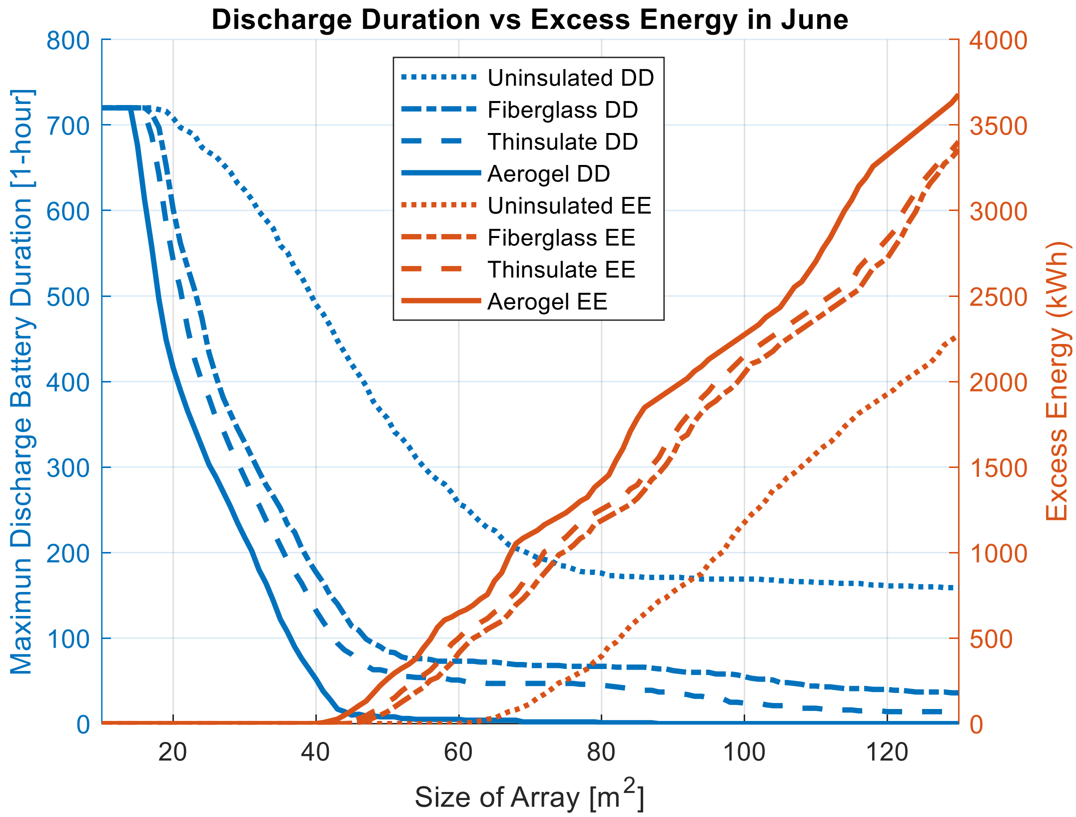

Figure 18. Excess energy produced and the duration that the 40 kWh battery is fully discharged plotted against an increasing solar array size. The uninsulated case is represented by the dotted line, fiberglass by the dot-dash line, Thinsulate by the dashed line, and aerogel by the solid line.

The figure indicates that for the baseline uninsulated case (dotted line), the lowest combined value of the discharged battery duration and excess energy is at an array size that is approximately 76 m^2. This array size minimizes both the time at which the battery is fully discharged and the time when there is excess energy generated. However, for the uninsulated condition, there is a sizable amount of time where the battery is discharged regardless of the solar array size. Insulation can correct this and provide a more temperature-stable environment for living and working, by minimizing heat transfer to the outside air.

After incorporating insulation, the lowest combined value indicates that the array size needed is decreased to approximately 55 m^2 for fiberglass insulation, referencing Figure 18. This level of insulation is cost-effective as a 21 m^2 reduction in the solar array saves $5,145 in component costs, with the fiberglass liner only costing $5,000. Similarly, the transition from a fiberglass liner to a Thinsulate liner is cost-effective, as the $1,225 savings from a 55 → 50 m^2 array nearly offsets the $1,400 liner price differential.

However, when the insulation level increases from Thinsulate to Aerogel, the $1,960 savings from the 50 → 42 m^2 solar array cannot offset the $57,600 increase in liner cost. Due to these factors, the Thinsulate liner was used for further analysis in order to determine the operating cost of the HES.

A two-dimensional sweep of configurations for the HES was performed. This included calculating the operating cost for the HES as governed by Equations (4) and (5). By calculating the cost of every combination of an array size between 1 m^2 and 100 m^2 coupled with a battery bank between 1 kWh and 100 kWh, the model is able to generate a heat map for the operating cost of the system over a time period. Figure 19 displays the cost map for the system when operating for one week.

$$HES\ Cost = f(A_a, kWh, R) \tag{3}$$

Equation 4. HES cost as a function of the area of the array - A_a [m^2], the size of the lithium-ion battery kWh [kWh], and the insulation R value used R [unitless].

$$Operating\ Cost = HES\ Cost + [t_{DB} \times FuelRate \times FBCF] \tag{4}$$

Equation 5. Operating cost. The function sums the HES cost with the cost of the fuel used by the generator, as determined by the time that the battery is discharged – t_{DB} [hours], the fuel consumption rate of the generator *FuelRate* [L/hr] and the Fully Burdened Cost of Fuel *FBCF* [$].

As shown in Equation (5), the model also includes a cost penalty for every hour that the battery is drained, and the ECU must be run on generator power. This penalty is calculated using the FBCF of $4 per liter.

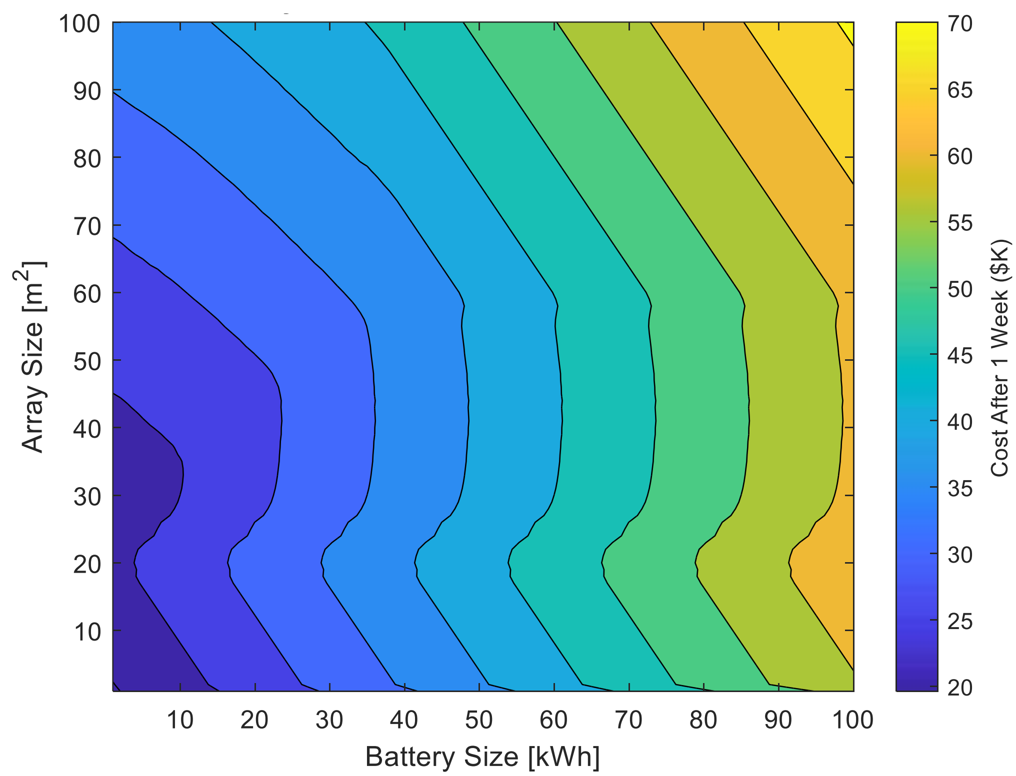

Figure 19. Overall component and operating cost varying both solar array and battery size for Thinsulate insulation, for one week of use.

Figure 19 demonstrates that after including the cost of running a generator to make up for the time that the battery is discharged, the overall cost relationship is mostly linear and is strictly based on the size of the array and battery. The figure illustrates the optimal system in terms of cost is at point (0,0), which means that a renewable system is not cost-effective in this scenario - the baseline generator should operate the ECU.

However, when the model is run using weather data for the entire year, the backup generator fuel savings offset the renewable energy component costs, resulting in an optimal point. Figure 20 displays the resulting optimal system design point.

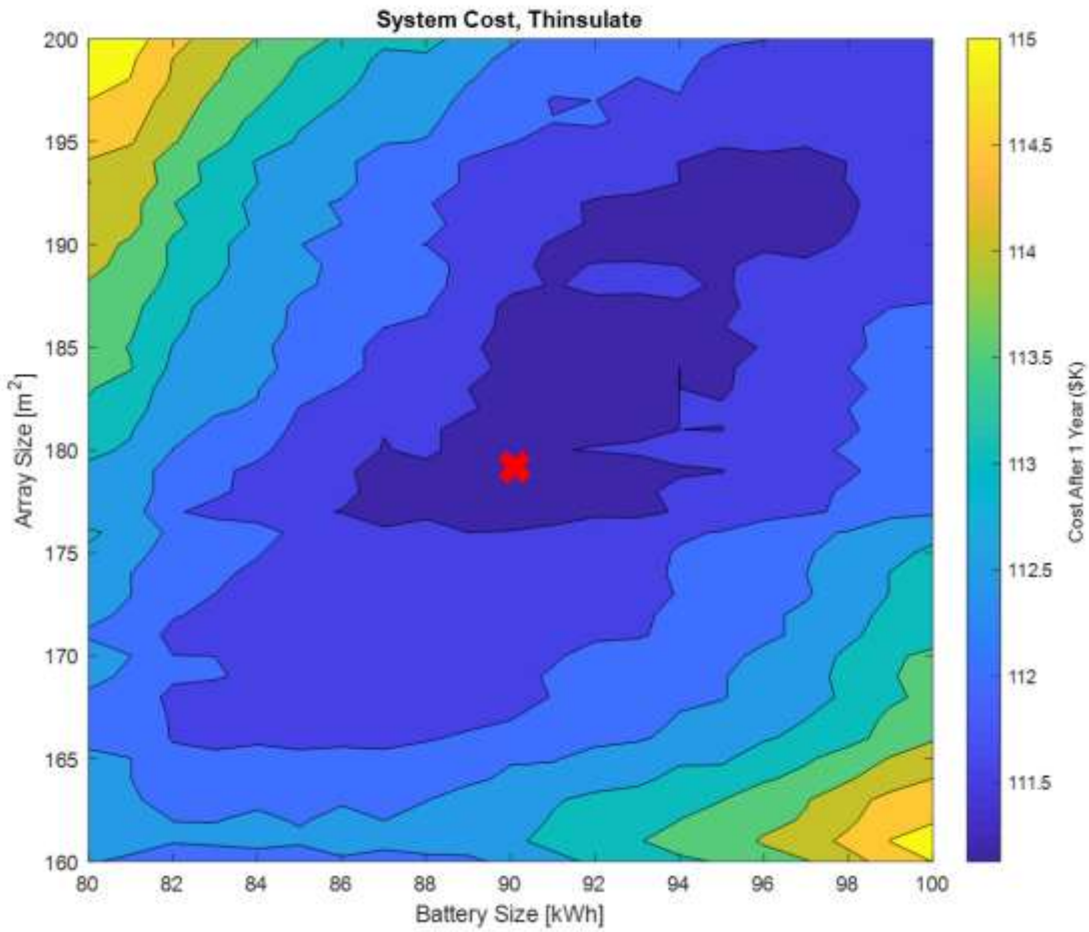

Figure 20. Overall component and operating cost varying both the solar array and battery size for Thinsulate insulation, for one year of use in Kabul Afghanistan.

For the one-year Thinsulate insulation scenario, the optimal system design includes a 179 m^2 array (29 kW) and a 90 kWh battery. A $111,200 total operating cost was calculated by the model, including components and fuel consumed by the generator over the course of the year.

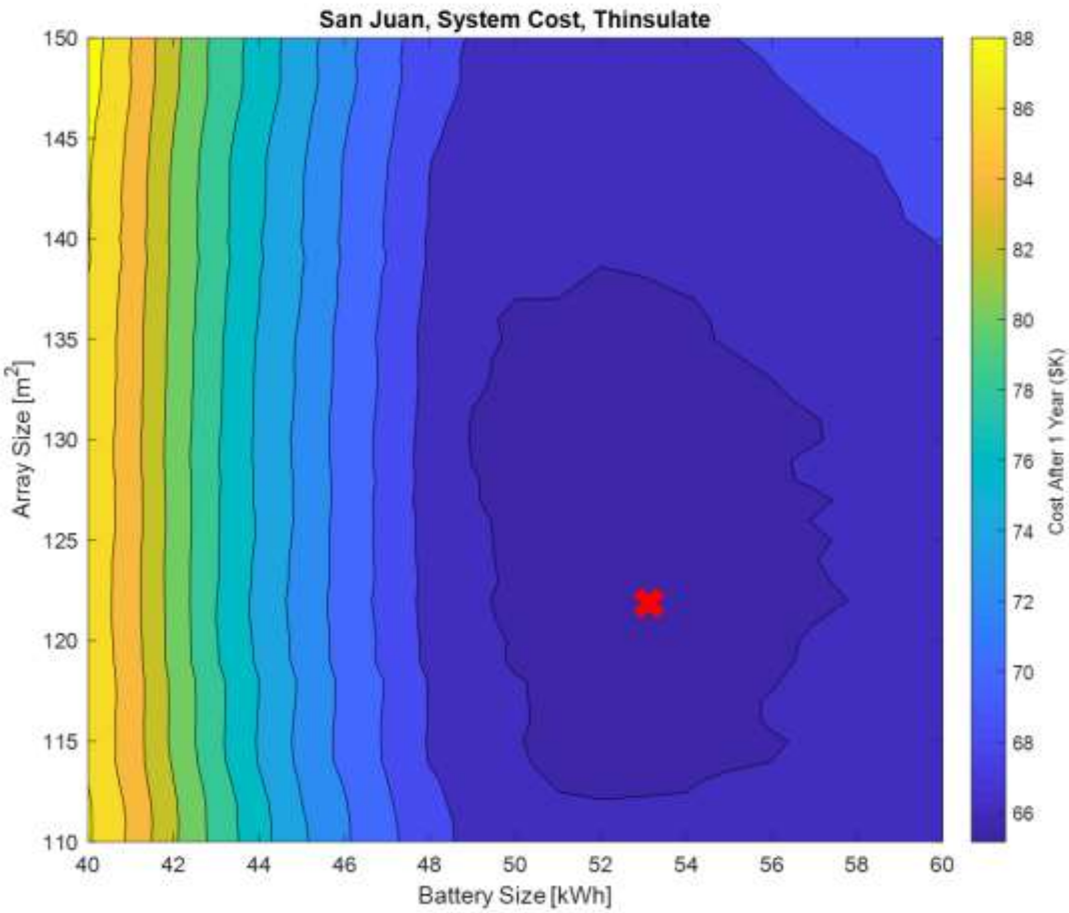

Figure 21. Overall component and operating cost varying both the solar array and battery size for Thinsulate insulation, for one year of use in San Juan Puerto Rico.

In order to contrast the result from Kabul, Afghanistan, the simulation was repeated using weather data from San Juan, Puerto Rico. This scenario still resulted in the optimal point using Thinsulate as insulation, and the optimal system design included a smaller 122 m^2 array (19.6 kW) connected to a 53 kWh battery as shown in Figure 21. A $65,160 total cost was calculated by the model, including components and fuel. The full analysis was run for other insulation values, with their optimal design costs listed in Table 3.

Table 3. Cost Analysis Results

Insulation Type	Kabul, Afghanistan 1-Year Cost [$K]	Kabul, Afghanistan Component Cost [$K]	San Juan, Puerto Rico 1-Year Cost [$K]	San Juan, Puerto Rico Component Cost [$K]
Uninsulated	127	113	109	89
Fiberglass	121	92	69	60
Thinsulate	111	86	65	58
Aerogel	145	133	115	109

For Kabul, Afghanistan, optimal solutions for each insulation type had an array size that ranged from 154 m^2 to 257 m^2 with battery capacity that ranged from 77 kWh to 126 kWh. The overall optimal energy system had component costs for the solar array and battery backup system of $86,197. Over the course of one year, the fuel cost associated with running the backup generator was $25,003, which is an average of fewer than 100 minutes of operation per day. The annual operating cost of the HES system is 31.1% of the $357K baseline generator-only case.

The simulated system for San Juan, Puerto Rico, yielded even more dramatic results. Optimal systems for all insulation types had array sizes that ranged from 108 m^2 to 197 m^2, with battery systems sized between 45 kWh and 101 kWh. The lowest annual cost had a component cost of $58,000 and used only $7.7K of fuel over one year (30 minutes of average usage a day). This system resulted in an annual operating cost of 18.3%, compared to the baseline, generator only system.

Optimal solutions from both locations resulted in dramatic savings in fuel costs, ranging from $332K - $349K per year. Additionally, consideration should be given to not only the cost benefit of the HES system but to the available land able to host these PV systems. With array sizes ranging between 108 m^2 to 257 m^2 to support one ECU connected to one facility, a camp of multiple structures would require a larger footprint to obtain the optimal annual cost after integrating a HES. To illustrate this using the result from Kabul, Afghanistan, a camp of 30 tents would require an array size of an American football field (5,350 m^2). Attention should given to the site specific feasibility of a PV array of that magnitude or if that location will have to implement a less than optimized system.

Conclusion

This paper presented the development of an innovative cost-performance model capable of optimizing solar array size, battery backup system size, and shelter insulation type at any location. The model can minimize a shelter's component and operating cost as well as reduce the reliance of isolated military and disaster relief sites on fuel resupply. The results of the case study analysis illustrate the unique capabilities of the model in (1) analyzing the performance of a single shelter, which allows the model to be scaled to any base size; (2) computing system energy requirements based on weather station data, ensuring the model can be adapted to any location worldwide; and (3) incorporating insulation type into energy calculations, enabling the model to consider a wide range of shelter materials. The developed model should prove useful to remote site planners, enabling them to design an optimal system to minimize the annual operating cost of fabric shelters, while incorporating site-specific climate data.

Two case studies were analyzed to demonstrate the use of the model and display its unique capabilities in selecting optimal design configurations. When using insolation, weather, and energy requirement data to optimize a shelter in Southwest Asia with Thinsulate insulation, the model generated an optimal system configuration consisting of a 179 m^2 solar array and a 90 kWh lithium-ion battery. When compared to a diesel generator, the modeled energy system would reduce fuel consumption by 93% and save $246 thousand within one year. Using climate data from San Juan, Puerto Rico the model's optimized system was a 122 m^2 array coupled with a 53 kWh battery. The HES reduced baseline fuel consumption by 92% and saved $292 thousand after one year.

A hybrid solar and battery energy system, when paired with an optimal level of shelter insulation, is a promising candidate to power ECUs in shelters for military or disaster relief operations. They provide additional energy resilience to mission essential components and reduce the amount of fuel resupply convoys needed to operate the camp.

IV. Scholarly Article 2: Cost Analysis of Optimized Islanded Energy Systems in a Dispersed Air Base Conflict

Jay Pearson and Steven Schuldt, Ph.D., P.E.

Abstract

Operating an air base in a contested environment is a complex and challenging task facing the United States Air Force. Using a large network of small distributed bases to launch air operations from, the Air Force will need to provide each location with the necessary supplies to operate effectively, including a limited amount of fuel. To prolong the critical resource, a hybrid energy system can be used to supplement the generators powering the base. This paper demonstrates a novel Hybrid Energy Renewable Delivery System (HERDS) model capable of estimating expected load of the camp, design and size a HES by minimizing the entire system's net present cost, and account for the transportation costs of moving the system from a staged location to an operational site. To demonstrate the model's capabilities, a case study was performed on Clark Air Base, Philippines. The optimal solution resulted in a 676 kW photovoltaic array, a 1,846 kWh battery backup system coupled with a 200 kW generator for a net present cost (NPC) of $4.99 million, saving $4.66 million, when compared to the baseline case of operating a generator full time. An additional savings of $165 thousand was seen by optimizing the type of airframes used to transport the system's 22 aircraft pallets to the base. The HERDS model is a promising capability that is expected to assist military planners increase site resiliency and make the most out of the available fuel.

Introduction

After nearly two decades of war, counterterrorism, and counterinsurgency, the United States (US) Department of Defense (DoD) has shifted its primary focus to near-peer conflict. As made clear by the 2018 National Defense Strategy (NDS), this shift is a dramatic change in strategy and will affect all levels of the US military [48]. In an armed conflict with near-peer competitors, the US will likely be challenged for air superiority; therefore, US forces may need to be on constant alert within the contested airspace.

Operating in a contested environment is a stark change in the way US military conducts business. One concept that is under development involves conducting operations from many smaller air bases [49]. This strategy allows the Air Force to generate sorties in one location and move operations before the base is targeted for attack. Conducting operations from a large number of bases inherently increases the logistic tail required to support their mission. This logistic requirement consists of fuel, munitions, food, and water resupply, and it is vulnerable to disruption and attack from adversaries [4].

Consequently, this strategy requires a large number of personnel to operate with minimal guidance and without an ongoing resupply of materials. Most importantly, the individual air bases will have a limited amount of fuel available to conduct their missions, including fuel to conduct air operations and run the generators necessary to meet the demand of all electronics, HVAC systems, and communication gear. A 2016 report conducted on the energy systems of remote operating bases concluded that these electric load demands are expanding and proportionally increasing the generator demand for fuel [1]. In order to balance the equation of a dispersed, independent operating platform and an expanding electric load, alternative means of power generation must be considered.

Investing in energy systems such as solar photovoltaics and wind turbines allows for alternative methods of generating energy. These systems can be combined with energy-storage platforms and an existing generator capability to provide the needed energy resilience to maintain operations without frequent resupply. These individual components can be integrated into a hybrid energy system (HES), defined as any system that combines different energy generation technologies to create a more robust power infrastructure. The majority of HESs consist of solar photovoltaic panels connected to a battery backup system that supplements a diesel generator [5]. These systems can intelligently supply power from different sources depending on the current demand and external conditions. Having a diversified portfolio of energy generation sources allows for the limited available liquid fuel to be prioritized for flight operations.

While integrating HESs into existing power grids is a straightforward process, several questions must be answered before the system can be designed and implemented. (1) What is the electrical load requirement for a base consisting of fabric shelters? (2) What is the optimal system size to meet power requirements at the lowest lifecycle cost? (3) How does the transportation costs of the HES contribute to the potential savings experienced by adding a HES? This paper seeks to answer these questions by exploring optimal sizing options for different operational locations using Hybrid Optimization Model for Multiple Energy Resources (HOMER) software as well as the Aircraft Selection Model (ASM) to find the most cost-effective method to airlift cargo using multiple airframes [36] [50].

This paper is structured as follows: Section II provides a background for the motivation of integrating HESs into isolated bases as well as a background of efforts to model these interactions. Section III defines the parameters used in both the HOMER software and the Aircraft Selection Model (ASM) as well as detailing how they integrate with the overall cost model, while Section IV demonstrates the unique capabilities of the Hybrid Energy Renewable Delivery System (HERDS) model to minimize the transportation and operational cost of the HES by analyzing a case study set in the Philippines. Finally, Section V provides a summary of the study and concluding thoughts.

Background

Near-peer conflict is the new focus for all future programs in the US military [48]. To achieve this strategy, the Air Force has the challenging task of determining how to conduct operations in a contested battlespace. There will be a prevailing threat of air raids from manned and unmanned air platforms, as well as long-range missile attacks [49]. From the US's perspective, this kind of battlespace has not been seen since the Vietnam conflict, and the skills needed for this type of conflict have eroded in the decades since. In order to identify needed strategy changes the Air Force commissioned RAND to explore the possible courses of action needed to train airmen and implement new techniques and equipment to be better prepared for future operations [49].

The report focused on the possibility of a conflict in the area surrounding the South China Sea and identified that a mixture of different types of bases was required in a contested battlespace – "stay-and-fight", "drop-in", and "fighter forward arming and refueling point (FARP)." The stay-and-fight bases will have a larger footprint, operate on the edge of the contested battlespace, and have more permanent infrastructure to include grid-tied power and large-scale fuel storage. The drop-in bases will be similar to the forward operating posts that are operated in Afghanistan and Iraq. These bases will primarily use expeditionary equipment with electricity mainly supplied from liquid fuel generators. Additionally, the bases are meant to be temporary and, if attacked, abandoned while evacuating aircraft and personnel. The fighter FARP bases are conceptualized as austere airfields, where everything needed to conduct operations would be flown in on cargo aircraft and only used for short periods at a time.

In practice, a distributed network of bases would allow for continued air operations in a contested environment. Every flying wing would have the authority to conduct operations from approximately five different airfields; however, standing up that many bases would require a large logistical chain to keep every base functioning. Critical supplies such as food, water, munitions, and fuel would have to be airlifted, trucked, or transported by ship to each location. The demand for these supplies only increases, considering the growth in manpower needed to support air operations (security, maintenance, engineering, and other combat support roles) from many different sites. Resources would have to be transported from an already established base to a stay-and-fight location, only to then be distributed to all the drop-in and FARP sites in the area.

Since the drop-in bases would not be connected to any source of local prime power, all electricity would be produced from liquid fuel generators requiring more than 2270 liters per day [38] [51]. With such a high level of fuel consumption, using alternative methods of energy generation would decrease the site’s reliance on fuel and resupply, while increasing its energy resiliency.

Aligning with the 2018 NDS, integrating resilient infrastructure in the form of HESs will allow these drop-in sites to become more effective [48]. Energy storage is a vital component of this system; it allows for the generator to operate at peak efficiency, and it also provides the user the ability to turn off the generator either for silent operations or regular maintenance [17]. To illustrate this concept, Natick conduced a demonstration at Fort Leonard Wood, showcasing an 80 kWh battery connected to a 15 kW generator, resulting in a total fuel consumption decreases by 80% [8]. Solar photovoltaics convert radiation from the sun into electricity and are another key component of a HES. Connecting a solar array to an energy storage system also allows any excess energy produced during peak hours to be captured and discharged during period of darkness, further reducing the fuel consumed by the generator. Studies have shown how these types of HESs can be used to reduce isolated communities' reliance on fossil fuel power generation [5]. Several military studies have also demonstrated the feasibility of connecting PV panels to soft-walled shelters to reduce the overall power demand [38] [12] [23]. Additionally, tents with integrated PV cells have proven effective in meeting the electricity needs of a displaced refugee population [39] [40].

As an alternative or addition to a solar array, wind turbines can harness another natural resource. Since wind can be prevalent all hours of the day, it is a well-suited complement to photovoltaics. Several studies have also analyzed case studies using the combination of wind, PV, and diesel generation to show the benefits of integration [15] [16]. There are a few drawbacks to these systems, however. First, these systems are complex and may be challenging to operate in contingency environments. Since wind turbines involve moving parts, these systems require more maintenance and repairs than passive solar arrays. Second, as mobility and ease of shipping are important in these circumstances, few locations in the world might justify the weight and cost of such a system [17].

The task of optimizing HESs has also been the focal point for many research streams. These models center around the economic tradeoff between the costs associated with purchasing a HES and the energy savings that are received from the system [29] [13] [52]. Using HOMER to optimize the microgrid system is one of the most prevalent methodologies in this line of research [33] [32] [34].

One of the primary considerations for distributed basing is the logistics and cost to transport the right people and supplies to the right places. A significant assumption that the RAND report considers is that most of the needed material will be prepositioned at the theater storage site in order to allow for faster deployment of forces and material [49]. This material can then be transported to stay-and-fight locations and be further forward-deployed to drop-in bases in the area. In order to move the expeditionary equipment, airlift operations will need to be optimized to either minimize the number of airframes required or the amount of fuel consumed. The aircraft selection model (ASM) optimizes the combination of mobility aircraft, the C-130J-30, C-17A, and the C-5A, to achieve these objectives [50].

Despite the significant contributions of the aforementioned research studies and demonstrations, there is no reported research that focused on: (1) computing a fabric shelter camp's energy demand based on local weather data; (2) minimizing the transportation logistics involved in airlifting an optimized HES; and (3) generating optimal tradeoffs between fuel consumption savings of a HES with the fuel cost incurred during transportation. Accordingly, this paper demonstrates a novel model that addresses the above-mentioned limitations.

Methodology

The Hybrid Energy Renewable Delivery System (HERDS) model was constructed with the intention of optimizing a HES system to increase a site's energy resiliency and to reduce the amount of fuel it consumes by generating power. The HERDS model is formulated in three distinct stages: the data inputs needed to run the model, the calculations performed from the input parameters, and the resulting output values and configurations. In the input stage, the site location and number of personal stationed at the base are needed in addition to the physical, performance, and cost attributes of the different components in the HES. During the calculations stage, an electric load profile is generated and used to compute optimal HES combinations that can then be airlifted with a select combination of aircraft. The final outputs of the model are the configurations of the HES, the airframes needed for system transportation and a total cost in present dollar terms that can be used to compare alternative courses of action. Figure 22 outlines the overall process being presented.

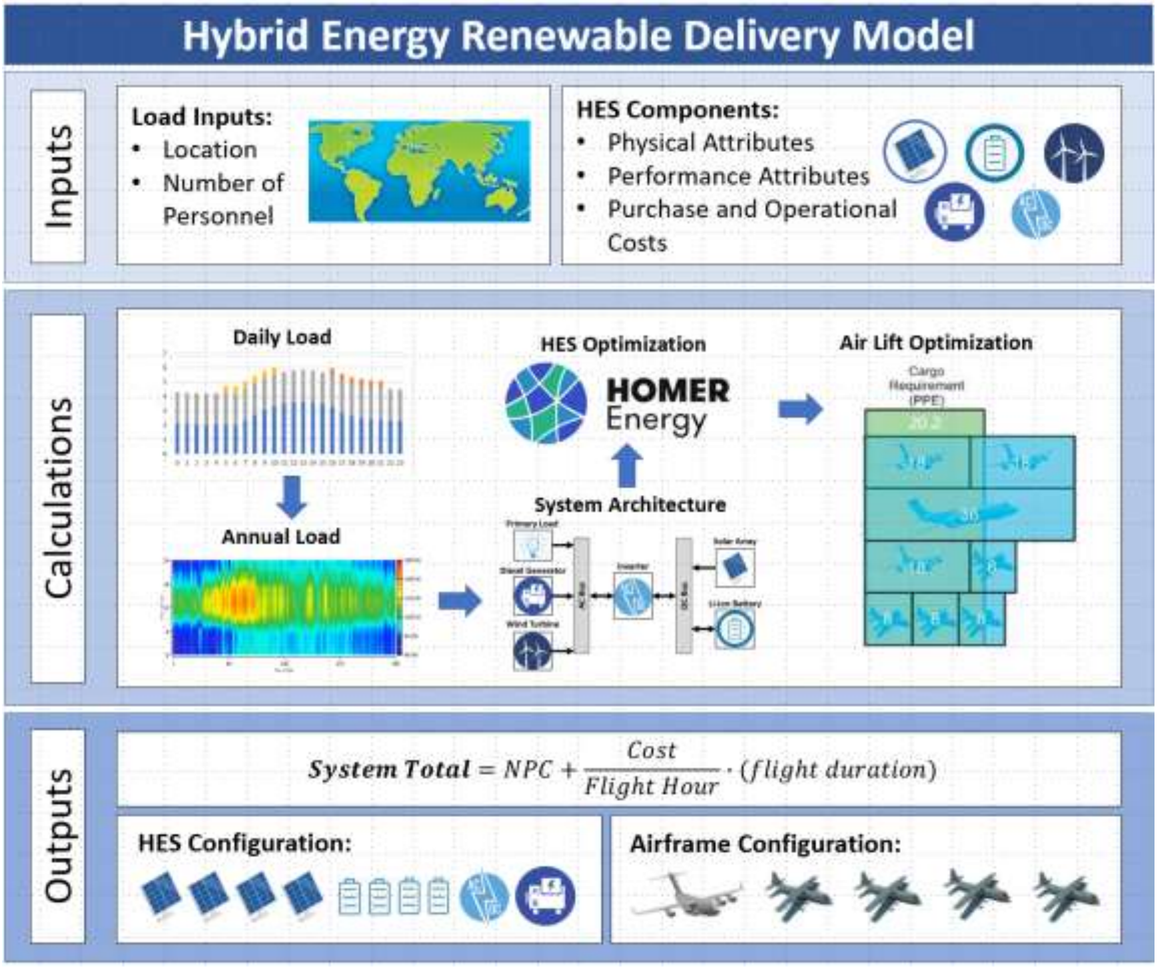

Figure 22. An overview of the input parameters, calculations performed, and expected outputs of the HERDS model [53].

Utilizing the HOMER software simplifies this process. Once a location is selected, the software downloads the appropriate resource data from the National Renewable Energy Lab's (NREL) database, as well as National Aeronautics and Space Administration's (NASA) Surface Meteorology and Solar Energy database [36]. This data is then used to predict the amount of energy produced by the microgrid's architecture. The different HES components, such as solar panels, wind turbines, energy storage, and inverters, can be added and edited individually in order to replicate a real-world system. Figure 23 displays a generic HES architecture that can be used within

HOMER. The software also allows the user to edit the economic parameters of the model as a whole and for each HES component.

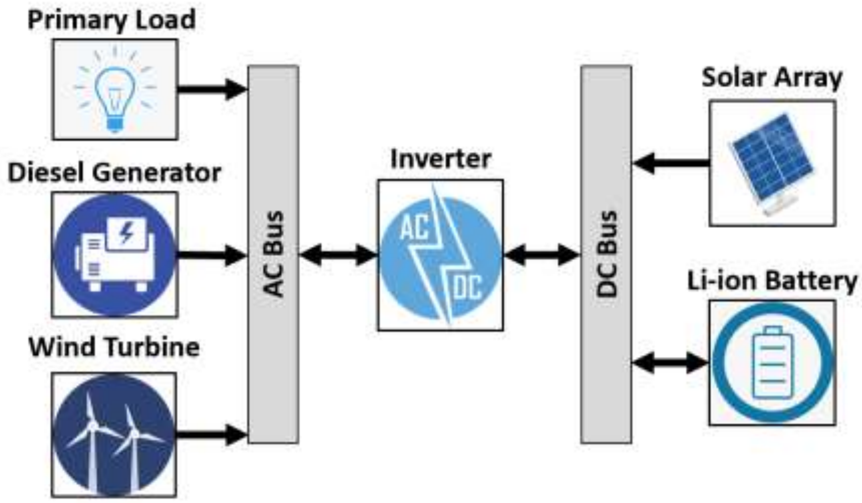

Figure 23. Architecture of a generic HES

In order to model a site and generate an optimally sized HES, the electrical load requirements must be known. One load that all tents share is the power required to maintain the shelter at a stable temperature. An environmental control unit (ECU) is attached to every tent in the base and is responsible for most of the energy consumption across the encampment [26]. Data from metering demonstrations at test sites indicate a relationship between the external ambient temperature and the load required to heat or cool the tent [38]. This relationship can then be applied to conduction heat transfer equations in order to determine the power required by the ECU to maintain the desired temperature within a tent, as shown in Equation (6) [37] [10].

$$P_{ECU}\ [kW] = \frac{3 \cdot A_t \cdot U \cdot |T_o - T_i|}{\eta} \times \frac{1}{1000} + 2\ kW \qquad (1)$$

Equation 6. ECU power draw equation. η represents the energy efficiency ratio of the ECU [43], $A_t\ [m^2]$ is the exposed surface area of the tent, T_o [℃] is the outside air temperature, T_i [℃] is the inside air temperature, U $[W/m^2 \cdot ℃]$ is the overall coefficient of heat transmission including the air films, tent material, and insulation. 2 kW is added as a base load requirement to run the ventilation fan. The 3 is a constant to account for additional heat transfer through convection, radiation, and air infiltration [38]. 1000 is used to convert the units from Watts to kW.

Equation (6) is used to account for the thermal resistive effects of the different layers between the exterior and the interior environment of the shelter. The U-value (Equation 7) sums the resistive elements between the ambient temperature (To) and the interior temperature (Ti) to account for the changes in the heat flow across the different materials, accounting for their thickness and thermal conductive properties. Figure 24 displays the relationship between the interior and exterior temperature in regards to heat flow across the different material layers of the tent.

$$U = \frac{1}{R_{Exterior\ Air} + \frac{x_1}{k_1} + R_{Interior\ Air} + \frac{x_2}{k_2} + R_{Interior\ Air}} \qquad (2)$$

Equation 7. Cumulative heat transmission coefficient, where x_i is the thickness of the physical layer, and k_i is the thermal conductance of the material.

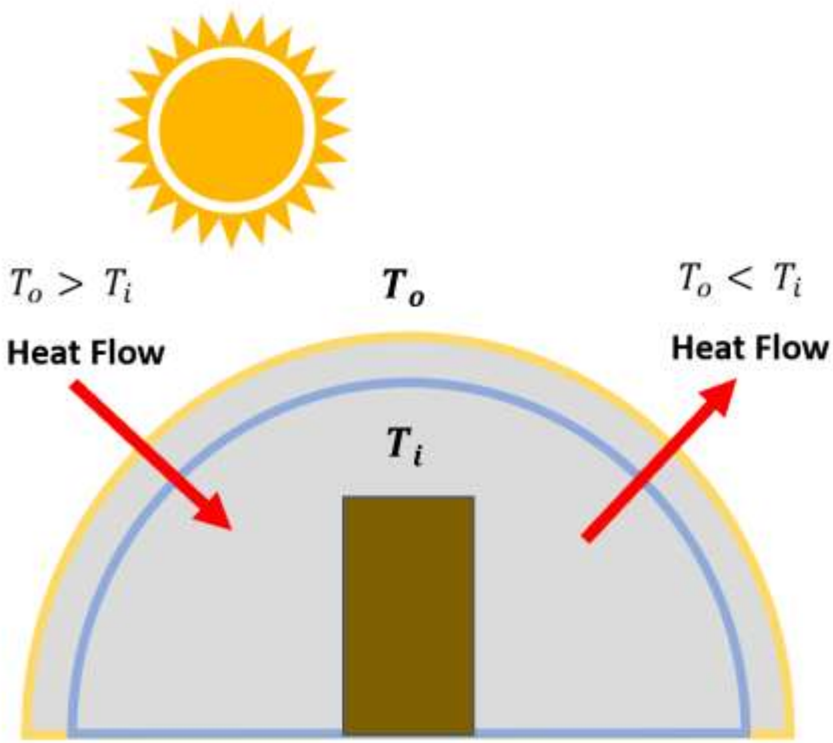

Figure 24. Visualization of the resistance to heat flow. T_o represents the exterior ambient temperature; T_i represents the interior temperature.

In addition to the electrical load from the ECU, the tents draw power from the system for other requirements. Some of these loads are broken down by the tent function, either a billeting tent or a mission-oriented shelter. Billeting tents are where the airmen rest when they are not on shift and store their personal belongings. Mission-oriented shelters house the array of sensors and communication equipment used by the base and are manned 24 hours per day. Metering reports from Afghanistan show that other loads occur at regular intervals during the day, such as when the lights come on in a billeting tent or when a new shift starts in the mission-oriented tents and make up approximately 0.2% of the overall camp load [7]. The combination of all the loading factors is listed in Table 4.

Table 4. Power Load Parameters

Tent Type	Load Type	Load Value [W]	Time of Day
Billeting	Lights	80	0600 - 2000
	Charging Electronics	100	1600 - 2000
	ECU	2,000 – 6,000 (Eq 1)	0000 - 2359
Mission	Sensors and Communications	2,200	0000 - 2359
	Shift 1 Variable Load	500	0500 - 1000
	Shift 2 Variable Load	500	1600 - 2100
	ECU	2,000 – 6,000 (Eq 1)	0000 - 2359

Before HES sizing can occur, HOMER requires the user to either select from a set of generic components or input system performance data, as well as the purchase and operational costs associated with the equipment. After the microgrid architecture has been established and the annual loading requirement is defined, the software then runs simulations for every combination of components (diesel generator only, diesel generator and a battery system, PV and battery system, etc.) and computes the optimized system for each combination using Net Present Cost (NPC), as shown in Equation (8).

$$NPC = Initial\ Cost + \sum_{t=1}^{n} \frac{(Costs)_t}{(1+i)^t} \qquad (3)$$

Equation 8. Net present cost equation. *n* is equal to the number of periods within the project timeframe, *t* represents the period being accounted for in the summation, *i* is the interest rate of the period. All other values are expressed in dollars.

NPC considers the initial purchase of the equipment, the replacement cost for all components, the system's maintenance cost, and the fuel consumed by the generator. Equation (8) can then be used to convert the period dependent costs to the present value, allowing for projects of different sizes, lifecycles, and geographic locations to be compared against each other.

However, HOMER is not able to incorporate transportation costs into its optimization calculations. To account for these costs, the optimal HES will need to be converted into pallet position equivalents and then, using the aircraft selection model, the cheapest transportion option is be selected, and a total airlift cost is calculated based on the flight time between the staged material's location and the drop-in base site [50].

Calculating pallet position equivalents is dependent on the type of resource being called for. Using the Air Force's standard 463L pallet constraints, the resource can be divided up either by weight or volume. The maximum weight for one pallet position is 4,535 kg (10,000 lbs), and the maximum volume for one pallet is limited to 2.74 m high by 2.24 m long by 2.44 m tall [54]. Using the resulting pallet equivalents, the best combination of aircraft needed to airlift the HES to the base is determined. The most common types of aircraft used for airlift operations are the C-130J-30, C-17A, and the C-5A. Their basic specifications are listed in Table 5 [50].

Table 5. Aircraft Comparison [55]

	C-130J-30	**C-17A**	**C-5A**
Speed	410 mph	450 mph	518 mph
Max Payload	19,900 kg	77,500 kg	122,400 kg
Range	2,100 nm	2,400 nm	4350 nm
Max Pallet Positions	8	18	36
Cost per flight hour	$5,741	$16,379	$35,899

The ASM then determines the number and type of aircraft required to airlift the system. First, it calculates all possible combinations of aircraft that can transport the pallets by weight and then pallet positions. Next, it determines the total flight cost for each combination of aircraft and selects the lowest value as the optimal choice. The total flight cost is then added to the net present cost of the HES.

Analysis

To demonstrate the unique capabilities of the HERDS model, a case study was analyzed utilizing a drop-in base, composed of 300 personnel at Clark Air Base, Philippines. This size base was chosen because the personnel there will be using expeditionary equipment and will likely only have fabric shelters to sleep and work from [49]. This size camp will not have access to prepositioned fuel sources and will have to prioritize the fuel they have available to primarily support flight line operations. These traits make a drop-in base an ideal situation to integrate a HES. Clark Air Base was chosen because of its proximity to the South China Sea. This region has been the focus of many recent war gaming scenarios and continues to pose a significant logistics challenge.

Several assumptions are made to accurately simulate the battlefield circumstances. First, all required material for a HES is already prepositioned at three hypothetical staging areas in the following countries: Japan, Guam, or Australia. Next, all needed BEAR base equipment (tents, generators, electrical equipment, etc.) are already in place and require no further material from additional airlifts. To simulate the existing power grid, a 200 kW generator was added to the model to generate any power that could not be met with PV cells or wind turbines. Because the generator capability is already assumed to be in place, a purchase cost of $0.01/kW (the smallest allowable value) was included. Additionally, all HES equipment is assumed to be purchased without a loan. Accordingly, a discount rate of 0.01% (lowest allowable value) was used. Finally, the

HES equipment, once transported to Clark Air Base, will continue to be utilized for the duration of the conflict and beyond [49]. To model utilization of the components until failure, a project lifespan of 15 years was used.

To generate the initial electric load of the shelters, time-series data for the ambient temperature in the area was collected from NASA's global weather data in 1-hour intervals [46] [47]. This temperature data is applied to Equation (6) to generate the load of the ECU connected to the tent. For this case study, the modeled shelter contains a 2.54 cm thick Thinsulate layer of insulation, which has an individual U-value of 1.2 $[W/m^2\ ^\circ C]$ and a cumulative heat transmission coefficient of 0.9 $[W/m^2\ ^\circ C]$. The calculated ECU load is then added to the other loads listed in Table 4 to generate the estimated daily load profiles for fabric shelters at Clark Air Base, Philippines. Figure 25 displays resulting loads for one day for both a billeting and a mission tent.

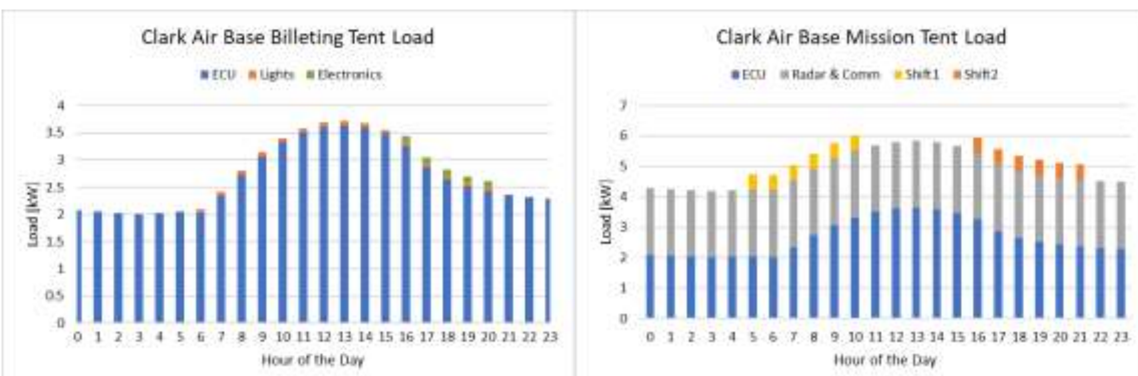

Figure 25. Individual billeting and mission tent loads

These individual tent loads were then scaled up to reflect the size of a drop-in base. The 300 personnel needed to operate the base were divided among 25 billeting tents and 5 mission tents [6]. The scaled-up daily loads were uploaded into HOMER; the resulting annual load is displayed in Figure 26.

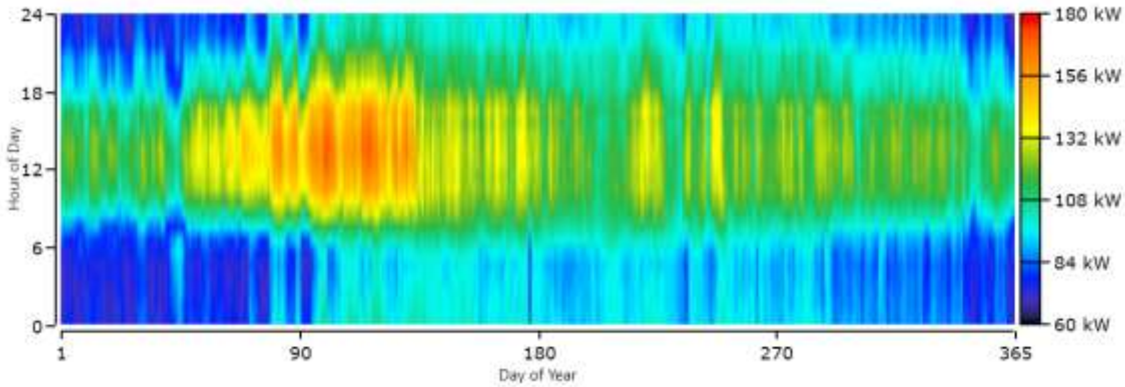

Figure 26. Yearly total loads for Clark Air Base, Philippines

The estimated annual load for the base was imported into HOMER and used to compute the different combinations of HESs. For this case study, specific components were chosen due to their market availability, their performance specifications, and their ability to be transported in pallets aboard aircraft.

The PV panels being modeled in this study are the SunPower E20. They have a rate capacity of 327 W and an efficiency of 20.4%, and when compared to the average panel efficiency of 15-18%, SunPower E20 panels have near top level efficiency rating on the commercial market [56]. In order to minimize the area required for the array, the efficiency of a panel was a prime consideration for the case study. The model is using an initial cost of $3,000 per kW. Table 6 lists more of the manufacture's specifications for the solar panel [57].

Wind turbines used in the simulation are representative of the Kingspan KW6, which is rated at 6 kW, has a 15m tall tower, and a 5.6 m rotor diameter. This makes it an ideal size for accessing the wind above the structures of the camp, while still being small enough not to interfere with air operations [33]. The turbine's cost data are listed in Table 6.

Energy Storage was calculated using HOMER's standard 1 kWh Li-ion battery model. This allows HOMER to run an optimization for energy storage at 1 kWh intervals, resulting in a precise value for the needed energy storage. Since the final value is expected to be on the order of 2 MWh, the final value will be converted into 210 kWh iterations of Tesla's power bank system in order to model the airlift requirements [58].

To simulate the in-place generator, initial capital cost was minimized so it would have a minimal affect the overall system NPC. The fuel price was set at $2.00 per liter to adjust for cost of transportation to the site.

Using the components listed in Table 6, HOMER generated 5,060 different systems and arrived at the following results. Each HES listed in Table 7 is the system with the lowest NPC over the 15 year lifespan for that combination.

HES 1 and HES 2 resulted in similar sized arrays, energy storage and NPCs. The main difference in the two systems is that HES 1 only has a combination of solar PV and battery backup along with a generator, while HES 2 adds a single wind turbine to the system. The addition of wind turbine caused the NPC to increase slightly for HES 2 and resulted in using 1,600 L more fuel per year. Next, the transportation costs of both HES combinations were calculated.

Table 6. Model Component Specifications

Component	Specification	Value
SunPower E20	Cell Type	Mono-crystalline
	Dimensions	1558 x 1046 x 46mm
	Weight	18.6 kg
	Rated Capacity	327 W
	Temperature Coefficient	-0.35%
	Operating Temperature	45℃
	Efficiency	20.4%
	SunPower E-20 327	$3,000/kW
	Operations and Maintenance	$45/kW/year
Kingspan KW6	Rated Capacity	6 kW
	Rotor Diameter	5.6 m
	Hub Height	15 m
	Purchase Cost	$49,150/unit
	Operations and Maintenance	$2,500/unit/year
	Weight	7,094 kg
Standard 1 kWh Li-ion	Capacity	1 kWh
	Nominal Voltage	6 V
	Round Trip Efficiency	90%
	Maximum Depth of Discharge	100%
	Weight (210 kWh battery)	1622 kg
	Weight (200 kVA Inverter)	1202 kg
	Purchase Cost	$445/kWh
	Operations and Maintenance	$10/kWh/year
In-place Generator	Rating	200
	Fuel Consumption Rate	52.4L/hr
	Initial Capital	$2.00
	Operations and Maintenance	$0.01/kWh
	Fuel Price	$2.00/L

Table 7. Optimized Combinations of Components

HES #	PV [kW]	Wind [unit]	Gen [kW]	Battery [kWh]	NPC [$K]	Initial Capital [$K]	Fuel/Year [L]
1	676		200	1,846	4,990	2,960	32,036
2	666	1	200	1,756	5,040	2,940	33,635
3		1	200	4	9,820	51	267,511
4			200	11	9,810	5	269,475
5			200		9,810	0.002	269,477

To divide the HES into pallet equivalents, the following criteria were used. Photovoltaic panel pallets will be governed by volume due to individual panels only weighing 18.6 kg [57]. Racking systems similar to the Sollega Solar Buckets will also be included [59], as well as individual microinverters, and all needed connection equipment. Each photovoltaic panel pallet has a rating of 40 kW.

The Kingspan KW6's 15 m tower can be divided into different sections to meet the dimensional requirements of a pallet and later bolted together on site. Due to weight requirements, one entire system was split between two aircraft pallets. One pallet contained the base and tower sections while the other pallet contained the wind turbine and blades. Altogether, the pallet combination had a rated capacity of 6 kW [60].

Energy storage systems are generally heavier than most other HES components. Systems such as the Tesla Powerpack can store up to 210 kWh and weigh 1622 kg; thus, only two battery banks can be transported per pallet [58]. Table 8 displays the details and contents of each pallet type.

Table 8. Pallet Divisions

Pallet Type (rating)	**Pallet Weight [kg]**	**Item**	**Number per Pallet**
Photovoltaic (40 kW)	2826	Solar Panel (327 W)	122
		Racking System	160
		Micro Inverters	130
Wind 1 of 2 (6 kW)	4373	Tower and Base	1
Wind 2 of 2	2885	Turbine, Blades and Parts	1
Energy Storage (420 kWh)	4446	Battery (210 kWh)	2
		Inverter	1

The resulting pallets were then divided up among the different airframes listed in Table 5. The ASM was employed by checking the capacity (both pallet positions and weight) of the largest airframes to transport the load, then creating all possible combinations of smaller airframes and checking for the lowest cost per flight hour of the combination. Table 9 displays all the different combinations of aircraft that can transport the HESs and their cost per flight hour.

Table 9. Airlift Combinations for HES 1 and 2 [55]

System	C-5A	C-17A	C-130J-30	Cost per flight hour [$]
HES 1	1			35,899
22 pallets		2		32,758
57,352 kg		1	1	22,120
			3	**17,223**
HES 2	1			35,899
24 pallets		2		32,758
64,610 kg		1	1	**22,120**
			4	22,964

The HESs resulted in different optimal combinations of aircraft for transporting the materials. This is primarily due to HES 2 including a wind turbine that weighs an extra 7,250 kg. The wind turbine caused the needed pallets to exceed the maximum payload of three C-130J-30s by 4,900 kg. Without the turbine, HES 1 was able to fit within three C-130J-30s and result in a lower cost per flight hour.

As stated in the RAND report, all the material needed to support these bases is assumed to be prepositioned in the nearby allied countries of Japan, Guam, and Australia. Figure 27 shows each location in relation to Clark Air Base and the estimated flight duration between each location.

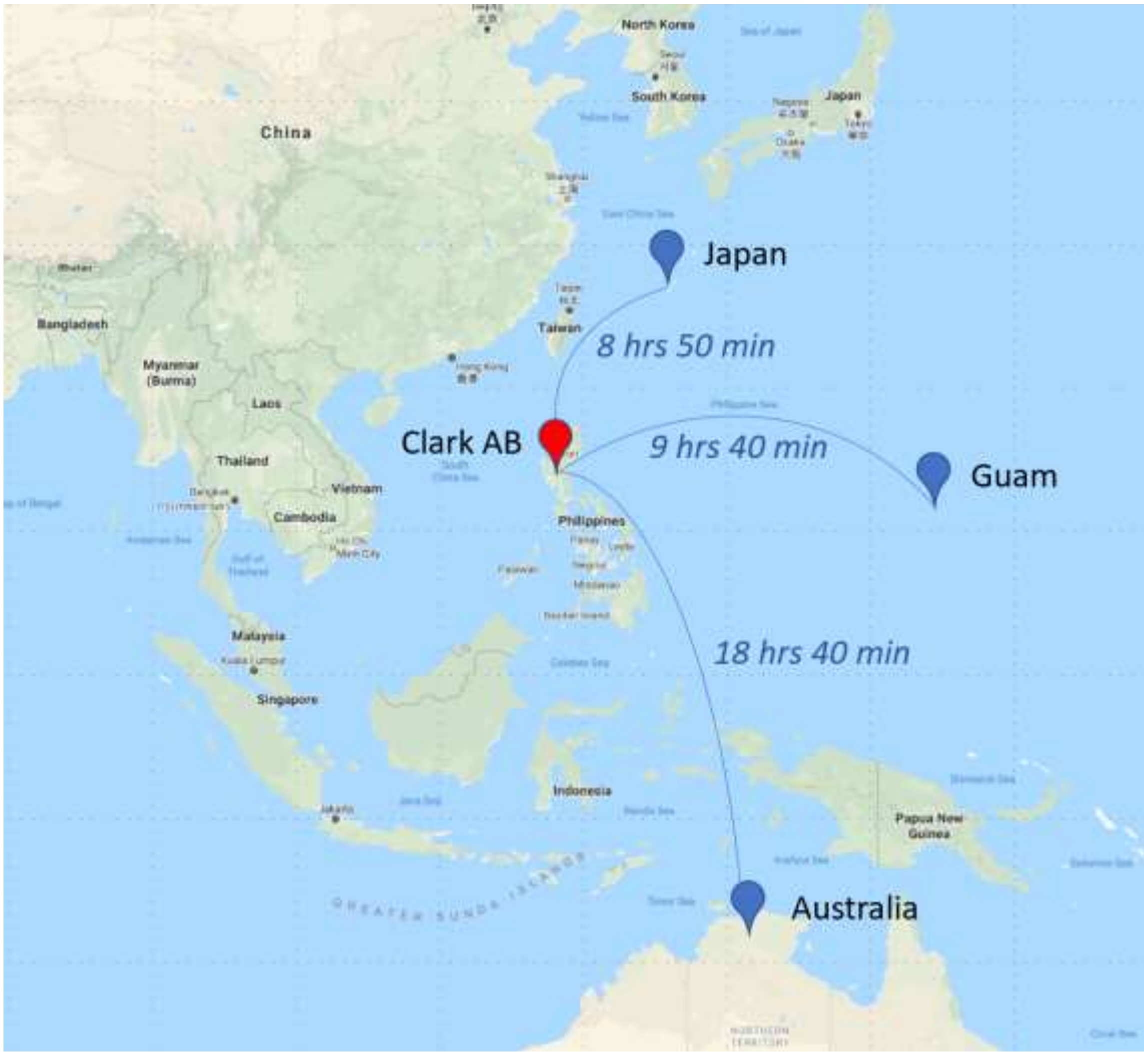

Figure 27. Flight duration to Clark Air Base from three possible staging areas around the South China Sea [61].

As shown in Figure 27, the closest hypothetical staging point for Clark Air Base is in Japan. The total estimated flight duration of eight hours and fifty minutes was used to approximate the total transportation cost of airlifting the material to the drop-in base. Table 10 shows the final calculated costs of operating and transporting the HESs.

Table 10. Total cost of bringing HESs to the drop in base

System	System NPC [$]	Cost per Flight Hour [$/hr]	Flight Duration	Transportation Costs [$]	Total Cost [$]
HES 1	4,990,000	17,223	8 hrs 50 min	152,136	5,142,136
HES 2	5,040,000	22,120	8 hrs 50 min	195,393	5,235,393

Both systems are relatively close in total price, only differing by $100K. Both systems, even with transportation included, are expected to save the US Air Force $4.7 or $4.6 million respectively, over the system's 15-year lifespan. The baseline case for powering these temporary facilities is listed in Table 7 as HES 5. That configuration has an NPC of $9.8 million and uses 269,477 liters of fuel per year. HES 1, by comparison, saves 54.4% in cost and consumes 12% the amount of fuel of using a generator alone.

In order to explore the variability of the model, a sensitivity analysis was performed for fuel price and project duration. Fuel price was hypothesized to be important to the HES optimization model because as the cost of fuel increased, a larger HES system would be required, in addition to the insignificant initial cost of the generator at a rate of $0.01/kW. The fuel price was varied from $1-10/L to determine if it caused HOMER to implement a higher reliance on renewable energy components instead of utilizing the generator. The project lifespan was also varied to model the anticipated short duration that these HESs would be used. Project duration was explored between 1 and 5 years. Figure 28 shows the size of the photovoltaic (PV) array and the Energy Storage (ES) component for the optimal system at each interval in the sensitivity analysis.

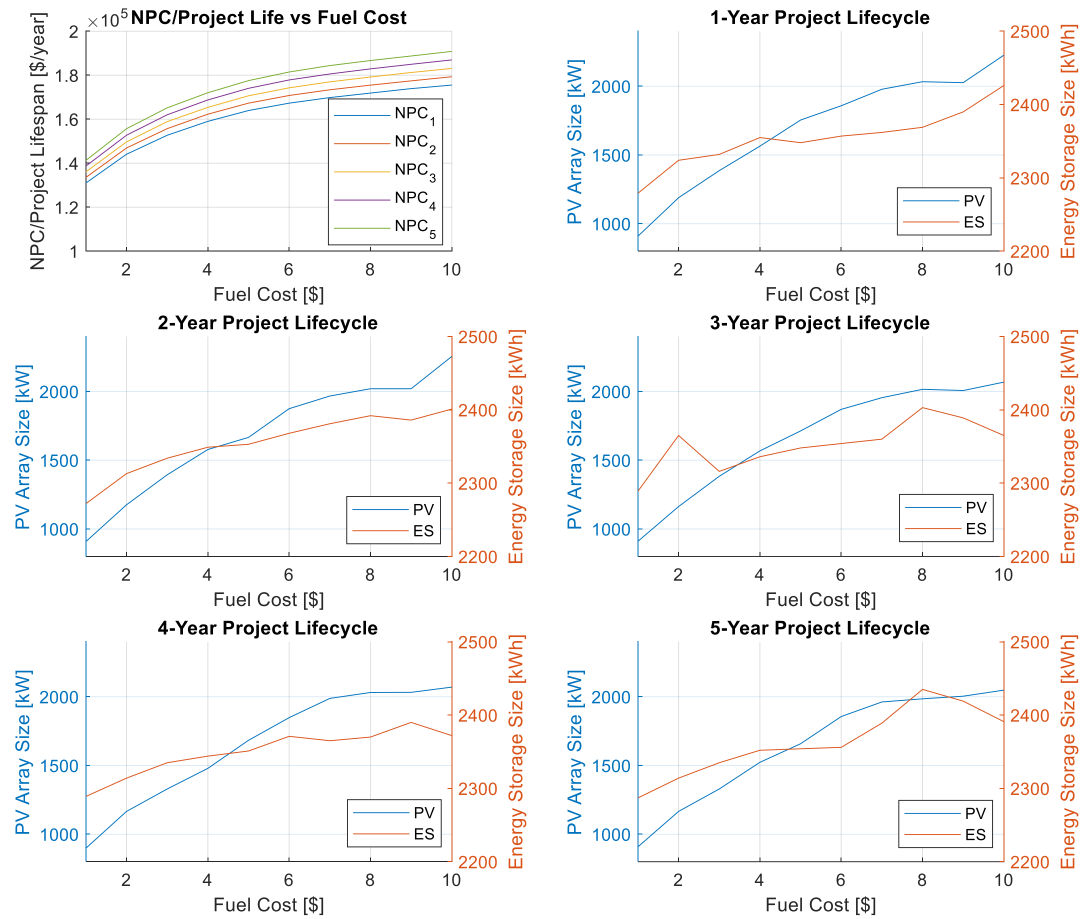

Figure 28. Sensitivity analysis of the HES optimization. Net present cost, PV array size, and energy storage (ES) size was compared against a changing fuel price varied between $1-10/L, project lifecycle varied from 1-5 years.

The results of the analysis showed a near linear relationship with an increasing fuel price to an increase in size and cost of the HES. This can be demonstrated by the top-left graph in Figure 28. Each system NPC for every fuel cost iteration was divided by the project duration, resulting in the same increasing rate of cost for every project lifespan. These similar rates are also due to the fact that HOMER produced the same optimized system configuration at every iteration. This system had a combination of solar panels, a backup battery system, a generator and was the overall optimized result every time. This result only reinforces the conclusion that the system configuration HES 1 from Table 7 is the best HES combination for Clark Air Base.

One other aspect that became apparent during the sensitivity analysis is that the components' salvage value was artificially deflating the results. Salvage value refers to the amount of money that could be received for selling a component at the end of the project lifecycle. A large portion of the overall NPC was due to the salvage value and did not accurately reflect the systems lifecycle cost. As an example, a 2 MW solar array costing $2.8M has an expected lifespan of 25 years. If the overall project has a lifespan of 2 years, the PV panels will have only lost 2/25ths of their initial value and can be sold to recoup costs; this is reflected by an NPC that is significantly lower than the 2.8M initial cost. The salvage value term within the NPC calculation does not reflect how the military handles its assets. Once purchased, the military will continue to use the components until they are upgraded or no longer functioning. To mitigate this term, the final project duration was set to 15 years. This is when the first component (Li-ion battery pack) within the HES architecture is due to be replaced, and by ending the project after 15 years, any salvage value incurred will be opposed by the replacement cost of the battery pack.

Conclusion

This paper presented the innovative Expeditionary Energy System Selector model to design a hybrid energy system in support of an expeditionary base in a contested environment. The HERDS model is capable of minimizing the transportation and lifecycle cost of a HES, based on a specific climate of the base. A case study was evaluated to highlight the significance and demonstrate the HERDS model's unique capabilities to (1) predict the power requirements of a camp using fabric shelters; (2) design an optimal HES to meet the required load at a minimal operating cost; (3) account for airlift requirements and costs and assimilate those values into a single cost to be compared against other projects.

The case study was able to quantify the benefits of implementing a HES designed by the model. The standard case of powering a base with a generator had an NPC of $9.81 million, while the best alternative HES had an NPC of $4.99 million, which was only 51% of the baseline cost. This savings directly reflects the 237,441 liters of fuel saved a year by the HES. An additional savings of $165 thousand was also identified by transporting the HES with three C-130J-30s instead of a single C-5 from its staging area to the base's location.

These distinctive capabilities of the HERDS model accurately and efficiently evaluate all feasible design configurations in order to select the optimal HES that minimizes transportation and lifecycle costs. This model will enable base planners to construct cost-effective, energy-resilient bases, all while reducing the exposed logistical tail.

V. Conclusions and Recommendations

Research Conclusions

With the goals of demonstrating expeditionary energy assurance using hybrid energy systems (HES), this thesis aimed to accomplish these three objective statements:

1. Analyze the characteristics and predict the power loads of temporary fabric shelters.

2. Optimize the HES size and component types using location-specific climate data.

3. Demonstrate cost and mission benefits from the implementation of HESs in forward-deployed locations.

The first objective was accomplished in Chapter 3. In "Meeting temporary facility energy demand with climate-optimized off-grid energy systems," the presented model related the external temperature of the environment directly to the electrical load of the environmental control unit (ECU). The model also was able to account for the thermal resistive effects of the different material layers in the tent's structure over a wide variety of insulation types. Chapter 4, "Cost analysis of optimized islanded energy systems in a dispersed air base conflict," built on this model, adding human-dependent loads such as turning on lights, operating communications and radar equipment, and using various other appliances during the day.

The second objective was addressed in both Chapters 3 and 4, utilizing two different methodologies. The model presented in Chapter 3 optimized the HES system through an iterative approach, assessing a fuel cost penalty every time the solar photovoltaic generated energy could not meet the load of the ECU. By analyzing a large range of sizes for the solar array and the energy storage system, the annual minimal operating cost for each system was used to determine the optimal HES for each location. The model presented in Chapter 4 also accomplished this objective through the utilization of the HOMER software package. HOMER allowed for a variable HES architecture in terms of components used and the size of each component, expanding the overall range of possible outcomes. The net present cost (NPC) of each HES was then compared in order to identify the optimal solution.

The final objective was accomplished in both Chapters 3 and 4 by comparing the optimized solutions of each model with the current forward operating base status quo of continually operating a generator to produce the needed power. This comparison was accomplished in terms of the annual operating cost of the baseline generator system versus the operating cost of the optimized HES. In Chapter 3, the presented model resulted in a system that reduced the annual operation cost by 69% and 82% in Afghanistan and Puerto Rico, respectively. Chapter 4's Hybrid Energy Renewable Delivery System (HERDS) model demonstrated the potential to reduce the operating cost over a 15-year time period of a drop-in base in the Philippines by 70%.

Research Significance

Research combining the two fields of renewable energy application and optimization has been a popular topic for the last decade. There are numerous articles discussing methodologies for designing the optimal hybrid energy system, as well as the estimated energy and cost savings that will occur after implementing the system. However, these models do not account for the varied and high energy intensity of soft-walled shelters. This thesis presents a model to estimate these loads based on the surrounding climate and then optimizes a HES to minimize the annual operating cost. Much of the previous research also incorporates a salvage value to their calculations, which does not reflect how the military purchases and uses equipment. The presented models do not account for, or have mitigated the effects of, a salvage value and incorporated the assumption that once purchased, the equipment will continue to be used. Chapter 4 further builds on the research to estimate the cost savings of HESs by including and optimizing the cost to airlift the final optimized system to the site where it will be implemented. By developing a model to account for the electric demands of a soft-walled shelter, optimizing a HES based on those demands, and including the cost to airlift the whole system to the site, this thesis has enlarged the academic body of knowledge on the subject of hybrid energy system optimization.

Research Contributions

This research was able to produce a novel mathematical model for estimating the electrical load of various sized bases and refugee camps at any location worldwide. This model was then built upon to develop a tool for base planners to construct more cost-effective and energy-resilient bases. This thesis has the potential to shape the way the Air Force and other Department of Defense expeditionary sites assure their energy supply, more efficiently use their available fuel, and accomplish the overall goals of the mission. This research culminated in the development of a peer-reviewed journal article, one conference paper, and two poster presentations.

Recommendations for Future Research

There is still a significant potential for new research possibilities within this field. There will always be more optimization models to develop and an increasing variety of case studies to demonstrate model capabilities. Additional areas that should be considered for future research are as follows:

1. HES field testing: Theoretical modeling is useful to explain a concept, but demonstrating the concept in the real world involves an entirely different challenge. Research into control mechanisms for HESs and energy frequency regulation is still emerging.
2. Improving the ECU load model: The presented model can captures the basic effects of conduction heat transfer through a tent surface. However, quantifying the effects of convection and radiation heat transfer would allow the use of the model to become a more robust and accepted practice.
3. Identifying denser sources of energy: The use of traditional renewable energy technology is effective but at the cost of otherwise useable land. Exploring technologies that present a denser source of energy would increase the energy resiliency of forward-deployed locations while reducing their overall footprint.
4. Explore the operational concerns of pilots: Using Air Force bases as the target location for renewable technology might result in resistive interactions with pilots regarding the possible glare from solar panels even after implementing the FAA’s guidance on solar technologies at airports [62]. The radar interruptions caused by nearby wind turbines are also concerning in addition to other

operational concerns. Investigating these concerns and ultimately mitigating them would undoubtedly benefit the service.

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14. ABSTRACT
Remote contingency military operations often require the use of temporary facilities powered by inefficient diesel generators that are expensive to operate and maintain. Site planners can reduce operating costs by augmenting generators with hybrid energy systems, but they must select the optimal design configuration based on the region's climate to meet the power demand at the lowest cost. To assist planners, this paper proposes two innovative, climate-optimized, hybrid energy system selection models. The first model is capable of selecting the facility insulation type, solar array size, and battery backup system to minimize the annual operating cost. The Hybrid Energy Renewable Delivery System (HERDS) model builds on this model by minimizing the entire system's net present cost, and accounts for the transportation costs of airlifting the system to an operational site. To demonstrate the first model's capability in various climates, model performance was evaluated for applications in southwest Asia and the Caribbean. An additional case study was performed on Clark Air Base, Philippines to highlight the HERDS model's capabilities. The capability of both models is expected to support planners of remote sites in their ongoing effort to minimize fuel requirements, lower annual operating costs and increase site resiliency.

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