USING GEOGRAPHIC INFORMATION SYSTEMS TO EVALUATE ENERGY INITIATIVES IN AUSTERE ENVIRONMENTS

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Abstract

Organizations that operate in austere environments at the end of long logistics chains face significant energy challenges which often represent financial and security vulnerabilities. Reducing fuel consumption in these operations causes a proportional fuel reduction throughout the supply system as the need for transportation of fuel is reduced. Accordingly, the total fuel reduction across the supply system should be considered to capture the fully burdened cost savings when conducting economic analysis of energy reduction initiatives. This research examined the energy savings potential of improving the thermal properties of expeditionary shelters, and then evaluated these measures using a fully burdened cost savings technique. Geographic Information Systems, Radiant Time Series cooling load analysis, and fully burdened concepts were applied to develop a model that analyzes the economic effectiveness of various shelter improvements in any climate and location in the world. Specifically, solar flies developed through Solar Integrated Power Shelter System (SIPSS) program for installation on fabric shelters were examined. The model was validated against test data provided by the SIPSS program, and then it was applied to two case studies. Results indicated that the energy savings in transportation associated with point-of-use energy reduction initiatives can represent a substantial portion of the overall fuels savings, which validates the idea that cost savings should be evaluated on a fully-burdened basis. Additionally, the SIPSS solar flies were overwhelming economically justified in most regions studied, but a lack of effectiveness in certain regions validated the need for the developed methodology.

For my wife and daughter, the joy of my life

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D. Jason Murley

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I. Introduction

The lack of energy availability and security continues to present challenges to providing a heightened quality of life, and in many cases, political stability in remote and austere regions. Militaries, humanitarian organizations, medical functions, and some industries struggle to execute their missions in austere environments because their operations often depend on supplying high quantities of fuel to the end of long supply lines. This reliance creates an operational vulnerability and high financial cost that threatens the success of their respective missions (Brown, Desroches, Garbesi, & Meier, 2012). The United States (U.S.) Department of Defense (DoD), in particular, has placed an increasing focus on reducing energy requirements in austere environments, stating “as long as U.S. forces rely on large volumes of energy, particularly petroleum-based fuels, the vulnerability and volatility of supplies will continue to raise risks and costs for the armed forces” (DOD, 2011). Due to the high costs associated with transporting fuel to remote regions, reductions in energy use at the end of the supply chain, or point-of-use, are compounded because of the proportional reductions in transportation requirements (Dubbs, 2011). As a result, future initiatives aimed at reducing point-of-use energy must be considered along with their associated transportation fuel reductions to evaluate the overall effects on fuel costs; however, previous studies have not included the fully-burdened cost effects when considering implementation of new technology.

Numerous studies have indicated that air-conditioning represents a prime opportunity to reduce point-of-use fuel consumption in remote regions. Operations in austere environments require lightweight, transportable shelters to protect personnel from the elements, which often consist of living trailers, shipping containers, or fabric shelters. The requirement to be lightweight, easily constructible, and mobile results in poor insulating characteristics of the shelters. Therefore, air conditioning these facilities represents a large portion of the overall base camp power use due to the high energy requirements of air conditioning combined with the minimal insulating characteristics of the shelter. Many energy reduction technologies are currently in development to address this issue, including the Air Force Civil Engineer Center's Solar Integrated Power Shelter System program, which is focused on developing equipment that can be used to reduce the energy required to cool expeditionary fabric shelters. However, there are limited methods for evaluating the efficiency and economic benefits of implementing this technology across a wide range of operating environments.

This research filled two existing knowledge gaps by developing a model that economically evaluates energy reduction initiatives within the context of austere operating environments and logistics costs. This problem was examined through the lens of the U.S. military, which continually operates in high-risk austere environments with long supply lines, although the results of this research can be applied to a wide variety of organizations. In this chapter, a formal problem statement and investigative questions are posed to provide a clear definition of the issue. A preview of the methods and research techniques used to answer the problem, along with the assumptions and limitations associated with these techniques are also discussed. Finally, this chapter outlines the structure for the remainder of the thesis.

Background

Organizations that rely on high quantities of fuel in austere environments increase the risk of mission failure, as illustrated by current U.S. military policy. The National Security Strategy of the United States continues to place a major focus on preventing terrorist safe havens in ungoverned or lawless regions. This focus will continue to place U.S. forces at the end of long supply lines that traverse large regions of political instability and increased risk of attack. A 2011 Department of Defense (DoD) report stated that "as long as U.S. forces rely on large volumes of energy, particularly petroleum-based fuels, the vulnerability and volatility of supplies will continue to raise risks and costs for the armed forces" (DoD, 2011). Furthermore, global petroleum fuel prices have soared in recent years, drastically increasing the cost of U.S. military operations for the federal government and taxpayer. These conditions have greatly increased the need for new energy reduction technology and contingency planning methods to ensure the success of future combat operations.

The fuel required to operate contingency bases is a prime target for reductions in energy consumption because decreases in fuel consumption are obtainable without decreasing direct combat capability. Furthermore, heating, ventilating, and air conditioning (HVAC) systems represent a large portion of the overall base operating support electrical load. Some estimates place the overall portion of HVAC loads from 59% (Boswell, 2007) up to 67% (McCaskey, 2011) of the overall base operating load.

These estimates are based on typical HVAC loads for expeditionary shelters associated with standard deployable equipment kits, known as Harvest Falcon and Base Expeditionary Airfield Resource (BEAR) kit, respectively. These shelters provide relatively low protection from solar irradiance, thermal conduction, and infiltration loads, so they are an important aspect of decreasing the overall contingency base load. Several research efforts are underway to develop equipment that reduces the power required to cool expeditionary shelters; however, these efforts are typically focused on developing technology for use in an extreme desert climate, with little regard for efficiency in other types of climates. Furthermore, new technologies are not migrating out of the research lab into the field because researchers are constantly improving technology and focusing on long-term fielding of war reserve equipment. Although this may be an appropriate approach to meet long-term requirements, it ignores the immediate benefits that could be realized by implementing today's technology. The development of a global model that provides economic justification for the immediate implementation of new technologies would be beneficial. Such a model requires a validated technique for conducting cooling load analysis of fabric structures, which represents a knowledge gap in existing literature.

Meanwhile, while considering point-of-use energy consumption of HVAC equipment is important, an economic justification should include the fully burdened cost of fuel (FBCF), which is defined as "the cost of fuel itself plus the apportioned cost of all fuel delivery logistics and related force protection" (DAU, 2009). One study estimated that the Army spent up to $600 per gallon to deliver fuel to remote outposts in Iraq and Afghanistan (Dimotakis, Grober, & Lewis, 2006), and more than 3,000 U.S. service members were killed in combat while transporting fuel through the Iraq or Afghanistan battlespace (Army Environmental Policy Institute, 2009). Clearly, the logistics costs and security vulnerabilities associated with energy consumption should be considered when evaluating the potential benefits of energy reduction efforts. However, the evaluation of transportation cost of fuel is a complex endeavor when considering a multitude of contributory factors such as transportation networks, terrain, climate, political considerations, capital infrastructure costs, and regional stability (Dubbs, 2011). Although numerous calculating and modeling techniques have been successfully implemented to calculate FBCF, no existing research was identified that used geospatial analysis techniques in FBCF estimation (Roscoe, 2010). Furthermore, limited existing research was discovered that conclusively used FBCF techniques to aid in evaluating the economic justification of energy technology.

The collection of these issues related to HVAC energy consumption and associated logistics burdens represents a complex geographical problem. Point-of-use energy consumption is tied closely to geography because different regions experience different climatic norms with respect to temperature, humidity, wind, and solar irradiance. Additionally, fully-burdened cost analysis requires an in depth study of transportation networks, terrain, and political stability, all of which can be analyzed geographically, also. A Geographic Information Systems (GIS) tool that accounts for point-of-use energy consumption and associated logistics burdens could be helpful for engineers and planners to evaluate future energy efficient technology.

Problem Statement

Soaring fuel consumption associated with supporting activities in remote and austere conditions represents an increasing vulnerability in the current security and financial environments. Many initiatives are being developed to reduce costs, but the economic analysis of implementing these initiatives often does not include the cost of transporting fuel across long distances. Specifically, expeditionary shelters are a large consumer of fuel due to air conditioning requirements and lightweight construction. Energy reduction technologies are being developed to reduce energy requirements associated with cooling; however, there are currently no effective ways to estimate their efficiency or to quantify the economic benefits of implementation across a wide range of operating environments.

Research Objective and Investigative Questions

This research intends to develop a GIS-based model that estimates the fully-burdened cost savings associated with implementing energy reduction equipment by examining the effects of reducing the air conditioning requirements of shelters in austere environments. The model should be applicable across a wide variety of operating locations and climates to aid engineers and logisticians in austere environments. This objective evokes a variety of interim questions that must be evaluated during model development and implementation:

1) What is the proper method for modeling the energy required to cool fabric structures in austere environments?

2) What are the most predictive and most available climatic data for use in the GIS model?

3) What factors should be considered when developing GIS based transportation networks? Where should the system boundaries be set?

4) How should technology implementation be evaluated from an economic perspective?

Methodology

A GIS-based model to economically justify the implementation of energy reduction technologies was developed in this research. Specifically, the use of solar flies, which are additional layers of fabric installed above the exterior of a fabric shelter, were examined by evaluating their effect on power required to cool a shelter. This was accomplished by examining the difference in fuel required to cool a standard shelter versus a shelter with an installed solar fly. These differences in fuel consumption were then examined across the logistics system to identify the fully burdened cost savings associated with installing flies. The overall methodology can be broken down into two major components: a cooling load analysis component and a fully burdened cost component.

An existing cooling load modeling technique, the Radiant Time Series method, was selected and applied to the standard Air Force expeditionary fabric shelter to evaluate the fuel required to cool it. Many of the required material properties necessary to develop a shelter model are unknown due to proprietary concerns. Therefore, material properties were approximated, and the thermal performance of the model was compared to field data to validate the model. This validation was performed both for the standard fabric shelter and for a standard shelter with an installed solar fly. GIS-based raster climate data provided the capability to evaluate shelter performance worldwide in terms of annual fuel required to cool one fabric shelter. A comparison between the standard shelter and the shelter with an installed solar fly yielded the fuel savings resulting from installation of the solar fly.

HVAC consumptions were then combined with GIS-based transportation network data to estimate the total fuel consumption required to power an air conditioner. The total fuel consumption was then evaluated at a variety of fuel prices and equipment costs to determine the economic viability of installing solar flies by using a discounted payback period calculation in conjunction with a sensitivity analysis. Lastly, two regions with varying climates and transportation networks were selected as case studies for model application. While this study focuses on the benefits of installing solar flies, the methodology could be applied to numerous other energy reduction efforts. Such a diverse model requires a systematic set of assumptions and limitations.

Assumptions and Limitations

Creating a model that is applicable to global planning requires that some assumptions and limitations be imposed. Without these assumptions, the complexity of the model would quickly exceed its usefulness. A series of general assumptions and limitations are discussed below, and additional discussion will be included in the methodology and results section to highlight specific consequences of the assumptions.

Cooling load models are limited both by experimental data supplied by research agencies and the availability of climate information in austere locations. For example, hourly solar irradiation data is unavailable for many locations in the world; this fact makes implementation of a transient analysis radiation method challenging. The development of a cooling load model under these constraints required several simplifications to ensure that it can be applied globally with limited data. Also, as discussed earlier, the material properties of the equipment under study are considered proprietary information and were not released for study, so material properties were estimated based on typical construction materials and validated using test data supplied by the Air Force Civil Engineer Center.

There are also assumptions associated with calculation of fully burdened effects using GIS tools. Transportation costs were assumed to be dependent only on distance within the examined logistics system, although terrain, road quality, traffic, and a number of other factors could significantly affect transportation costs. Logistics system boundaries were also drawn using political boundaries to limit the area to be analyzed for practicality. Lastly, the network analyst tool within the software package that was used to analyze FBCF introduces additional assumptions into the geographic model regarding how roads are connected and related to each other. These assumptions can vary widely with the availability of network data. Individual limitations related to geographic data are detailed during discussion of methodology and results.

Preview

The remaining chapters focus on presenting additional detail related to the problem statement, proposed solutions, and results. Chapter 2 provides a review of past research on operational energy, technological improvements, and geographic system modeling as a basis for further development. In Chapter 3, the specifics of creating necessary models are discussed to include cooling load model selection, transportation network development, setting of system boundaries, and data collection. Results and analysis are presented in Chapter 4 to include data validation against baseline data and existing contingency planning factors. Research conclusions and suggestions for further research are presented in Chapter 5.

II. Literature Review

This chapter establishes the importance of operational energy in austere locations, discusses applied cooling load modeling techniques and current shortcomings, reviews previously researched energy reduction methods, and develops the idea of fully burdened costs and how they apply in an operational environment. Operational energy challenges are unavoidable given the limited energy resources in remote regions of the world, and the need for air conditioning compounds these challenges due to its high consumption of fuel. Furthermore, the light-weight construction of expeditionary shelters adds to this burden because of the low insulating qualities of the construction materials. These challenges can impact a wide range of activities from military operations, humanitarian efforts, and commercial endeavors such as oil and gas field support.

Two major knowledge gaps exist which this research intends to address. First, there is little research regarding appropriate cooling load analysis methods for fabric structures. Therefore, three major cooling load modeling techniques were evaluated to determine which approach is the most appropriate to use in conjunction with fabric construction. Secondly, the fully burdened effects of implementing energy efficient technology have not been previously considered when economically evaluating energy reducing initiatives. The extent of these knowledge gaps will be fully identified in this chapter to establish the need for a new geospatial model capable of evaluating the cooling load and fully burdened effects of implementing new solar fly technology with fabric shelters.

Impact of Energy Availability on World Affairs

Energy continues to be a scarce resource in many remote regions of the world. Currently, 1.4 billion people lack access to basic electrical service, which represents more than 20% of the global population (International Energy Agency, 2010). Furthermore, approximately 87% of people who lack access to electricity live in rural areas that have little chance of acquiring electrical service in the next 20 years (International Energy Agency, 2010). The inability to obtain energy has a large impact on the quality of life of the affected population, with impacts on access to clean water, sanitation, healthcare, and residential living conditions. Basic access to energy is also a prerequisite for global progress in eradicating extreme poverty, improving healthcare, achieving universal primary education, and promoting gender equality (International Energy Agency, 2010). These vulnerabilities make the affected populations especially vulnerable to crisis situations. Goodhand (2003) noted that there is a direct correlation between war and poverty which results in a chaotic cycle that is difficult for many regions to escape. Additionally, impoverished communities are more likely to experience a catastrophic disaster because of preexisting substandard living conditions, and the ability to cope with disasters is also diminished by the lack of physical infrastructure (Lal, Singh, & Holland, 2009).

The inferior conditions referenced above attract some types of organizations to these remote regions for a variety of reasons. The political instability and vulnerability to disaster can lead to military or humanitarian operations, while untouched natural resources can attract various industries to develop commercial endeavors in these regions. The infrastructure limitations require that these organizations be self-sufficient in powering mission-critical response activities (Lal, Singh, & Holland, 2009). Specifically, the United States (U.S.) military employs a large inventory of cooled, fabric shelters in austere environments. While the military's reliance on petroleum fuel to cool these shelters made it the focus of the current research effort, conclusions from this research may be applicable to any activity that employs air-conditioned structures in austere regions.

U.S. National Security Strategy Implications

The U.S. continues to place an importance on "waging a global campaign against al-Qaida and its terrorist affiliates" (Obama, 2010). One major component of preventing terrorism is denying terrorist safe havens (Obama, 2010), which are areas that terrorists can plan and operate in relative safety. Safe havens are often found in "under governed or lawless regions" (Department of State, 2007). The current political environment often drives modern day counterterrorism operations to merge with counterinsurgency operations, despite the fact that many experts argue for operational separation between the two types of operations (Boyle, 2010). Counterinsurgency warfare presents a multitude of logistics problems as militaries struggle to establish, operate, and supply garrison-like forward operating bases in un-permissive and semi-permissive environments. These long supply lines across hostile and politically instable regions increase costs and security vulnerabilities (Reyes, 2009). These facts emphasize that any point-of-use fuel consumption must be considered along with the fully burdened cost of fuel, a concept that will be developed later in the literature review.

Operational Energy Strategy

Petroleum fuel represents an increasing financial and security vulnerability for the U.S. The Department of Defense (DoD) noted that:

> At the same time that military demand for energy is growing, global and battlefield energy supplies are under pressure. At the operational and tactical level, fuel logistics have proven vulnerable to attack in recent conflicts. Strategically, energy is important for economic stability and growth, with nations around the world increasingly competing for the same energy resources. As long as U.S. forces rely on large volumes of energy, particularly petroleum-based fuels, the vulnerability and volatility of supplies will continue to raise risks and costs for the armed forces. (2011)

To combat the effects of increasing energy vulnerabilities, DoD outlined three major focus areas for improvement. These areas include reducing the fuel required to conduct military operations, expanding the supply of energy, and ensuring that energy security is developed in the future force. Energy experts have noted that the "rising cost of fuel and vulnerability of supply lines demand that we improve our expeditionary capability" (Boswell, 2007).

Targeting Air Conditioning for Energy Reductions

The U.S. relies on its expeditionary military capability to project its power worldwide in support of national security objectives. This reliance requires a core competency of the U.S. military to rapidly deploy to austere environments with the potential to occupy an area for an extended period of time. Extended occupations in potentially hostile environments create the need for expeditionary bases from which military forces can conduct operations (Boswell, 2007). The population at some major garrison locations often swells to the point where many tertiary combat support activities consume a substantial amount of valuable resources. For example, Balad Air Base in Iraq maintained a base population of approximately 30,000 personnel (Loney, 2011). Large populations result in a correspondingly large electrical load associated with HVAC requirements to cool living and working spaces for base personnel.

These contingency bases require a substantial portion of the overall fuel consumed in a combat zone. Fuel consumption related to maintaining and operating a forward base is a prime target for fuel reduction efforts. While reducing actual operating costs of combat vehicles is difficult without impacting mission effectiveness, contingency bases offer an area of reduction with relatively minimal mission impacts. Within the BOS fuel consumption category, HVAC loads account for approximately 59 to 67 percent of the overall BOS load (Boswell, 2007; McCaskey, 2010). New advancements in HVAC energy efficiencies can have a large impact on the overall contingency energy reduction effort (Boswell, 2007). Specifically, expeditionary shelters have a large capacity for energy improvements due to their poor insulating characteristics. One potential solution to reducing energy consumption related to HVAC is to reduce overall HVAC capacity and accept higher indoor air temperatures, or in some cases, eliminate HVAC systems altogether. However, the decision to expose personnel and equipment to extreme temperatures must be weighed carefully against their task performance and overall well being.

The Importance of Air Conditioning in Austere Environments

Thermal comfort is important to ensure optimum performance and health of the human body. Epstein and Moran (2006) noted that thermal stress has an inverse correlation with work efficiency and productivity, and survival can even be threatened in extreme environments. Additionally, many electrical and mechanical systems require a conditioned environment for operation, which presents an interesting problem for designers because thermal comfort and energy consumption are often directly related. There is a fine balance between energy reduction efforts and performance effects related to thermal comfort. Many energy efficiency proposals compromise some level of thermal comfort for occupants; these proposals may be valid, but the potentially negative performance impacts must also be considered.

The indoor design point temperature is a critical parameter to establishing a comfortable environment while maintaining an acceptable level of energy efficiency. This is especially true in a deployed environment where a delicate balance exists between human comfort, physical performance, equipment health, and energy efficiency. The Field Deployable Environmental Control Units (FDECU) currently fielded by the U.S. Air Force as a part of the Base Expeditionary Airfield Resource (BEAR) kits allow occupants control of the interior temperature via a thermostat (Department of the Air Force, 2009). The ability to change the indoor temperature set-point can result in the use of excessive energy when a thermostat is set to an extreme temperature.

Research performed by the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) has resulted in a wealth of thermal comfort information for designers (ASHRAE, 2009; Brager & de Dear, 2001). The two major factors dealing with thermal comfort are operative temperature and humidity; acceptable combinations of operative temperature and humidity were developed during previous research by ASHRAE and are shown in Figure 1. Operative temperature is an adjusted temperature based on how an occupant exchanges heat with the environment through radiation and convection (ASHRAE, 2009).

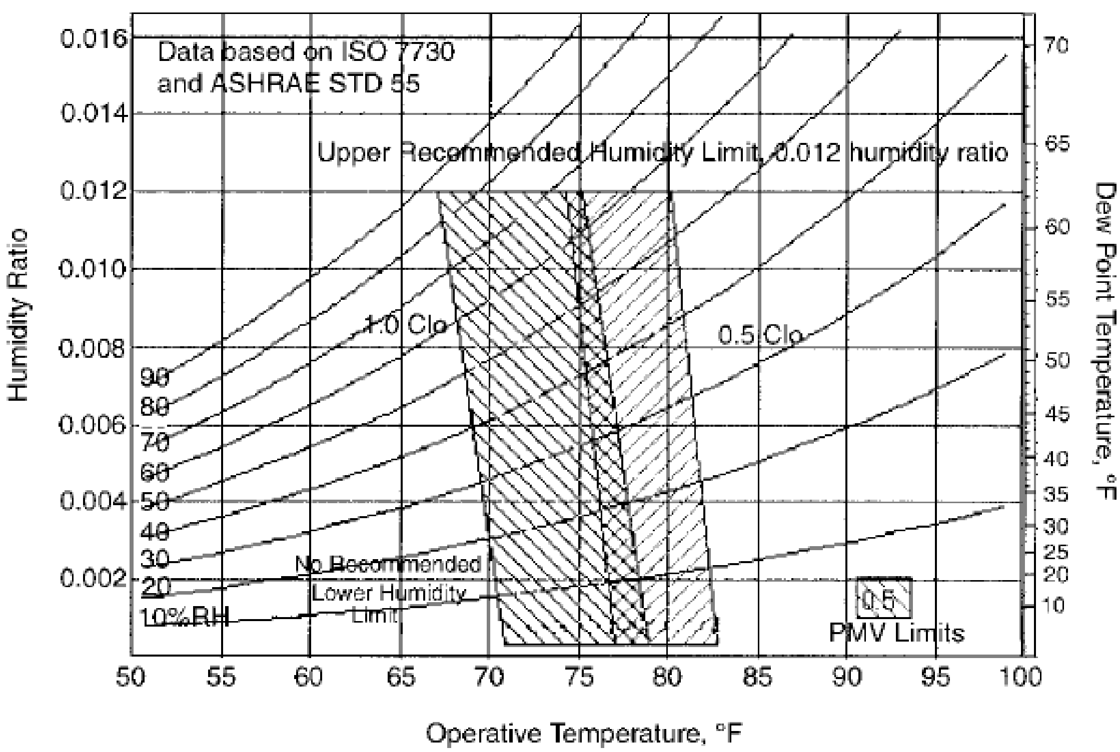


Figure 1. Thermal Comfort Range (ASHRAE, 2009)

The comfort diagram is separated into summer and winter categories based on the expected apparel worn by occupants, and additional data were published to account for airflow, abnormal clothing, and certain physical activities. This information allows engineers to set appropriate indoor design temperatures to accommodate thermal comfort and energy efficiency concerns.

Fully Burdened Cost of Fuel

There are various methods of examining how fuel is consumed during contingency operations with complex logistics systems. The simplest examination of fuel consumption is often referred to as "point-of-use" fuel consumption, which refers to measuring only the fuel that is consumed by a single activity. Point-of-use comparisons can be useful for examining multiple energy reduction options at a single location; however, it does not consider large-scale impacts of energy consumption across the supply chain. By comparison, the Defense Acquisition Guidebook (2012) defines the Fully Burdened Cost of Fuel (FBCF) as "the cost of fuel itself plus the apportioned cost of all fuel delivery logistics and related force protection required beyond the DESC point of sale to ensure refueling of the systems." Most existing literature, including Corley (2009), Roscoe (2010), and Dubbs (2011) reference this definition when referring to FBCF. As supply lines increase in length and complexity, FBCF becomes more important for evaluating how much fuel is really consumed across the entire system to power a single activity at a specific location. Various methods exist for estimating fully-burdened cost effects, and differences exist even within the U.S. military, where each service has developed its own methodology for evaluating fully-burdened costs (Roscoe, 2010).

The level of fully burdened analysis can range from overly simple to extremely complex. Prado et al. (2011) examined the fully burdened effects of employing microgrids with photovoltaic arrays and developed a model to simulate how microgrids integrate various power sources and loads across a normal diurnal cycle. After examining the point-of-use consumption, they evaluated the fully burdened effects of microgrid implementation by applying a supply chain fuel efficiency factor, which is a ratio of the fuel expended in the supply chain divided by the fuel consumed in generation at a base. A supply chain fuel efficiency of zero would indicate that no fuel was used in the supply chain to consume fuel at the point-of-use. Conversely, a supply chain fuel efficiency of five would indicate that five gallons of fuel were consumed during transportation for every one gallon consumed at the point of use (Prado, Seager, Mechtenberg, & Bennet, 2011). However, no methodology was provided by the authors regarding how the supply chain fuel efficiency factor should be determined. Without further development, this technique can introduce large errors into a model.

On the opposite end of the spectrum, micro-level FBCF analysis can be conducted on fuel consuming activities. Dubbs (2011) examined each segment of the supply chain from initial production to final, tactical distribution from a cost perspective. Data were gathered from real-world supply operations in Afghanistan to estimate in-transit fuel consumption. Details were considered down to the convoy structure level by specifically examining how many vehicles were required along particular routes. Similar data were collected pertaining to the air transport of fuel for outlying bases. Using this data, an input/output model was constructed to determine the FBCF effect for certain bases in Afghanistan. The Dubbs study produced two major outcome parameters. First, an average fuel multiplier parameter was established to describe how much fuel is required in transit per gallon of fuel consumed at the point of use. This parameter is similar to the supply chain fuel efficiency factor proposed by Prado et al. (2011); however, the input/output model provides a much better basis for how this parameter should be developed and implemented in future research. Additionally, Dubbs (2011) also considered a marginal fuel multiplier parameter that explains the relationship between FBCF and supply chain capacity.

While the economics of fuel consumption is an important driver of energy efficiency, a more important consideration is the lives that are put at risk by transporting fuel through dangerous regions. The analysis of human costs associated with providing fuel to support ongoing operations is difficult to quantify. Eady et al. (2009) attempted to quantify the human risk associated with transporting fuel by noting that 10 to 12% of all land casualties occurred during resupply operations, which primarily consist of fuel and water. Using this factor as a baseline, the fully burdened effects of fuel reduction on resupply casualties was examined, and it was estimated that four lives could be saved each year by implementing thin film photovoltaic to supplement traditional generators within a Stryker Brigade Combat Team (Eady et. al, 2009).

Expeditionary Shelters

The military is frequently deployed in locations that have little or no existing facility or infrastructure systems to support operations or basic living needs. To operate in austere environments, the military uses lightweight fabric shelters as the basic building block to house its personnel in expedient situations. Each military service typically procures its own lightweight shelter equipment sets. Specifically, the standard shelter used by the U.S. Air Force is the Alaska Structures Small Shelter System (SSS), which is shown in Figure 2. The small shelter system consists of an aluminum arch, an exterior fabric to provide protection from the elements, an interior fabric liner to provide some measure of insulation and closure to the building envelope, a fabric floor, and two end wall pieces. A traditional door is installed on one end of the shelter, and windows and heating exhaust ports are found on most shelters. The shelters are typically installed on crushed gravel or AM-2 steel matting, and stakes are used to secure the shelters firmly in place. Shelters are 32.5 feet in length and 20 feet in width, which provides 650 square feet of total floor space. Air conditioning and heating is provided by a 5-ton skid mounted unit, commonly known as the Field Deployable Environmental Control Unit (FDECU). The FDECU is a heat pump system containing both condenser and evaporator coils in which airflow is provided to the interior of the shelter through a collapsible, fabric duct that runs the length of the shelter. A thermostat is provided to control the interior temperature of the tent, and a venting option provides continuous airflow through the tent even when the heating element or compressor is not running (Department of the Air Force, 2009).

Figure 2. Alaska Small Shelter Systems installed in Afghanistan (Murley, 2011)

This type of shelter provides a mobile, lightweight housing capability that can be deployed and constructed quickly in austere environments. Shelter fabrics consist of a thin polyvinyl chloride coated polyester fabric, which provides relatively low insulating performance and thermal storage capacity (Devulder, Wilson, & Chilton, 2007). Unfortunately, many fabric shelter properties that are typically incorporated into design in traditional construction are considered proprietary or are unknown even by the manufacturer. Thermal conductance, specific heat, and shelter infiltration values may be either unknown or not provided by the manufacturer. Since these parameters have significant impact on the energy consumption of the shelter, the lack of information presents a significant challenge for researchers who are attempting to improve the energy performance of fabric shelters. However, an appropriate cooling load model with estimated material properties could be used to simulate shelter thermal performance and aid in future development of energy reduction technologies.

Technology Development

There are several ongoing research efforts to reduce the energy demand related to cooling expeditionary shelters. Each military service has a program specially aimed at developing new equipment for field use. Specifically, the U.S. Air Force is developing new technology under the Solar Integrated Powered Shelter System (SIPSS) program at the Air Force Civil Engineer Center (AFCEC). The main goal of the project is to "demonstrate a deployable SIPSS that improves energy efficiency 50 percent and generates at least three kilowatts of solar power" (Fisher, Peck, & Sand, 2010). The major efforts of the project focus on solar flies, insulated liners, and photovoltaic integrated solar flies that increase thermal efficiency. Figure 3 shows an example of an expeditionary shelter covered with a solar fly with an integrated photovoltaic array. Researchers would like to increase the thermal efficiency of the shelters to a point at which one Environmental Control Unit (ECU) can be used to cool two shelters, which would significantly reduce the overall energy consumption of a contingency base. Projections show that there is a potential energy savings of up to 2.25 megawatts at some large contingency installations, which represents the equivalent of three generators typically associated with Air Force deployed power plants(Fisher, Peck, & Sand, 2010).

Figure 3. SIPSS Shelter with Photovoltaic Fly (Fisher, 2010)

Various avenues of future large-scale acquisition of solar flies and associated equipment are being discussed, but off-the-shelf equipment is currently available to military personnel seeking expedient, energy efficient shelter solutions. If large-scale acquisition does occur, it remains unclear if SIPSS equipment would be included in standard Unit Type Code (UTC) kits, the standard unit that the Air Force uses for deploying personnel and equipment. Another option includes a separate renewable and load demand reducing UTC that can be deployed as necessary. Direct purchasing from the field is another option that could be used to equip shelters in current conflicts to avoid waiting on the lengthy Air Force acquisition process. Optional deployable equipment sets and direct purchasing place a high importance on being able to determine when energy reduction equipment is economically justified based on costs, geography, and climate data (AFCESA, 2011; Fisher and Keith, 2011).

The 2011 SIPSS research program was conducted at Fort Irwin to test a wide variety of shelters and associated energy reduction equipment provided by various manufacturers. Fort Irwin is located in the Mojave Desert in California, which presents a hot, dry, desert environment for testing. Testing in extreme climates is critical to ensure that equipment is able to perform adequately in harsh environments, and it also aligns the testing program with recent military requirements for energy efficient shelters in hot environments, such as Iraq. However, designing for such extreme conditions can actually result in decreased efficiency in less extreme climates if equipment is not properly configured. Air conditioning units are most efficient when they operate close to their designed capacity (ASHRAE, 2009), which means that equipment sets that are designed for extreme heat may not operate as efficiently in moderate climates because the air conditioning units are oversized. While fiscal constraints may prevent research programs from conducting field tests, a cooling load model that could simulate shelter performance in a wide variety of climates would be beneficial. Ideally, equipment sets could be customized to ensure that the shelter configuration and ECU selection are matched to the climate to ensure maximum efficiency across a wide range of climates.

Cooling Load Modeling Techniques

The ability to model cooling loads is of prime importance to establish a methodology for evaluating various thermal efficiency efforts. Specifics of the detailed models used for this research are discussed in Chapter 3; however, cooling fundamentals and previous modeling efforts must be reviewed as a basis for model development. Additionally, there is little existing research concerning cooling loads on fabric shelters. Several methods are available for evaluating thermal loads, but the selection of appropriate techniques and parameters are dependent on application types, climate, available data, and temperature set-points.

Load modeling techniques for HVAC can typically be described as steady-state or transient methods. Steady-state modeling techniques are often effective with respect to heating loads; however, radiation and thermal storage effects diminish the effectiveness of steady-state modeling with respect to cooling loads (ASHRAE, 2009). These effects are especially relevant when considering structures with a large thermal mass. Thermal mass is related to construction material selection and techniques, and is technically described in terms of mass, and specific heat. For example, a structure built with stone has more ability to store heat than a simple plywood structure. These concepts will be further developed during discussion of transient modeling techniques. Despite the potentially negative aspects of steady state modeling with respect to cooling load analysis, one large advantage of using steady-state analysis is simplicity because they depend only on outdoor design temperature, indoor set-point temperature, exterior area of the shelter, and the thermal conductance of the exterior wall (ASHRAE, 2009). All of this information is readily obtainable across a wide variety of construction materials and environments. Furthermore, many expeditionary shelters have minimal thermal storage capacity, which decreases the errors typically associated with ignoring transient effects. For these reasons, some forms of steady-state analysis may be used during research despite potentially negative consequences commonly associated with steady-state modeling of cooling loads (ASHRAE, 2009).

In contrast to steady-state analysis, radiation effects must be considered in transient cooling load analysis because they can represent a significant portion of the overall heat load. Additionally, transient analysis allows designers to account for heat that is stored in the thermal mass of the exterior walls of a conditioned space (Spitler, 2009). This method sometimes allows designers to reduce equipment size and energy use by accounting for the fact that some heat remains in the exterior walls during the hottest part of the day. This is due to the fact that building materials absorb and store heat for some period of time before releasing the heat into an interior space, which can reduce the peak cooling load by delaying some heat transfer into the conditioned space until later in the day after the peak outdoor air temperature has occurred (Spitler, 2009). This benefit is attractive for operational energy modeling since energy reduction opportunities are being sought. However, the inclusion of radiation parameters results in the need for additional climate data for application at specific locations. The accuracy of cooling load modeling techniques is also dependent on using construction materials with known parameters (Spitler, 2009). Despite these limitations, transient methods offer the best chance at developing the most accurate model.

Three major techniques of transient cooling load analysis are currently published by the American Society of Heating, Refrigeration, and Air Conditioning (ASHRAE). These techniques are the Heat Balance (HB) method, the Cooling Load Temperature Difference (CLTD) method, and the Radiant Time Series (RTS) method. The Heat Balance Method is the oldest and most comprehensive method from an engineering standpoint. This method consists of four distinct sub-processes: heat balance of the outside face of the exterior wall, the wall conduction process, the interior wall heat balance, and the air-heat balance. The primary advantage to using the HB method is accuracy, while the major disadvantage of the HB method is that it requires a series of intensive, iterative calculations (Spitler, 2009). This method complicates modeling, especially when the heat model is only one piece of a larger model. Therefore, this complexity is not compatible with conducting large-scale modeling of shelter performance across an entire geographical region.

The CLTD method is a combination of two older modeling methods, known as the Transfer Function Method (TFM) and the Total Equivalent Temperature Differential Method with Time Averaging (TETD/TA). The resulting CLTD method depends on an existing library of previously characterized wall sections for analysis, and fabric wasnot considered during the research. Subjective estimates of the thermal storage characteristics of fabric shelters can be made for use with the CLTD method (ASHRAE, 2009), but these estimates require an experienced engineer and they do not provide the repeatability and conclusiveness necessary for academic research.

The RTS method seeks to preserve the accuracy of the HB method, but instead of using iterative calculations to account for transient effects, the RTS method develops a series of coefficients called the Conduction Time Series and Radiant Time Series factors, to apply at various times of day. The CTS factors characterize the time effects associated with conduction through the roof and walls by quantifying how much heat affects the interior space at each hour after it was first applied to the exterior surface. Similarly, the Radiant Time Series factor characterizes how the space responds to both solar and nonsolar radiation pulses with respect to time. An illustrative overview of the RTS calculation process is provided in Appendix A. This method is less time consuming and produces a more conservative cooling load estimate. The input parameters for modeling structures and climates are also relatively simple when compared to other methods. The major limitation of the RTS method is that time coefficients must be associated with different construction materials; if time coefficients are not already associated with a certain construction material, it can be difficult to develop an appropriate coefficient (Spitler, 2009). The RTS method also tends to over-predict cooling loads for structures constructed primarily of high conductance materials, such as fabric shelters. Previous research identified that this error is due to the lack of accounting for heat transferring back out of the building envelope through windows and other high conductance surfaces. Correction factors for these deficiencies were proposed by Nigusse (2007) to minimize these errors, but they were primarily intended for fenestrations, although potential use for fabric shelter analysis was briefly mentioned in the research (Nigusse, 2007). However, since the correction factors were not verified for use with fabric shelters, the more conservative approach is to consider the RTS method without the proposed correction factors.

Computational fluid dynamics (CFD) have also been used to characterize the thermal characteristics of fabric structures. Harvie (1996) noted that existing methods for assessing the thermal behavior of fabric structures were inadequate, and proposed a model based on CFD concepts and later successfully validated the model against field measurements taken on existing fabric structures. While this method provided good accuracy on a limited number of specific shelters, its complexity did not lend itself to regional analysis of energy consumption.

After considering the three cooling load modeling techniques, the RTS method was considered most appropriate for global analysis of fabric shelters based on its accuracy, ease of use, and required input parameters. Therefore, other cooling load research using RTS methods was studied to gain insight on research applications. Since most cooling load models are developed for practical design use, it was important to establish RTS as an appropriate research tool. In one study, the RTS method was used to calculate cooling loads to select the most appropriate insulating materials for buildings in hot and humid conditions. The cooling loads developed using RTS techniques were combined with energy and construction costs to economically justify the use of certain types of insulation (Aktacir, Byukalaca, & Yilmaz, 2010). This research has close parallels to evaluating the performance of solar flies on fabric shelters, and the fact that Aktacir, Büyükalaca,and Tuncay (2010) used an RTS approach and reached sound research conclusions was promising. In another study, RTS methods were used to evaluate the development of new weather data formats and occupant load profiles for cooling load analysis (Mui & Wong, 2006). Although this research is not directly applicable to cooling load analysis of fabric structures, it further establishes the RTS method as a valid research tool.

GIS Applications to Fully Burdened Fuel and Cooling Load Analysis

An apparent large hole in existing research was found during the literature review concerning the use of geospatial analysis when studying fully-burdened costs. This is surprising since GIS is a well accepted tool in the logistics industry, and logistics problems are often geographic in nature and well suited to geospatial analysis. In fact, many existing GIS software packages have pre-developed transportation network analysis and cost estimating capabilities (Yan, Zhou, & Huang, 2006). Geospatial analysis techniques have also been used extensively in facility energy consumption analysis (Swan & Ugursal, 2009), making it a strong candidate for use in fully burdened energy analysis. Furthermore, extensive, worldwide climate data has been produced in raster format by interpolation of historical weather observations (Hijmans et. al, 2005). This raster data can easily be incorporated into radiant time series modeling, although it appears that this has not been accomplished in existing research. With established successes in logistics and energy, geospatial analysis is clearly a valid tool for analyzing both point use and fully burdened benefits of implementing the SIPSS developed solar flies.

Summary

This chapter established the importance and research need to evaluate the economic effectiveness of implementing expeditionary energy reduction equipment. A review of existing research identified and discussed three major bodies of knowledge applicable to this research: fully burdened cost of fuel analysis, fabric shelter and associated energy reduction equipment, cooling load modeling. When evaluating fuel consumption in a complex logistics system, the point-of-use consumption does not accurately capture the total fuel requirement of a particular activity. Fully burdened fuel cost concepts were discussed to establish the importance of considering system-wide impacts of reducing point-of-use fuel consumption. Fabric shelter construction and contingency applications were discussed to provide an overview of their limitations with respect to energy use. To compensate for high cooling loads associated with fabric shelters, the AFCEC SIPSS program is developing equipment that attempts to reduce the cooling load and fuel consumptions associated with cooling fabric structures. A cooling load model that can be applied at any location worldwide with a minimal amount of meteorological data to evaluate these initiatives would be useful. The RTS cooling load method appears to be the most suitable tool to analyze the cooling loads of fabric structures in contingency environments due to its relative accuracy, ease of use, and simple input requirements. Cooling load estimates will provide the necessary information to estimate point-of-use fuel requirements to cool fabric shelters. In Chapter 3, these three existing bodies of knowledge will be combined in a unique, geospatial method that provides the capability to evaluate the economic benefits of installing SIPSS solar flies on fabric shelters anywhere in the world.

III. Methodology

A method to evaluate the economic effectiveness of installing solar flies on expeditionary fabric shelters is described in this chapter. The subsequent model has two primary components. The first component estimates the point-of-use fuel consumption required to cool a single shelter at any location. Development of this model component involved approximating shelter construction properties and environmental characteristics for use in an Radiant Time Series (RTS) cooling load analysis. Estimated cooling loads developed through this model were used to estimate point-of-use fuel consumptions attributable to heating, ventilating, and air conditioning (HVAC) activities. An existing Excel-based RTS tool developed by Spitler (2009) was adapted for use with global raster climate data to estimate point-of-use fuel consumptions. The second component accounts for the transportation fuel required to supply fuel to the ultimate point-of-use by using Geographic Information System (GIS) transportation network analysis tools. When these two model components are integrated, the total fuel consumption required to cool a single tent can be estimated using Equation 1,

$$\mathrm{F_{Total}} = \mathrm{F_P} + \mathrm{F_T} \tag{1}$$

where F_{Total} is the total fuel consumed in support of HVAC operations, F_P is the point-of-use HVAC fuel consumption, and F_T is the transportation fuel consumption in gallons.

This calculation can be repeated for both standard shelters and shelters with solar flies. Comparisons were drawn between the fuel consumption required to cool the standard shelter versus the shelter with installed energy measures, henceforth referred to as the baseline and test shelter, respectively. An economic payback period analysis and associated sensitivity analysis were performed is proposed to aid in the decision to implement solar flies. This approach is applied to two case studies at the end of Chapter 3. Afghanistan and Brazil were selected as the case studies because of their unique climates and transportation challenges. The methodology presented in this chapter is easily repeatable with other regions or types of energy equipment, so additional case studies could be produced in future research.

HVAC Point-of-Use Fuel Consumption Analysis

As noted in Equation 1, the first component of total fuel consumed due to HVAC operation is the point-of-use consumption by the Field Deployable Environmental Control Unit (FDECU) itself. A cooling load model was developed to estimate the point-of-use fuel consumption based on the performance of shelters tested in the Solar Integrated Powered Shelter System (SIPSS) program. Therefore, a detailed description of the SIPSS testing program and data is presented before discussing the methodology. After this review, the fabric shelter model construction and environmental factors pertinent to RTS analysis are discussed. An RTS analysis tool developed by Spitler provided the software necessary to develop and analyze this model. Model performance was validated by comparison to field data from the SIPSS tests, after which global applications of the RTS model using GIS raster climate data are discussed.

Data Collection

The testing methods and a review of the data produced by the SIPSS test program are reviewed in this section. The SIPSS program conducted many tests and produced a wealth of data. The process of selecting which tests and data to use is outlined below.

SIPSS Testing and Data Collection

Although a brief overview of the SIPSS program is provided in Chapter 2, additional technical detail is required to better understand the data generated during the test program. The 2011 SIPSS program tested a wide-range of equipment across an entire year. Due to the immense amount of data generated across all of the different types of shelters and equipment, only one type of shelter and one energy reduction initiative were selected from the SIPSS tests for analysis. The program divides shelters into gable and barrel styles based on their outward appearance and structure. Gable shelters are characterized by a series of flat, fabric walls that adjoin to form the tent, while barrel structures are identified by the long arch that is present across the width of the tent. Barrel shelters typically only have two flat surfaces, which are the walls on either end of the shelter. Since the Alaska Small Shelter System (SSS), the current standard expeditionary shelter for the U.S. Air Force, is a barrel shelter, barrel shelters were the focus of this research effort.

In 2011, energy reduction tests were conducted on barrel shelters equipped with various energy reduction technologies. The testing schedule is shown in Table 1. In order to simplify the requirements of the initial model, Test 6 was identified as the most suitable configuration because of its simplicity. The baseline shelter in Test 6 is a standard barrel shelter and ECU system comparable to the Alaska SSS described in Chapter 2, while the test shelter includes a solar fly that was installed on the standard shelter. The standard liner and ECU were still used with both the baseline and test shelters, so any energy savings seen in the test can be attributed directly to the solar fly. Other tests combine multiple types of energy reduction equipment simulataneously. Although these additional configurations were beneficial to the SIPSS program, it increases the complexity of the cooling load model when multiple changes are made to the structure. For this reason, the current research effort is limited to the shelters described in Test 6 of the 2011 SIPSS program.

Table 1. SIPSS test schedule for barrel style shelters (AFCESA, 2011)

Test Schedule at Ft. Irwin, CA			
Test	**Barrel Style Baseline Shelter**	**Barrel Style Test Shelter**	**Test Duration**
1	**No Fly (Standard Liner-B and ECU-A)**	**No Fly (Inflatable Reflective Liner and ECU-A)**	**10 Jan - 1 Mar**
2	**No Fly (Standard Liner-B and ECU-A)**	**No Fly (PCM Liner and ECU-A)**	**1 - 29 Mar**
3	**No Fly (Standard Liner-B and ECU-A)**	**Solar Mesh Fly-B (PCM Liner and ECU-A)**	**29 Mar - 3 May**
4	**No Fly (Standard Liner-B and ECU-A)**	**Solar Mesh Fly-B (PCM Liner and ECU-A)**	**3 May - 7 Jun**
5	**No Fly (Standard Liner-B and ECU-A)**	**Solar Mesh Fly-B (PCM Liner and ECU-A)**	**7 Jun - 11 Jul**
6	**No Fly (Standard Liner-B and ECU-A)**	**Solar Mesh Fly-B (Standard Liner-B and ECU-A)**	**11 Jul - 2 Aug**
7	**No Fly (Standard Liner-B and ECU-A)**	**Solar Mesh Fly-B (Inflatable Reflective Liner and ECU-A)**	**2 - 30 Aug**
8	**Solar Mesh Fly-B (Quilted Liner-B and ECU-A)**	**Solar Mesh Fly-B (Quilted Liner-B and ECU-A)**	**30 Aug - 21 Sep**
8b	**ECU-A (2 Shelters)**		**23 -26 Sep**
8c	**ECU-B (2 Shelters)**		**26 -30 Sep**

Test 6 was conducted from 11 July 2011 to 2 August 2011. Shelters were installed according to the manufacturer's instructions in an east-west longitudinal orientation at Logistics Supply Area Warrior at Fort Irwin. Each shelter contained a data box that housed data acquisition systems to collect 14 different parameters associated with each shelter. These data boxes were then connected to a central data acquisition box that recorded all shelter and environmental data and allowed for remote monitoring and access (Fisher & Keith, Solar Integrated Power Shelter System, 2011). Although the full dataset included data in 10-second intervals for a wide-range of parameters, data was provided for 15-minute and 1-hour intervals for ambient outdoor temperature, indoor temperature for both baseline and test shelters, ECU power demand for baseline and test shelters, and photovoltaic power output when applicable. Ultimately, the 1-hour incremented data were used in model development because of high levels of noise in the smaller increments. Data were provided in two main formats. Raw data for a number of days were provided to analyze diurnal power cycles. Additionally, summarized data were provided that was presorted into degree-day groups. This sorting technique ensured that comparisons between shelter configurations were made in similar ambient temperature conditions.

Several days worth of data were not considered for analysis due to variations in the data. For example, the indoor temperature increased rapidly at some points during testing. The shelter door was opened and potentially remained open during many these temperature increases, so these occurrences invalidate the data for use in developing a cooling load model. Ultimately, one day of data was selected for analysis because it exhibited no variations due to unwanted factors, and it also produced the lowest potential energy savings so that research conclusions are based on the most conservative results possible.

Data Review

A standard pattern can be found in the data for each daily test; a representative example is shown in Figure 4. As expected, the ambient temperature adheres to a standard diurnal cycle. Cooling loads typically exhibit minimum amplitudes of approximately 3.5 kilowatts between midnight and approximately 7:00 a.m. local time each day. This power usage is attributed to the continuous operation of the circulation fan with little or no operation of the heat pump. Power use typically peaked near 3:00 p.m. local time each day with typical maximum values near 25,000 Btu/hour, or 8 kilowatts. It is important to note that power maximums typically lead the maximum ambient temperature by 2 to 4 hours; this fact will be important during discussion of Radiant Time Series Method applications. After examining the data, development of a fabric shelter model focused on mimicking the behavior of the measured ECU power.

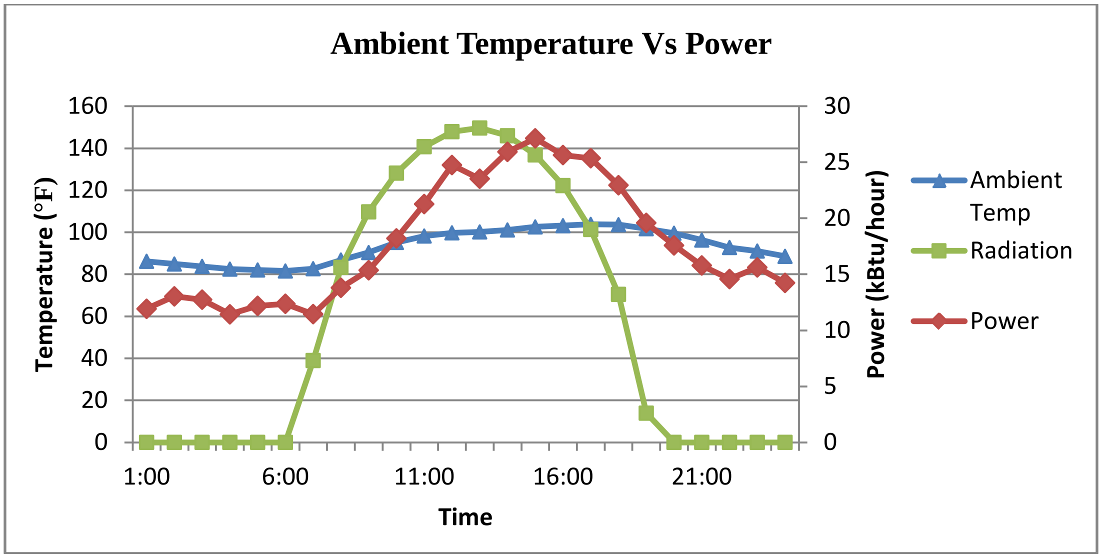


Figure 4. Graphic Data From Shelter Tests (AFCESA, 2011)

Model Development

There are four major factors pertinent to this research that affect RTS analysis: shelter geometry, fabric material properties, environmental characteristics, and additional loads related to interior loads and infiltration. RTS-based cooling load models have a variety of parameters related to these four factors. Each of the subject areas and their respective parameters are discussed below.

Shelter Construction

The characteristics of the SSS were approximated to simplify many aspects of RTS modeling. Many RTS calculations depend on calculating the incident angle of solar radiation on tent surfaces. Since the curvature of the main wall and roof of the shelter would make these calculations extremely complex, the shelter was approximated as a half-decagon with side lengths of 4.83 feet and interior angles of 144 degrees to simplify the model. These surfaces stretch the full 32.5-foot length of the shelter. No fenestrations were included in the model shelter; although windows are included on some shelters, they are usually left closed and consist of the same fabric as the rest of the tent. Typical shelters consist of two fabric layers. One layer forms the exterior surface of the shelter, while the other acts as an insulating liner to create an air gap between the exterior surface and the conditioned space of the tent. This gap was estimated to be 3 inches, although the actual distance varies between the aluminum frame members of the tent. Thermal bridging effects due to the aluminum frame were not considered in the model.

Table 2. Wall Characteristics of Fabric Shelter Model

Surface ID	1	2	3	4	5	6	7
Surface Name	East 1	West 1	North 1	North 2	Roof	South 1	South 2
Surface Type	Wall	Wall	Wall	Wall	Roof	Wall	Wall
Facing Direction (°)	90	270	360	360	0	180	180
Tilt Angle (°)	90	90	72	36	0	72	36
Area (square feet)	157	157	198.9	198.9	198.9	198.9	198.9

Material Properties

Since specific material properties were not provided by Alaska Shelters due to proprietary concerns, they were estimated based on known specifications of similar polyvinyl chloride-coated fabrics found in existing literature and are displayed in Table 3 (U.S. Army Natick Soldier RD&E Center, 2012; Devulder, Wilson, & Chilton, 2007). These properties were used to develop a simulated tent fabric material for modeling purposes. The overall tent wall of the baseline structure was then modeled as a five layer surface: an exterior air boundary layer, a tent fabric layer, an insulating air gap layer, an insulating liner layer, and an interior air boundary layer. For the test shelter, the solar fly was modeled as an additional layer of PVC coated polyester with an air gap of 3 inches between the exterior fabric and the solar fly. Solar absorption was set to a value of 0.18 based on prior research into optical properties of PVC coated polyester (Harvie, 1996). No existing data on the emissivity of fabric structures was found; therefore, the emissivity was set at the industry standard of 0.90 for normal construction materials (ASHRAE, 2009).

Table 3. Estimated Material Properties of Fabric

Property	Unit	Value
Thickness	in	0.0625
Thermal Conductance	$(\frac{Btu \bullet in}{hr \bullet ft^2 \bullet °F})$	1.317
Density	$(\frac{lb}{ft^3})$	134.2
Specific Heat	$(\frac{Btu}{lb \bullet °F})$	0.287
Thermal Resistance	$\frac{(hr \bullet ft^2 \bullet °F)}{Btu}$	0.0475

Environmental Characteristics

The Excel-based RTS modeling tool provided by Spitler (2009) contains an extensive library of geographic locations and climate data for much of North America. Although the library was modified for global use later in the research, the preexisting climate library was used for model validation. The climate library contains 0.4%, 1%, and 2% monthly design data for dry-bulb, wet-bulb, and daily temperature ranges. The percentage references how often the observed weather exceeds the design data. For example, a 2% maximum design temperature means that the actual daily high temperature will exceed the listed temperature 2% of the days in any given year. Additional parameters include time zone, latitude, longitude, ground reflectance, and clearness indices for developing solar irradiation effects. Since the SIPSS program datasets were collected at Fort Irwin, model development was based on the 2% design data for Daggett, California, which is approximately 30 miles southwest of Fort Irwin (Spitler, 2009). This is the closest location to Fort Irwin for which the dataset contains all parameters necessary to conduct RTS analysis. It is important to note that average climatic data was used to develop the shelter model; however, the actual test data used for model comparison reflects real weather recorded on a specific day. The ground reflectance was set to a value of 0.20 to simulate a crushed rock ground covering (Spitler, 2009), which is typical for most contingency shelter base camps.

Interior Cooling Loads and Infiltration

Interior cooling loads can be added to the model through the RTS tool as necessary. These loads include occupants, lighting, and equipment. The SIPSS data involved loads of these types during some tests, but it was difficult to determine from the data when specific loads were applied. Therefore, the model was developed without interior loads and was compared to field test data that also excluded interior loads. These interior loads are relatively inconsequential when compared to the extreme exterior loads of the desert summer climate at Fort Irwin. A relatively unbiased characterization of shelter materials and construction is still possible even though this parameter was removed from the model.

Infiltration is also a problematic parameter for building an expeditionary cooling load model; no infiltration data was available regarding the small shelter system. Varying wind directions and velocities could cause infiltration values to change considerably. This is especially relevant given the intent to implement the shelter cooling load model around the world. Availability of worldwide wind data and increases in associated model complexity drove a decision to use a fixed estimate of infiltration for the initial model. Infiltration was estimated at 2.5 air changes per hour based on the high end of residential construction infiltration value distributions (Spitler, 2009). This value is likely too low; however, it was the best value that was found in existing literature.

FDECU Conditions

During the model building process, a discrepancy was noted between the estimated cooling load and the measured FDECU power demand during the overnight hours. The FDECU power rarely fell below 12,000 Btu per hour, while the cooling load fell to nearly zero at night. This discrepancy was attributed to the fact that the ventilation fan of the FDECU remains on even when the thermostat has been satisfied and the heat pump turns off. The proposed remedy for this issue was to establish an adjustment in the model that prevents the estimated cooling load from falling below 12,000 Btu per hour when the original RTS estimate is between 0 and 12,000 Btu per hour. Once the RTS estimated cooling load falls below 0 Btu per hour, the model output is fixed at 0 Btu per hour to simulate turning the air conditioning off. It should be noted that heating loads would begin to affect the shelter power use at this point, but these loads were not considered during this research. The FDECU conditions are summarized in Table 4.

Table 4. FDECU Model Conditions

RTS Estimate (RTSE)	FDECU Condition	Model Output
RTSE ≤ 0 Btu/hr	FDECU Off	0 Btu/hr
0 Btu/hr ≤ RTSE ≤ 12,000 Btu/hr	Fan On, Heat Pump Off	12,000 Btu/hr
RTSE > 12,000 Btu/hr	Fan On, Heat Pump On	RTSE

Cooling Load Coefficient Development

The tent model described above was analyzed to determine the Conduction Time Series Factors (CTSF), Radiant Time Factors (RTF), and sol-air temperatures. These values describe how a shelter responds to radiation loads across a 24-hour period, as discussed in Chapter 2. These interim characteristics are useful for determining if the shelter model is performing as expected. CTSFs and RTFs generated for the baseline and test shelters using the Excel-based RTS tool are shown in Figure 5 through Figure 8. It is clear from the figures that cooling loads pass through the shelter wall and impact the interior space soon after affecting the exterior of the shelter. This is expected due to the shelter's low thermal mass and the low specific heat of the construction materials. It can also be seen that the solar fly on the test shelter slightly delays the transfer of radiation energy from the exterior to the interior of the shelter. This is most noticeable in first hour, in which the baseline shelter CTSF is 0.87, while the test shelter CTSF is 0.73. Overall, these characteristics confirm that the model performed as expected with very quick response to exterior radiation.

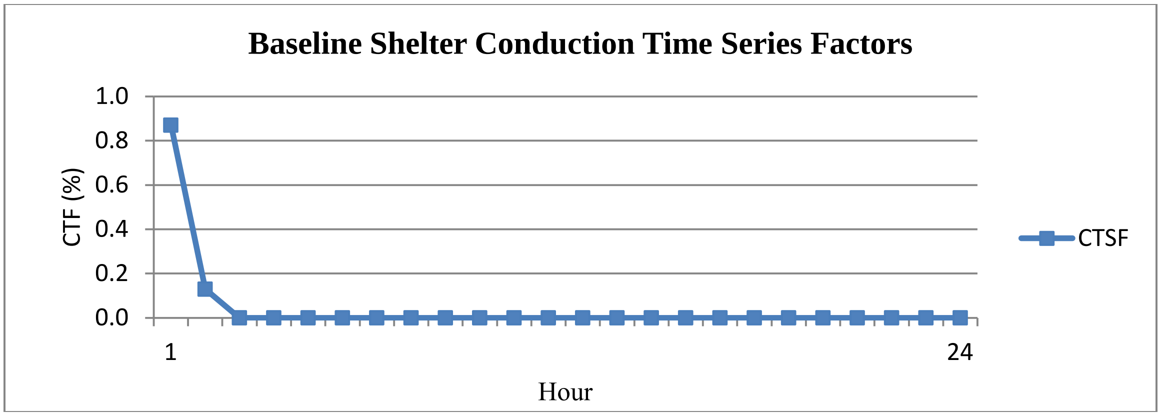


Figure 5. Conduction Time Series Factors for the Baseline Shelter

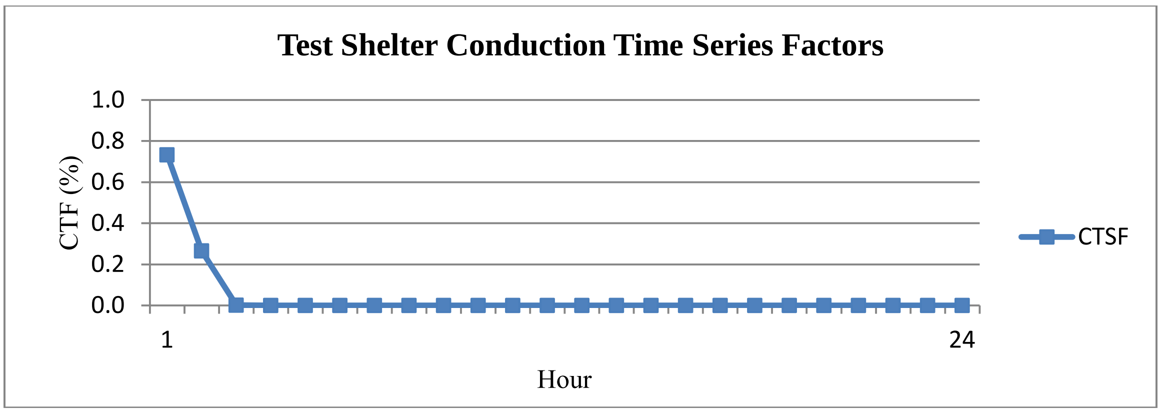


Figure 6. Conduction Time Series Factors for the Test Shelter

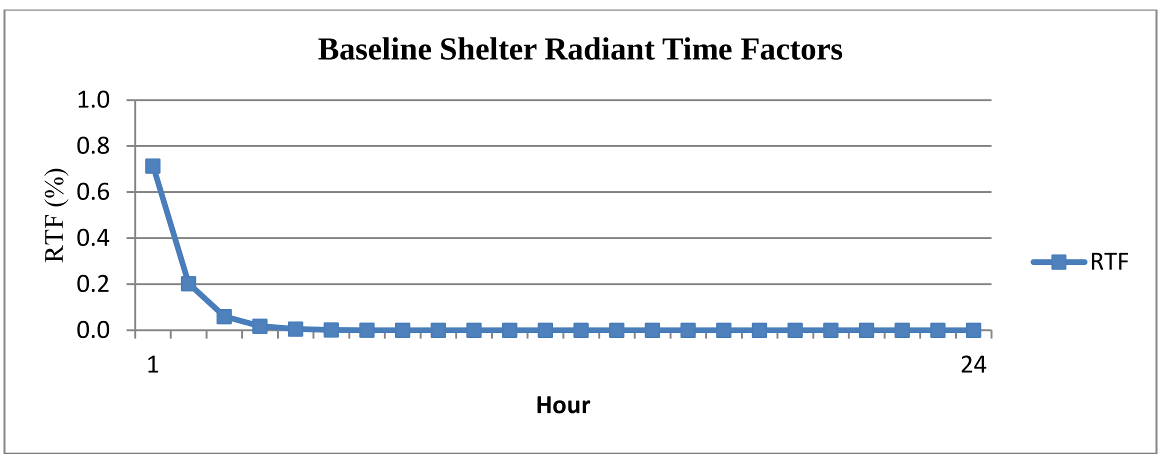


Figure 7. Radiant Time Series Factors for Baseline Shelter

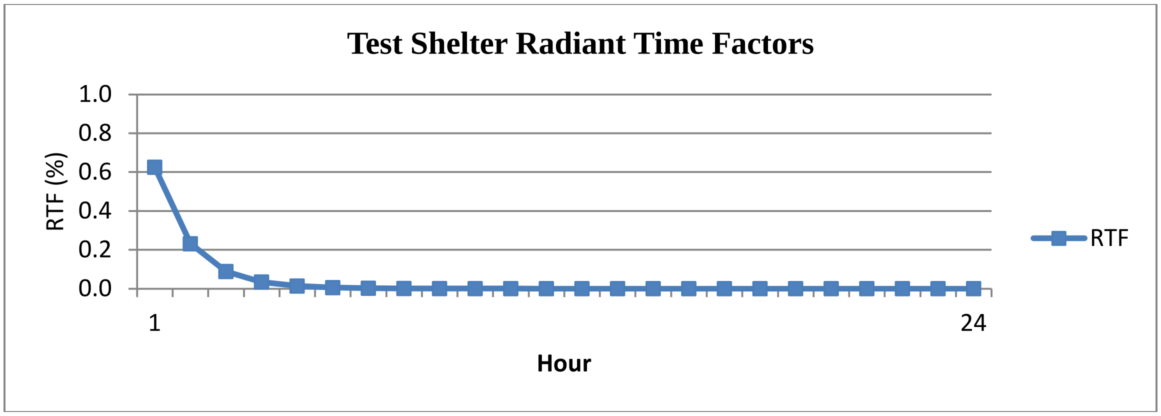


Figure 8. Radiant Time Series Factors for Test Shelter

Sol Air Temperature

Sol-air temperature calculations are an important sub-component of the overall RTS method. The sol-air temperature is a parameter that seeks to approximate a temperature necessary to mimic the effects of both the ambient temperature and radiation effects on the exterior surface of the shelter. The first step in calculating sol-air temperatures is to determine the incident radiation on the shelter. This process involves complex geometry to calculate the angle of the sun upon each surface of the shelter. Ensuring that the shelter geometry, time, and geographic location are correct in the model is essential to ensuring the accuracy of the model. The model results of the sol-air temperatures for a shelter at Fort Irwin are shown in Figure 9. Since sol-air temperatures are calculated only at the exterior surface of the shelter, both the baseline and test shelters exhibit identical behavior with respect to sol-air temperature. The behavior of this model agrees with the actual data because it results in a peak cooling load that occurs between peak solar radiation and peak ambient temperature. Additionally, the sol-air temperatures behave logically with respect to common knowledge of the sun's path across the sky.

The highest sol-air temperatures in the morning are seen on the east wall, while the highest temperatures in the afternoon are seen on the west wall. The review of this interim model information verified that the shelter model was constructed correctly and performed as expected. Since there are no obvious errors in the model construction, the next step was to compare estimates of required power for air conditioning to the field test data provided by the SIPSS program.

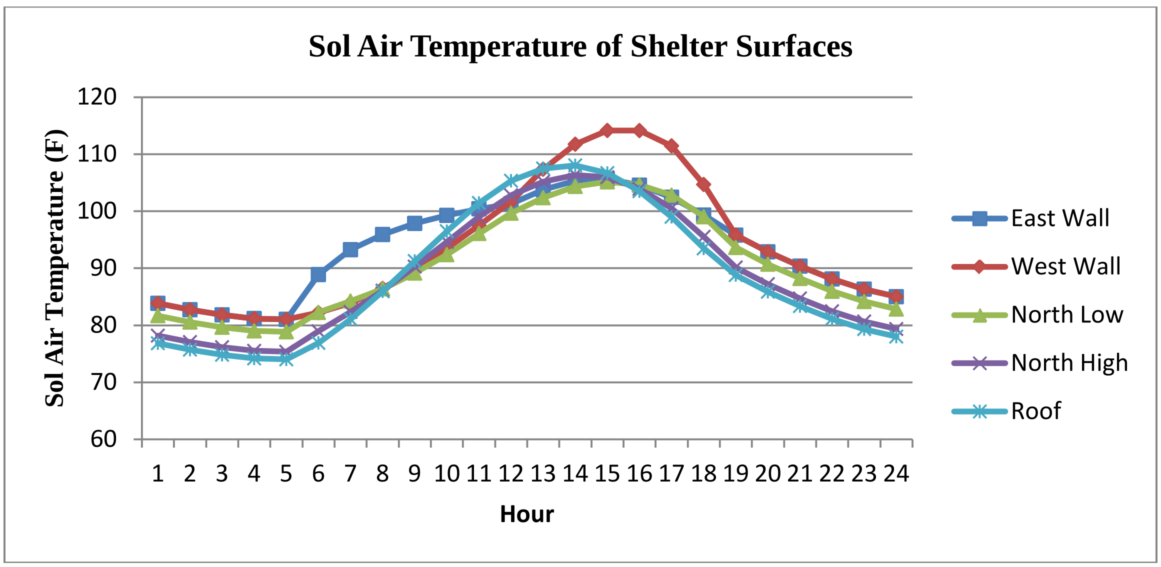


Figure 9. Calculated Sol Air Temperatures

<u>Validation</u>

After verification of the interim shelter characteristics, the cooling load analysis was performed on the baseline and test shelter models. The cooling load prediction and the measured test data are shown for both the baseline and test shelters in Figure 10 and Figure 11 for comparison. For the baseline shelter, the model slightly under predicted the total daily load by 4.5% when compared to the field test data, while the peak load was overestimated by 6.0%. Statistical correlation between the full model and field test data resulted in an R^2 value of 0.93. For the test shelter model with the energy reducing solar fly installed, the total daily load was under predicted by 7.8%, with the peak load being overestimated by 0.3%; this yielded an R^2 value of 0.75 when compared to the test shelter data. The timing of peak loads was predicted well in both baseline and solar fly equipped models, with no deviation between the model and the field test data.

The underestimation of the total daily load is slightly concerning since this is the metric that will ultimately be used when the model is applied regionally to evaluate the energy savings potential of the solar flies. One potential explanation for this discrepancy is the effect of ground heating, which is compounded by the fact that no thermal insulation is provided for the floor of the tent. Ground temperatures rise rapidly in the morning and often store energy well into the night, and some of this energy is transferred to the shelter through the floor. This would explain the early increase of cooling loads in the morning and the delayed decrease of cooling loads in the evening shown in the model estimates. However, there is currently no data to confirm that ground heat is the causal factor in this issue. This discrepancy will be noted in future research when the model is applied to predict energy savings. The model error seen in the peak loads was expected and it is explained by Nigusse's findings in 2007 regarding high conductance surfaces. Peak load amplitudes and timing are important to establishing model validity; since the results were consistent with existing literature, and since peak loads will be used for model comparison purposes only, model adjustments were not considered necessary. Although the primary purpose of this initial comparison was to validate the model for future use, it is interesting to note that the model predicted a 15.7% energy savings associated with installing solar flies, compared to actual energy savings of 12.6% from the field test data.

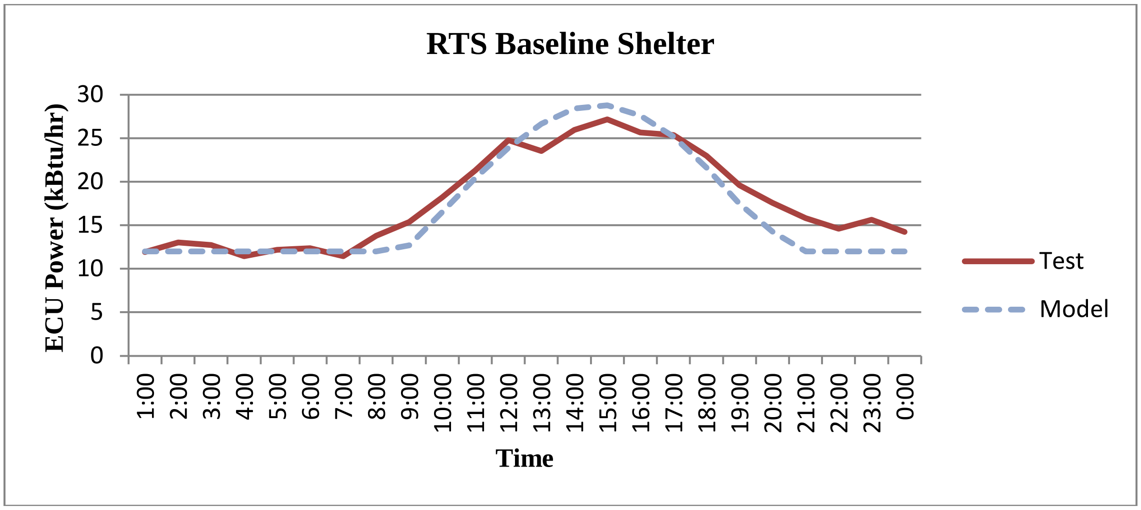


Figure 10. Cooling Load Model Estimates and Test Data for the Baseline Shelter

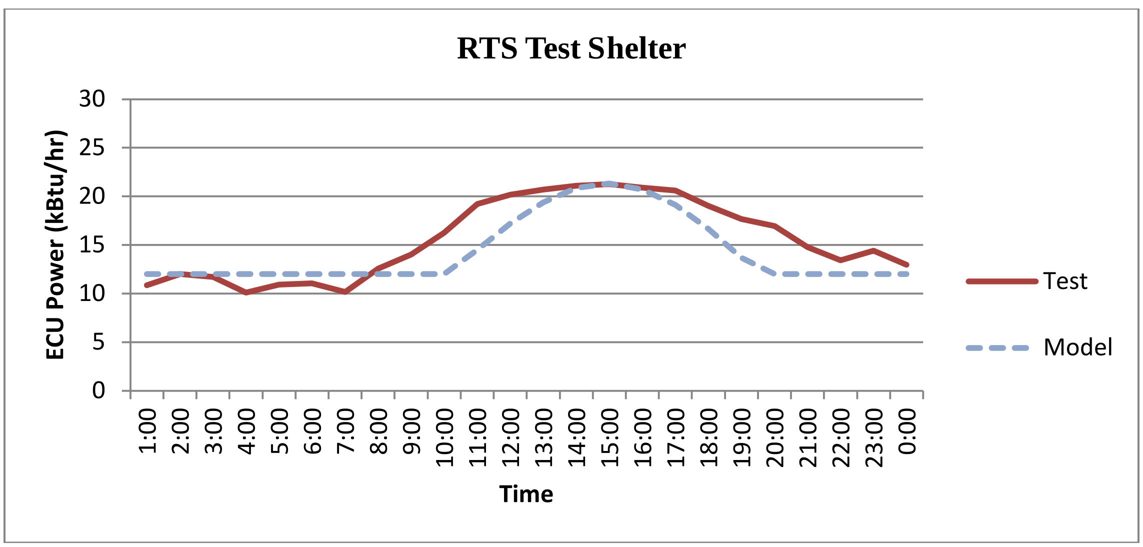


Figure 11. Cooling Load Model Estimates and Test Data for the Test Shelter

The relatively high correlations between model estimates and test data and low average error in daily consumptions proved this model to be more accurate than any other method attempted during this research. A steady-state model was also developed using the same material properties for comparison to the RTS model. As expected, it performed very poorly in comparison to the RTS models. The expected peak load had an error of 50% when compared to the test data for a baseline shelter with no installed solar fly. This confirms the idea that steady-state modeling is not a good tool for modeling cooling loads, even in low thermal storage structures. Additionally, the peak load in the steady-state model occurs three hours after the peak load in the test data. The main problem with the steady-state model is that it does not account for solar radiation effects on the cooling load. Radiation effects would greatly increase the cooling load, as well as shift it earlier in the day. Based on these results, the steady-state model received no further consideration for use in energy reduction models. Based on the relative success of the RTS shelter model and its ability to integrate with GIS raster data, it was used in all research from this point forward. With a validated cooling load model for fabric shelters established, attention was turned to integrating the new model with GIS techniques to develop a worldwide analysis capability.

Application to Global Environments

The RTS modeling tool provided by Spitler (2009) is an excellent way to estimate cooling loads for the North American locations contained in the existing climate library. However, the tool, in its existing format, is not suitable for analysis of large regions. In order to perform a regional analysis, data for specific point locations would need to be retrieved from a weather database and be entered manually into the climate library. Then, the entire RTS tool would need to be run for each individual location. After this was accomplished, the user would be left with cooling load estimates at discrete geographic points, with no established or validated method to interpolate between the locations. Since this model is being developed for specific use in austere regions, it must accommodate large areas with very little known weather data. Reliance on manually entering weather data associated with a high number of discrete points would cause the model to be impractical due to time constraints. Geospatial data and analysis techniques provide an opportunity to quickly evaluate fabric shelter cooling loads in austere regions. However, some manipulation of geospatial data is required to process it through the RTS modeling tool.

Using GIS Raster Data

Fortunately, climatologist, meteorologists, and mathematicians have already developed accurate methods of interpolating climate data. Spatially interpolated climate datasets are already used for a number of applications such as agriculture and environmental protection. Typically, climate data is interpolated in a grid format, also known as climate surfaces (Hijmans, Cameron, Parra, Jones, & Jarvis, 2005). These grids are geo-referenced so that they correspond to specific locations when overlaid on a map. Datasets are saved in raster format, which is a pixilated image that has an intensity indicator, such as a number or color. An organization called WorldClim collected much of the recorded weather history from across the world and spatially interpolated 22 climate factors using methods developed by Hijmans et al. (2005). An example of a global maximum temperature raster is shown in Figure 12.

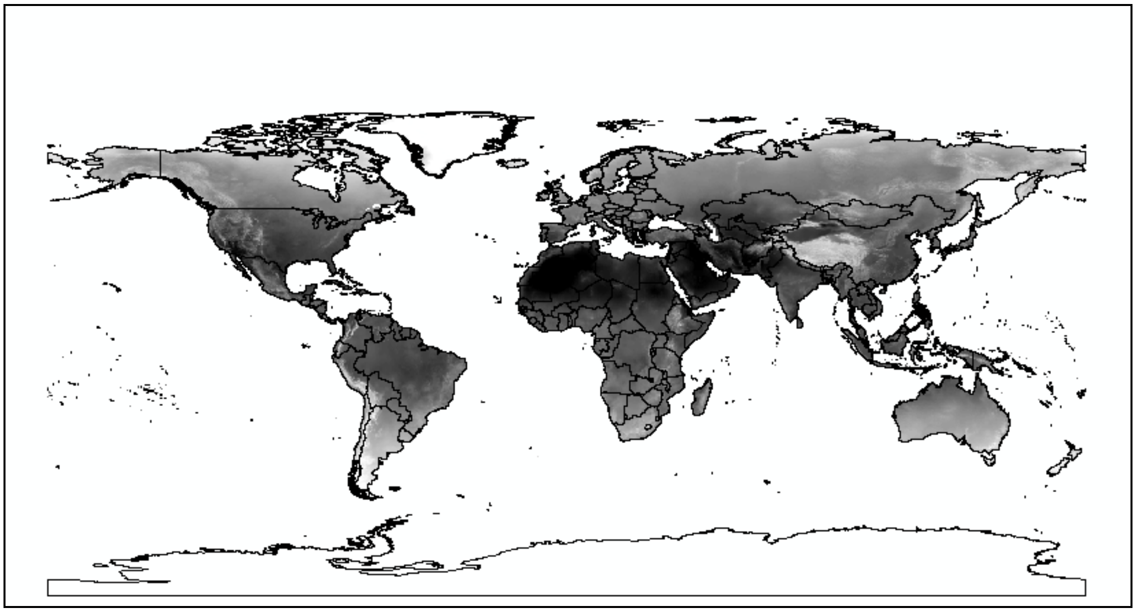


Figure 12. Global Raster Image for Maximum Temperature During July

For the purposes of this research, maximum temperature, minimum temperature, and elevation raster files were downloaded from WorldClim. These files were developed by researchers used a software package known as ANUSPLIN to perform a Spline A interpolation of the weather data that was collected at discrete points across the world (Hijmans, Cameron, Parra, Jones, & Jarvis, 2005). The result of interpolation is a global raster map that geographically shows the value of each of the climate parameters.

The datasets are available in several different resolutions, ranging from 30 arc-seconds to 10-arc minutes. Since the current research is concerned with energy analysis on a regional scale, very high resolution datasets were unnecessary. In fact, even the 10 arc-minute detail was a higher resolution than necessary for regional analysis, and the computing power required to conduct regional analysis with high resolution data was not available. For these reasons, the 10-arc minute data was converted to 100 kilometer by 100 kilometer zones. Conversion to the larger grid provided a better analysis product for regional energy reduction decisions. The 100-kilometer grids were created by overlaying the Military Grid Reference System (MGRS) on areas of interest. The MGRS is the most widely used geographic projection and reference system in the U.S. military, and it is based on the World Geodetic System 84 coordinate system, so information presented in this format is widely accepted and understood. After the overlay process, the mean for each parameter was calculated by averaging the raster data inside each grid cell through a zonal GIS process. Also, the geographic coordinates were calculated for the center of each grid cell for inclusion in the climate library. The resulting dataset includes a specific geographic location, elevation, maximum temperature, and minimum temperature for each grid cell. In Figure 13, the map on the left shows the original dry-bulb raster data for maximum temperatures in July for Afghanistan. The map on the right shows the MGRS grid overlaid over the country, and the mean dry-bulb temperature averaged within each grid.

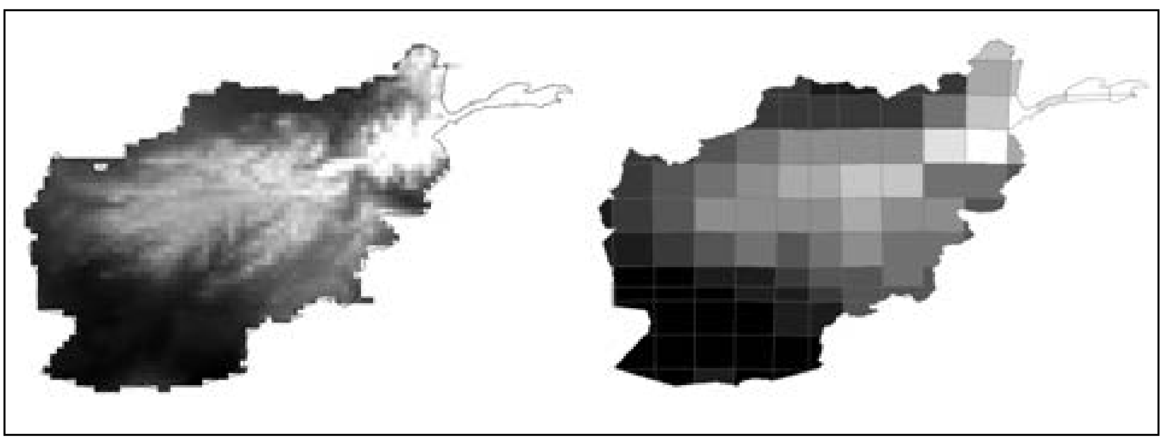


Figure 13. Raster and MGRS Zonal Maximum Temperature Data

Data Conversion

The temperature data provided by WorldClim was in units of degrees Celsius times a factor of ten for data management purposes. After adjusting for this factor, the data was converted to degrees Fahrenheit for use with the RTS tool. Mean daily temperature range is a parameter required by the RTS but not provided by WorldClim. Therefore, the mean temperature range was calculated by subtracting the mean daily minimum temperature from the mean daily maximum temperature. Elevation data were provided by WorldClim in meters; it was converted to feet for use with the RTS tool. The only remaining parameter needed for RTS calculation was the wet-bulb temperature. Unfortunately, this dataset was not provided by WorldClim in any form. For each of the case studies then, historical humidity ratio data was downloaded from the Air Force Weather Agency for every available point inside the country of interest. However, the humidity ratio data cannot be interpolated directly to wet-bulb temperature because it sometimes results in wet-bulb temperatures that exceed the dry-bulb temperature. Instead, the humidity ratio was converted to relative humidity in a 2-step process. In the first step, Equation 2 was used to convert the humidity ratio to the partial pressure of vapor at the dry-bulb temperature,

$$W = 0.621945\left(\frac{p_w}{p - p_w}\right) \tag{2}$$

where W is the humidity ratio, p_w is the partial pressure of water vapor in air, and p is the total air pressure. The relative humidity was then calculated using Equation 3,

$$\theta = \left(\frac{p_w}{p_{ws}}\right) \tag{3}$$

where Θ is the relative humidity and p_{ws} is the partial pressure of water vapor at saturation.

The resulting relative humidity was interpolated using an Inverse Distance Weighting (IDW) tool within ArcGIS, a GIS software package produced by Esri. Although IDW methods are not the most accurate techniques for interpolating weather data, they are recognized in literature as acceptable methods and are often desirable because of their relative simplicity (Hartkamp, De Beurs, Stein, & White, 1999). After the relative humidity was interpolated, it was converted back into a wet-bulb temperature by using Equation 4,

$$T_{WB} = T * \text{atan}[.0151977(\Theta + 8.313659)^{1/2} + \text{atan}\,(T + \Theta) - \text{atan}\,(\Theta - 1.676331) + .00391838(RH)^{3/2} \times \text{atan}\,(0.023101\Theta - 4.686035 \quad (4)$$

where T_{WB} is the wet-bulb temperature and T is the dry bulb temperature. This equation was used because there is no simple analytical solution to calculate wet-bulb temperature from dry-bulb temperature and relative humidity (Stull, 2011). After this conversion is performed for all grid zones in the region of interest, all climate datasets were in the appropriate format for use in the RTS modeling tool.

RTS Modeling Execution

A master data spreadsheet was developed to manage all of the climate data and the conversions discussed above. It was crucial to ensure that each geographic location remained associated with the correct climate data because any errors in the database could cause data to be associated with an incorrect grid zone. Inside the Excel-based

RTS modeling tool provided by Spitler (2009), the master data sheet was imported into a new tab for each region of interest. The preexisting climate library in the RTS tool was then repopulated by linking to the master data sheet. Since the RTS tool was only designed to run one location at a time, an Excel macro was written to execute cooling load analysis on each region without manually changing the region for each run. This feature significantly reduced the manual workload required to analyze large regions. Using the climate data and shelter model construction discussed in this chapter, the RTS modeling tool was executed to estimate average daily cooling loads for both the baseline and test shelters in each grid zone in the countries of interest.

Estimating Point-of-Use Fuel Consumption for HVAC

The cooling loads produced by the RTS modeling tool were used to estimate overall fuel consumption required to power a single FDECU for an entire year. This was accomplished by applying the energy density of diesel against the estimated cooling loads to determine point-of-use fuel consumption. The energy density of diesel was used to estimate how much fuel was required to offset the RTS calculated cooling load. However, a correction factor was applied to account for the inefficiency involved in powering an ECU with a generator. The MEP-012A generator was selected to develop the correction factor because it is the standard Air Force prime power generator for expeditionary use. It produces 750 kilowatts at full load with an associated fuel consumption of 55 gallons per hour (Department of the Air Force, 2008). In this case, it is helpful to quantify the generator capability in units of energy instead of power. The 750 kilowatts of power is equivalent to 2,700,000 kilo-Joules per hour. Dividing this number by 55 gallons per hour and converting to inch-pound units reveals an adjusted energy density of diesel of 46,528 Btu per gallon. This adjusted energy density quantifies only the portion of energy density that is actually converted to electrical power. In other words, only about 37.9 percent of the energy contained in a gallon of diesel can be converted to electrical power by the generator. This efficiency is an important consideration when considering fuel reduction initiatives because the savings is compounded when the inefficiencies of the generator are considered. The power loss in the distribution system was not included in the analysis since it varies with distribution distance, but it can typically be estimated at 5%. The end result of this process is the calculation of the total amount of fuel required to cool one shelter for an entire year. This quantity is calculated for each 100-kilometer grid zone specified in the model. Now that an annual fuel consumption required to cool a tent has been developed for every grid zone in the region of interest, attention can be turned to calculating the transportation fuel consumption associated with HVAC activities.

Transportation Fuel Consumption Model Development

As discussed in Chapter 2, the point-of-use fuel consumption contributes only a portion to the overall fully burdened fuel costs required to support HVAC capability within the larger logistics system. The total fuel consumption, which includes point-of-use and transportation components, must be calculated to account for the system-wide effects of HVAC fuel consumption before fully burdened costs can be calculated. With a methodology to estimate point-of-use consumption in place, attention was turned to transportation consumption. This component accounts for the fuel consumed to transport supply fuel to its ultimate point of use. Two major types of transportation were considered for this analysis. Transportation costs associated with ground travel were estimated using the Network Analyst tool in the ArcGIS software package, which calculates total distance between a point of origin and all other possible points in the region of interest based on the road network of the region under study. A transportation rate cost was developed to apply to the GIS calculated distance for purposes of calculating the total fuel consumed in the logistics system. For areas that are not serviced by roads, a similar air transportation cost was developed. The overall transportation costs were then combined with the point-of-use HVAC consumption to calculate the total fuel consumption needed to cool one tent.

GIS Transportation Network

For ground transportation, an organization called DIVA-GIS provided road shape file data for most countries in the world. These shape files were processed using the network analyst toolset in ArcGIS for the case studies of Afghanistan and Brazil. ArcGIS was used to build the transportation network from these shape files. The network analyst toolset combines all interconnecting roads and places nodes at their intersections. Instead of viewing each road individually, the software views all roads as one transportation network after this step is accomplished.

Distance Calculations

It is important to establish the boundaries of the logistics system early in the network building process. Boundaries can be established based on existing political boundaries, geographic features, or any other criteria selected by the user. For the purposes of this research, the borders of the country being examined were chosen as the system boundaries. This choice provides a relatively simple system boundary and limits the complexity of analysis; conversely, it ignores all costs associated with transporting fuel until the fuel arrives in the country being studied. While this ignores significant costs that occur outside the system boundaries, this simplification allowed focus to be placed on the energy reduction effects of implementing solar flies in the case study countries. The costs incurred outside of the system boundaries were accounted for through a cost sensitivity analysis that is discussed later in this chapter.

Points of origin must be selected early in the process to indicate the location at which fuel enters the modeled transportation system. Definition of the points of origin does not have to be exact; however, it should reasonably account for where the majority of fuel enters the defined logistics system boundaries. For the case studies in this research, the origination locations for Afghanistan were defined as the four major ground ports of entry (POE). The POEs are the locations at which most supplies entering Afghanistan cross the border. Although there are additional POEs, the four major ones used in this analysis were Chaman, Torkham/Khyber Pass, Shir Khan Bandar, and Hairatan, shown in Figure 14.

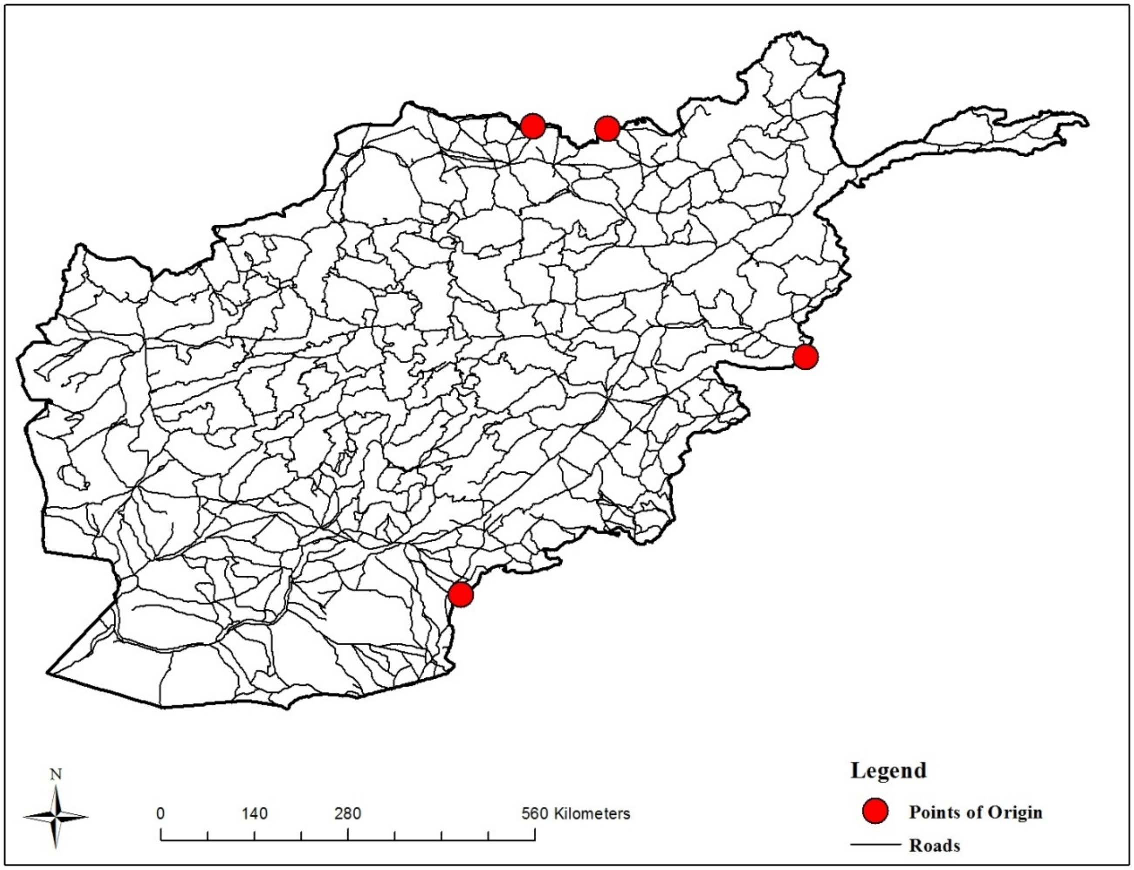


Figure 14. Point of Origins and road network in Afghanistan

Since Brazil is a net exporter of fuel, the origination locations were defined as the major petroleum refining areas in the country. All refinery operations in Brazil exceeding 100,000 barrels of petroleum per day were included, with two exceptions. Betim and Araucaria (Oil & Gas Journal, 2012) were excluded from the origination set because of difficulties adding nodes to the transportation system in these areas. The locations added to the system were Canoas, Paulínia, São José dos Campos, Cubatão, and São Francisco do Conde, shown in Figure 15.

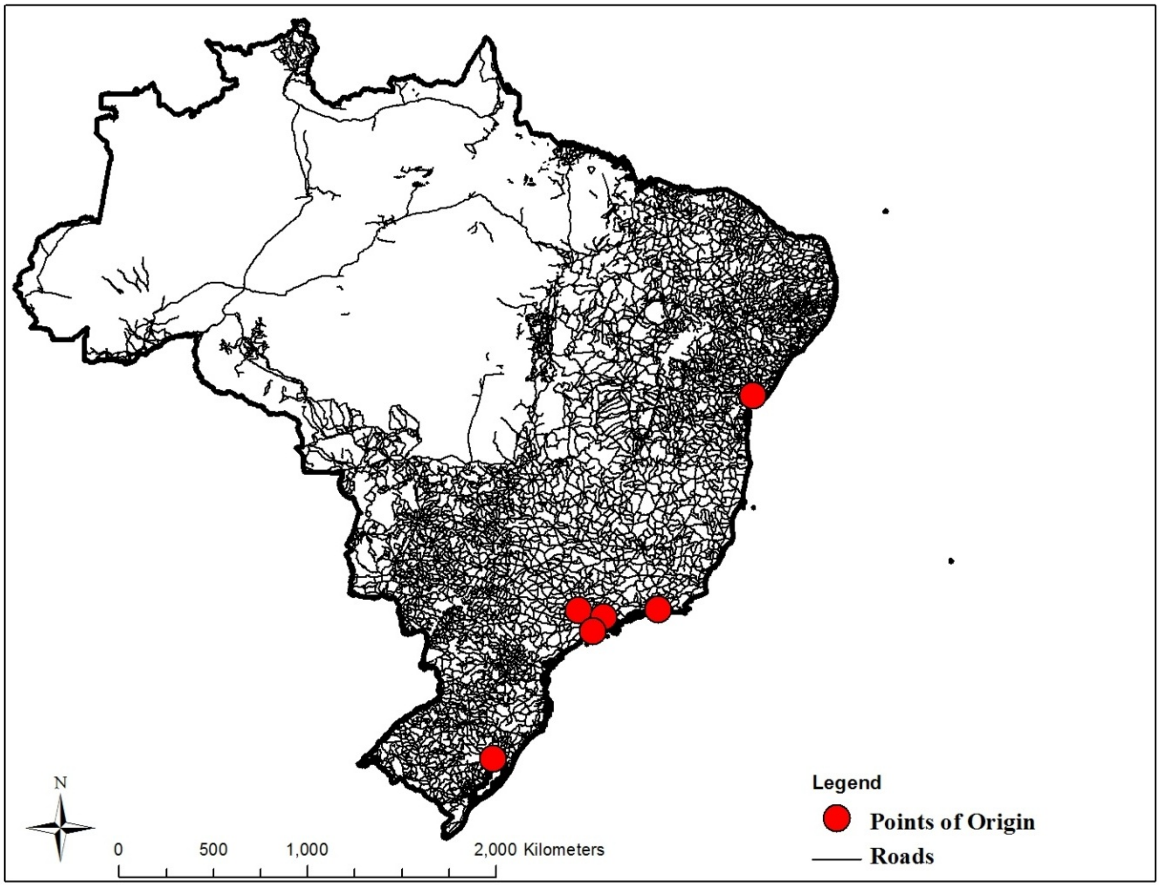


Figure 15. Point of Origins and road network in Brazil

The mean distance to all grid zones within the system were calculated from the nearest point of origin along the shortest possible road pathway. However, ArcGIS was unable to resolve distances to some points within the system; this is often due to the lack of roads, lack of data, or data connectivity errors. All areas in which ArcGIS could not produce a ground distance were assumed to be serviced by air. Straight line air travel distances were calculated from the developed road network to all remaining grid zones on the map using the near tool in ArcGIS. This method accounts for road travel to the furthest possible point via ground transportation, and then accounts for air travel by calculating the distance from each remaining grid zone to the nearest grid zone serviced by the road network. The hybrid transportation approach produces more conservative transportation fuel consumption estimates than assuming air travel from the origination all the way to points not serviced by roads. Therefore, this approach results in more conservative estimates of cost savings associated with installing solar flies on fabric shelters. With all transportation distances calculated, transportation fuel consumption rates were developed to apply to these distances to calculate the full transportation costs of fuel.

Transportation Fuel Factors

Transportation costs were based on Dubbs' (2011) microanalysis of fully burdened costs of fuel in Afghanistan in which ground and air vehicle fuel consumption data were collected to estimate overall system transportation costs. Since this data was available in Dubbs' research, it was used to develop transportation costs parameters. Ground transportation consumption rates are based on the Mine Resistant Ambush Protected (MRAP) vehicle and the Medium Tactical Vehicle Replacement (MTVR). The MRAP and the MTVR have fuel efficiencies of 5.5 miles per gallon and 4.5 miles per gallon, respectively. Each MTVR has the capacity to transport 1,800 gallons of fuel. The smallest, simplest convoy proposed for examination by Dubbs (2011) consists of two MTVRs and two MRAPS. Based on the fuel efficiencies listed above, the fuel consumption of the four vehicle convoy was calculated at approximately 0.808 gallons per mile by inverting the fuel consumption rates referenced above and then summing the values for each vehicle in the convoy.

After accounting for a round trip by dividing this value by two, a fuel transportation factor was calculated by dividing the resulting value by the supply capacity of the convoy, which is 3,600 gallons (2 MTVRs). This factor describes how much fuel is required to transport one gallon of fuel one mile. Distances were converted to kilometers for use in ArcGIS, which resulted in a final ground fuel transportation factor of approximately 0.0002790 gallons per kilometer per gallon supplied [(gal/km)/gal sup].

$$\frac{(2\text{ vehicles})(5.5\text{ mi/gal})^{-1} + (2\text{ vehicles})(4.5\text{ mi/gal})^{-1}}{(2\text{ vehicles})(1{,}800\text{ gal}) \times 2(\text{roundtrip})} \times \left(\frac{1\text{ mile}}{1.609\text{ km}}\right)$$

$$= .0002790\ \frac{\text{gal/km}}{\text{gallons supplied}}$$

This factor assumes that the MTVRs transport fuel at full capacity, but only the portion of fuel devoted to HVAC support purposes is accounted for using this equation. Equation 5 illustrates these relationships,

$$F_{TG} = 0.0002790 \times F_S \times D_G \tag{5}$$

where F_{TG} is the fuel consumed in ground transportation, F_S is the quantity of fuel supplied for HVAC use, and D_G is the ground distance traveled. For example, if 300 gallons of fuel at to be supplied to a point 1,000 kilometers distant for cooling purposes, the convoy will consume approximately 83.7 gallons of fuel to support that specific HVAC capability.

$$F_{TG} = 0.0002790\left[\frac{{}^{gal}/_{km}}{gal\ supplied)}\right] \times 300\ (gal\ supplied) \times 1{,}000\ km = 83.7\ gal$$

A similar consumption factor was developed for air transportation based on Dubb's (2011) research using the Navy's CH-53 helicopter to deliver fuel. The CH-53 travels at 280 kilometers per hour with an average fuel consumption of 600 gallons per hour. The maximum payload of the CH-53 is 36,000 pounds, which was estimated to be 6,000 gallons of potential fuel supply capability based on a fuel density of 6 pounds per gallon. Using the same approach described for ground transportation, the air transportation fuel consumption factor was calculated as 0.000713 gallons per kilometer per gallons supplied [(gal/km)/gal sup]. This factor accounts for the round trip travel of the helicopter. The fuel consumed due to the air transportation of supply fuel is expressed in EEquation 6,

$$F_{TA} = 0.000713 \times F_S \times D_A \tag{6}$$

where F_{TA} is the fuel consumed in air transportation and D_A is the distance traveled by air. Ground and air transportation fuel consumptions were summed to estimate the total amount of fuel, F_T, required to supply fuel to a site for cooling purposes. The overall transportation fuel consumption of supply fuel is expressed in Equation 7 and in its reduced form in Equation 8.

$$F_T = (0.0002790 \times F_S \times D_G) + (0..000713 \times F_S \times D_A) \tag{7}$$

$$F_T = F_{TG} + F_{TA} \tag{8}$$

Economic Analysis

After the fuel consumption related to transportation was calculated, it was added to the point-of-use HVAC fuel consumption to determine the annual total fuel consumption necessary to power one FDECU. This process was accomplished for each MGRS grid zone in the area of interest. After total fuel consumption was estimated, a fuel savings and cost analysis was conducted. Direct, point-of-use fuel reduction was analyzed by subtracting the estimated point-of-use fuel consumption for the test shelter with solar fly installed from the estimated point-of-use fuel consumption of the baseline shelter for each grid zone. A similar analysis was conducted to compare the fully burdened fuel consumptions for the baseline shelter and the shelter with an installed solar fly. Additionally, in order to determine the true economic benefit of installing solar flies, the total fuel savings was compared to the costs of installing the solar flies.

Payback Period

Payback period was selected as the most applicable economic measure to use in the decision to purchase and install solar flies for fabric shelters. Operations in austere environments require great flexibility in basing options, so locations, populations, and functions of contingency base camps are constantly changing. If it is determined that fabric shelters will not remain in use past the payback period, then installation of solar flies is not justified. Calculation of payback period for solar flies depends on the cost of the solar fly and fuel costs. Using standard economic analysis, the cost of the solar fly was used as the initial cost. Assuming no maintenance, the annual savings in fuel cost was used as the annual benefit of installation. Using the standard discount rate of 3.0% specified by the Department of Energy for energy projects (Rushing, Kneifel, & Lippiatt, 2010), the payback period was calculated with Equation 9 (Eschenbach, 2011),

$$P = A\frac{[(1+i)^{N_{DPP}} - 1]}{[i(1+i)^{N_{DPP}}]} \tag{9}$$

where P is Present Worth, i is the discount rate, and N_{DPP} is the discounted payback period. Setting present worth to zero and solving for N_{DPP} yields the discounted payback period.

With a method in place for calculating payback period, the capital costs and annual benefits must be defined. However, initial costs of the solar flies vary with each manufacturer, and the equipment costs are considered proprietary. Furthermore, the volatility of fuel costs presents challenges to estimating the impact of fuel costs on the payback period. Therefore, sensitivity analysis was used to compensate for the uncertainty in the costs.

Sensitivity Analysis

Market research was performed to identify baseline costs for fuel and equipment for the purposes of conducting a sensitivity analysis. The baseline initial cost of the equipment was set at $5,000, which accounts for the solar flies and shipping to the Point of Origin inside the logistics system under study. The transportation cost of moving the equipment inside the logistics system was then added to the overall equipment cost. Accounting for all three of these components ensures that both fuel and equipment are compared on a fully burdened basis. This procedure results in variable equipment costs when examining geographically separated MGRS grid zones. When calculating the transportation cost of the equipment, the overall payload volume of the MTVR was used to estimate that each truck could carry 72 shelters each. This is based on the 20 foot by 8.2 foot cargo space and the standard 3.3 foot by 8.5 foot by 4 foot crate that carries two solar flies. The baseline initial cost of $5,000 was then varied from -50% to +100% to illustrate the effects of different equipment costs on the payback period of the solar flies. A similar analysis was conducted for fuel price. Since fuel price varies drastically from region to region and can be highly volatile, the sensitivity analysis allows for greater flexibility in the economic analysis. The baseline fuel price was set at $5.00 per gallon, which represents the total cost to supply fuel to the point of origin inside the logistics system. Again, this cost was varied from -50% to +100% to show the effects on payback period of the solar flies. Changes in the fuel costs were applied to both the point-of-use and transportation components throughout the model. Now that a method has been proposed to evaluate the economic viability of installing solar flies on fabric shelters, the methodology was applied to two case studies.

Case Study Introductions

Two countries were selected for analysis using the methodology proposed in this chapter. Afghanistan was selected as the first case study due to its widely variable climate, unique transportation network, and current political interest. Brazil was selected as the second country for analysis because it has a warm, humid climate that is not seen in Afghanistan, and itt also has a unique transportation network due to the high level of development in the eastern regions of the country and lesser developed western regions. There are no political or military reasons why Brazil was selected for analysis. It simply presented unique geography, climate, and transportation network for analysis. The resulting technical and economic results from the application of this methodology to these two case studies are presented in Chapter 4.

Conclusion

In this chapter, a methodology was proposed to evaluate the economic effectiveness of installing solar flies on expeditionary fabric shelters. The solar flies are intended to reduce the cooling load and associated HVAC power requirements for the shelters. This energy reduction can be estimated in terms of reductions in overall fuel requirements. Two major components must be considered when estimating potential fuel reductions. The first is the direct, point-of-use fuel reduction associated with reducing the cooling load of a fabric structure. The point-of-use component describes the direct reduction of fuel required at the generator to power a single ECU. The second component accounts for the effects of the point-of-use fuel reductions throughout the transportation system. If less fuel is required at the point-of-use, less fuel is also required to transport fuel inside the logistics system. The fully burdened costs of fuel are realized by summing the point-of-use HVAC component and the GIS calculated transportation component. After the methodology was developed, it was applied to two case studies. The results of these case studies are described in Chapter 4.

IV. Results

The results from the two case studies introduced in Chapter 3 are presented in this chapter. The total fuel reductions for both case studies are presented, analyzed, and discussed for each grid zone in the region under study with an emphasis on economic and sensitivity analysis. All interim graphic results are provided in the appendices. Brief explanation and discussion of the results are provided in this chapter. Conclusive results were obtained for the vast majority of grid zones considered during modeling and validated against existing contingency planning factors. The resulting payback period information could be used to make solar fly implementation decisions.

Case Study 1: Afghanistan

Conclusive results were developed for 111 of the 112 grid zones analyzed in Afghanistan. The one remaining grid zone was removed from the analysis because of an anomaly in RTS simulation that caused invalid results. This anomaly was most likely caused by a modeling error related to an improbable trigonometric relationship that occurred when calculating incident angles of solar radiation; however, this explanation was not confirmed. The remaining 111 grid zones provide valid and conclusive results for analysis.

Fuel Consumption Reduction

As shown in the map in Figure 1, the model estimated large fuel savings throughout most of Afghanistan associated with the installation of solar flies on fabric shelters. The map shows the total annual fuel requirement reduction for one shelter associated with the installation of a SIPSS solar fly. For each grid zone, the annual fully burdened fuel consumption to power one shelter with installed solar fly was subtracted from the annual fully burdened fuel consumption to power one baseline shelter. Maps showing interim data such as distances, point-of-use, and total fuel consumptions for the baseline and test shelters are located in Appendix B.

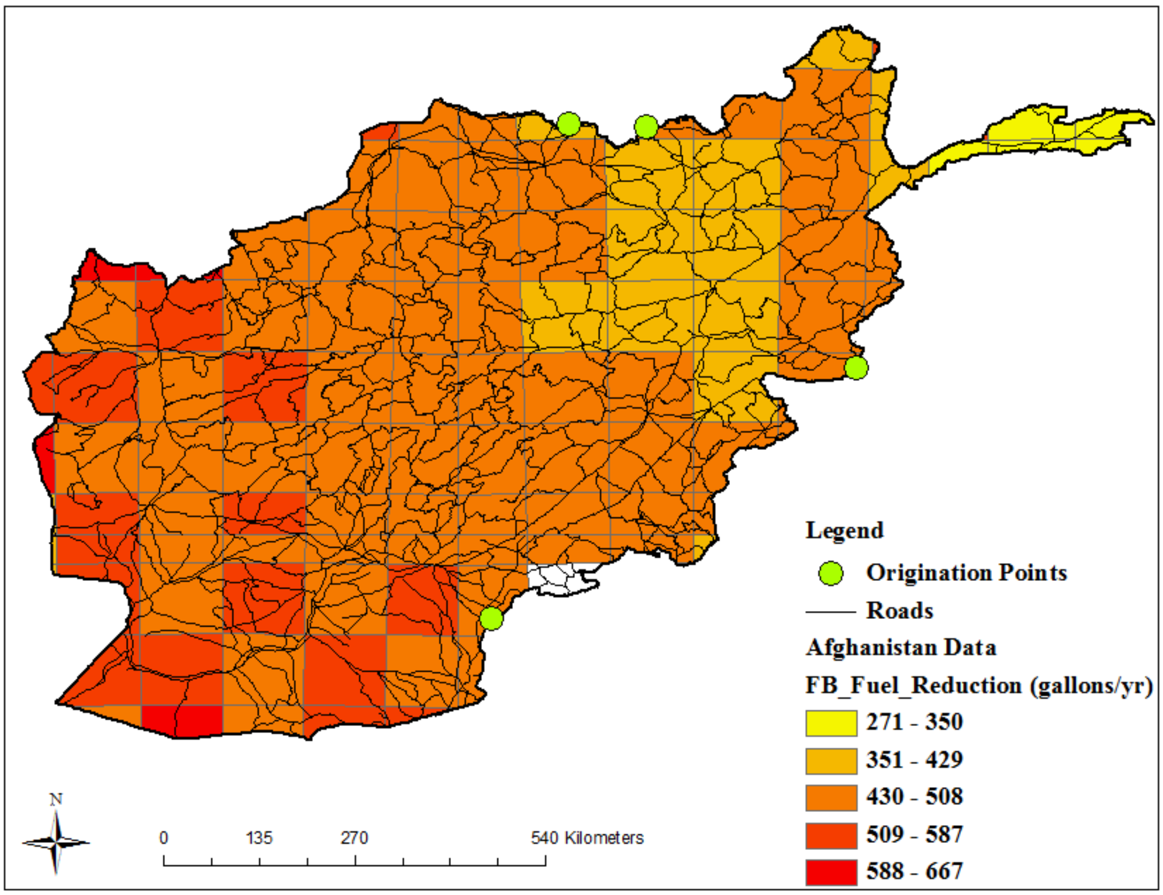


Figure 16. Annual Total Fuel Reductions Due to Solar Fly Installation.

The largest fuel reductions were seen in the western quarter of the country. This geographic distribution seems valid given the warmer climate and the longer distances required to transport fuel. The maximum fuel reduction seen in any grid zone was approximately 667 gallons per year. Fuel reductions in areas with a more temperate climate and with shorter distances from port were more modest, with the minimum predicted annual fuel reduction due to solar flies being projected at 270 gallons per tent. This is still a very significant quantity at base camps of even modest size. A standard Air Force expeditionary bare base or Army Forward Operating Base of approximately 1,200 personnel would see an annual reduction of 27,000 gallons of fuel conservatively assuming 12 personnel per tent.

The mean percent fuel reduction across all grid zones was 34.8%, which is applicable to both point-of-use and fully burdened results since the two are linearly related. This figure is significantly higher than the 12.6% energy savings seen during testing of the equipment at Fort Irwin. A histogram of the percent energy consumption reduction is shown in Figure 17. The median fuel reduction was 30.2%, and the standard deviation was 15.2%. The small increase in occurrences at the right side of the figure accounts for grid zones in which the need for air conditioning was eliminated by the use of solar flies.

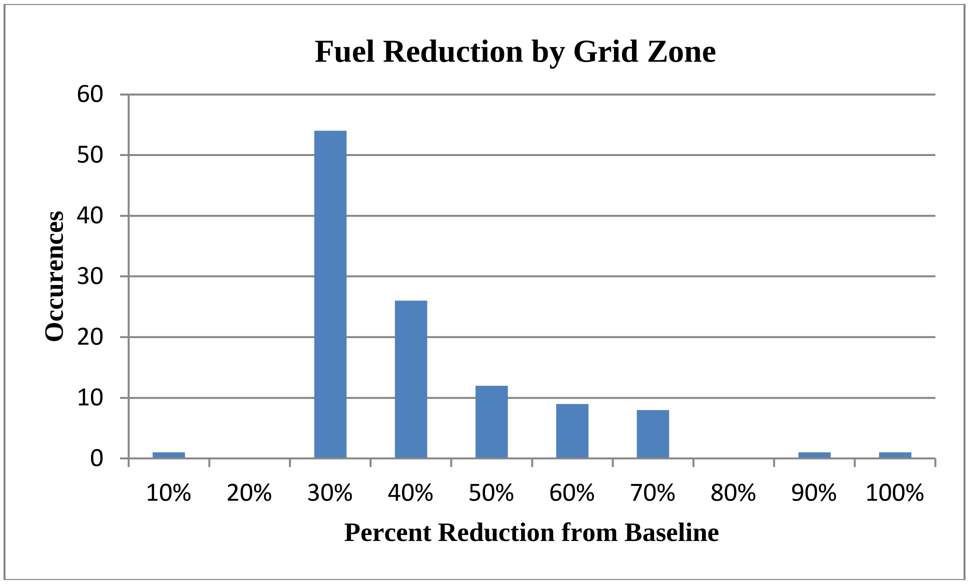


Figure 17. Fuel Reductions by Grid Zone

The difference in average fuel reduction between the SIPSS test data and the model can be attributed to two primary factors. First, the 12.6% energy savings measured at Fort Irwin does not account for generator inefficiencies. Since power readings were measured at the ECU during the SIPSS tests, the reduction in waste energy produced by the generator was not captured. However, this additional energy savings was accounted for in the model. Secondly, the SIPSS program only tested the solar fly during the month of July, when cooling was required throughout the day. Since the model was executed across an entire year, there were several instances in which the simulated solar fly changed the FDECU from a "Heat Pump On, Circulation Fan On" condition to a "Heat Pump Off, Circulation Fan On" condition. This transition accounts for a substantial fuel reduction. Furthermore, in limited cases, the cooling load was completely eliminated and the FDECU could be completely turned off. There are potential indoor air quality concerns with turning the circulation fan off; however, they were not considered in this research. In one grid zone, the FDECUs for cooling purposes could be completely eliminated with the use of solar flies; this grid zone is represented at the far right of the histogram in Figure 17. The transition between the FDECU operating conditions is the primary driver behind the right-side skew seen in the histogram. These fuel reduction results appear to be valid within the stated assumptions and limitations of the model.

Economic Analysis

The discounted payback period analysis described in Chapter 3 resulted in the histogram presented in Figure 18. The calculated mean discounted payback period was 2.37 years with a standard deviation of 0.42 years across all grid zones in the country. These results were calculated assuming the baseline equipment and fuel costs of $5,000 per solar fly and $5.00 per gallon of fuel. Note that the one occurrence with a payback period of less than 0.25 years is the biased data point discussed earlier.

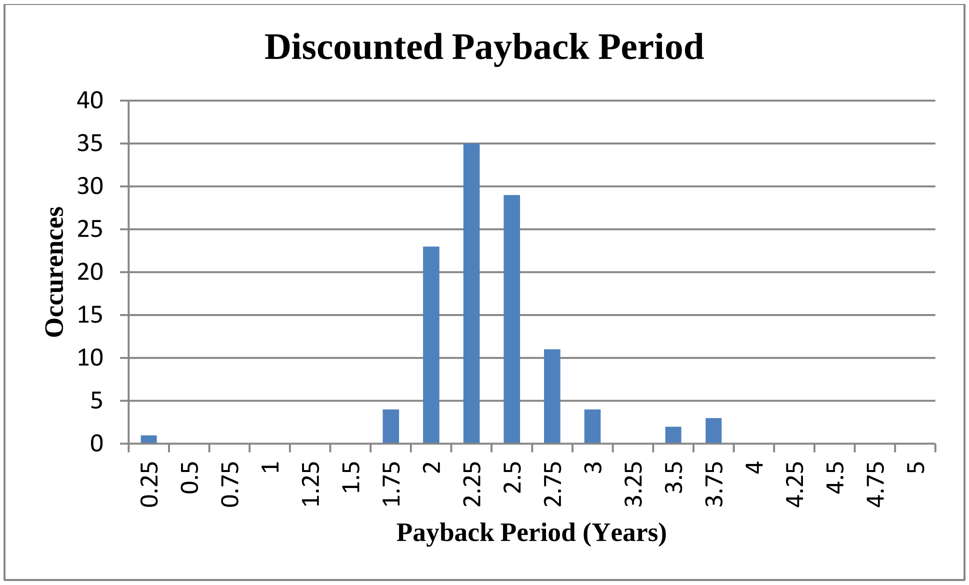


Figure 18. Discounted Payback Period by Grid Zone

A discounted payback period map is shown in Figure 19. From this map, it is seen that payback periods are typically shorter in the central and western portions of Afghanistan, with shorter payback periods in the northeastern sections. This result is logical due to the cooler temperatures prevalent in the northeastern mountains. This map provides a geographic decision aid related to where solar flies would be economically viable based on perceived future life of a base camp or tent. For example, if operations were forecasted to continue in Afghanistan for 2 additional years, solar flies would be economically justified in all grid zones with discounted payback periods of 2 years or less. A 2-year payback decision point is justified in *The Sandbook*, a contingency engineer planning guide published by United States Central Command. After 2 years, engineers are encouraged to consider more permanent structures, although fabric structures are not prohibited from use (Headquarters U.S. Central Command, 2009).

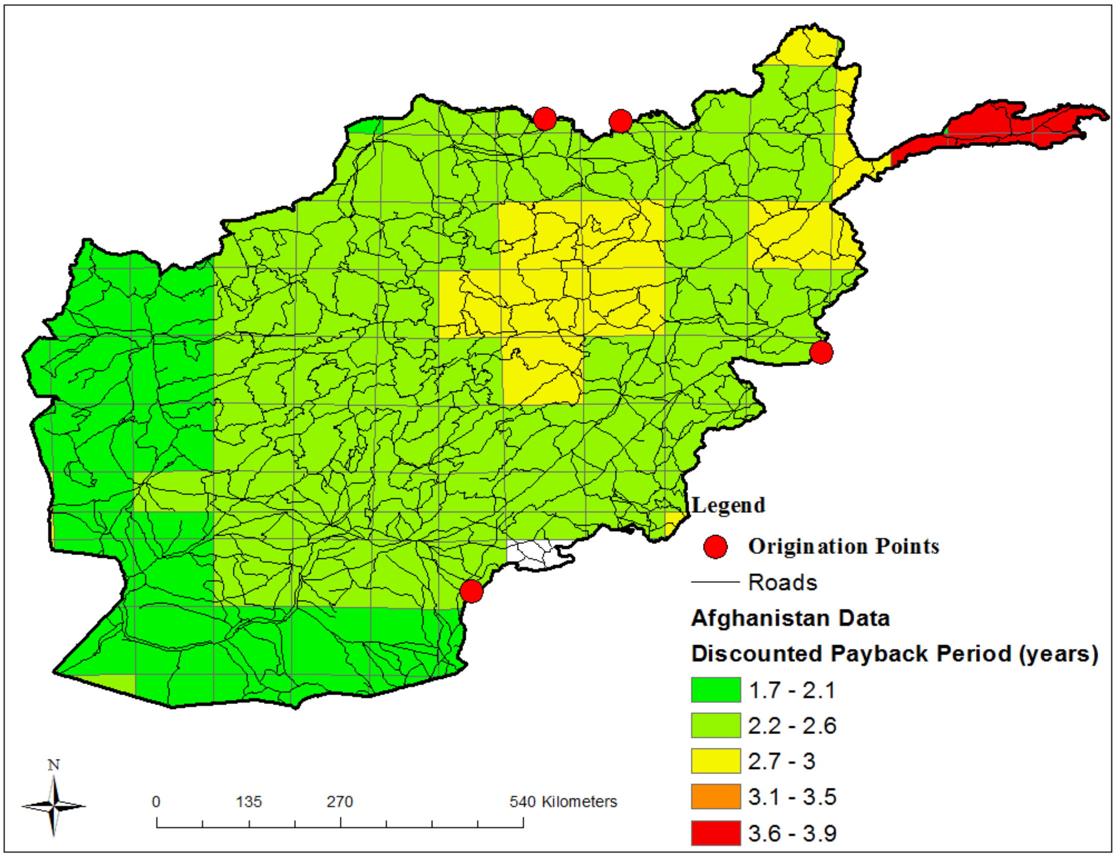


Figure 19. Discounted Payback Period Map

Sensitivity Analysis

A sensitivity analysis was conducted to determine the effects of varying fuel and equipment costs on the average discounted payback period across all grid zones as described in Chapter 3. The baseline fuel cost was $5.00 per gallon, and the baseline equipment cost was $5,000 per solar fly. These costs were then varied from -50% to 100% of the baseline to determine the effect on the payback period. Varying the equipment costs resulted in a linear change in payback period. Reducing the cost of the equipment by 50% reduced the predicted payback period to approximately 1 year. Since shelters are rarely installed for less than a year, the cost decrease would justify installing solar flies on nearly every tent installed in the future in Afghanistan. Doubling the equipment cost increased the mean discounted payback period from 2.2 years to approximately 4.5 years. This increase in mean payback period exceeds the 2-year temporary structure goal dictated by *The Sandbook.* As a result, solar flies in many grid zones would not be justified because the fabric shelters would likely be replaced with semi-permanent structures before reaching the payback period, assuming that the solar flies would not be reused after the fabric shelter was replaced.

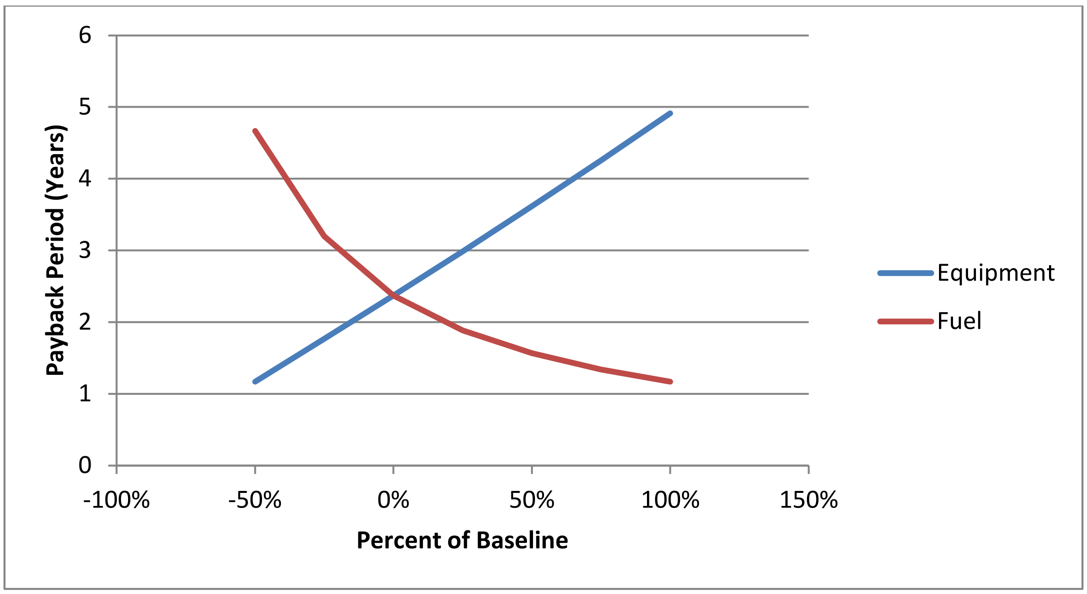


Figure 20. Sensitivity Analysis of Payback Period

The fuel price was also varied between -50% and +100% of the baseline cost of $5.00 per gallon. When the baseline cost was reduced by 50%, the mean discounted payback period of the solar flies approached reached 4.7 years, while the mean discounted payback period decreased to 1.2 years when the fuel cost was increased by 100%. The change can be characterized as an exponential decay because there is an indication of diminishing returns as the fuel price approaches the 100% above baseline case.

It is also important to note that the sensitivity analysis was conducted on the mean discounted payback period of all regions. The maximum payback period for a particular region can be much higher than the calculated mean. For example, if the equipment cost is increased by 100% for a few grid zones in the far northeast of the country, the discounted payback period exceeds 8 years. Although the results were aggregated for reporting purposes, implementation decisions should be based on the results of each individual grid zone.

Case Study 2: Brazil

Conclusive results were developed for 1,201 of 1,206 grid zones in Brazil. Of the five grid zones that produced inconclusive data, three of the zones were too small to produce valid results and the other two zones produced invalid results for unknown reasons. Additionally, there were numerous grid zones situated on the border of the country that were too small to even attempt analysis; these grid zones were excluded form the analysis process and are not included in the 1,206 zones discussed above. The results from the Brazil case study provided an interesting contrast to the Afghanistan results. The relative uniformity of the warm climate in Brazil provided some interesting insights into the behavior of the fuel reduction results. Analysis on the fuel consumption reduction, economic viability, and sensitivity are described below.

Fuel Consumption Reduction

A geospatial presentation of the fully burdened fuel reduction predictions due to installation of solar flies are shown in Figure 22. The interim maps showing the baseline and test model results are shown in Appendix C. Fuel reductions ranged from 406 to 1,701 gallons per year per tent. The largest fully burdened reductions were found in the northwest portion of the country. This is mainly a result of the long transportation distances and the fact that air transportation was required to reach this portion of the country based on the GIS road network analysis.

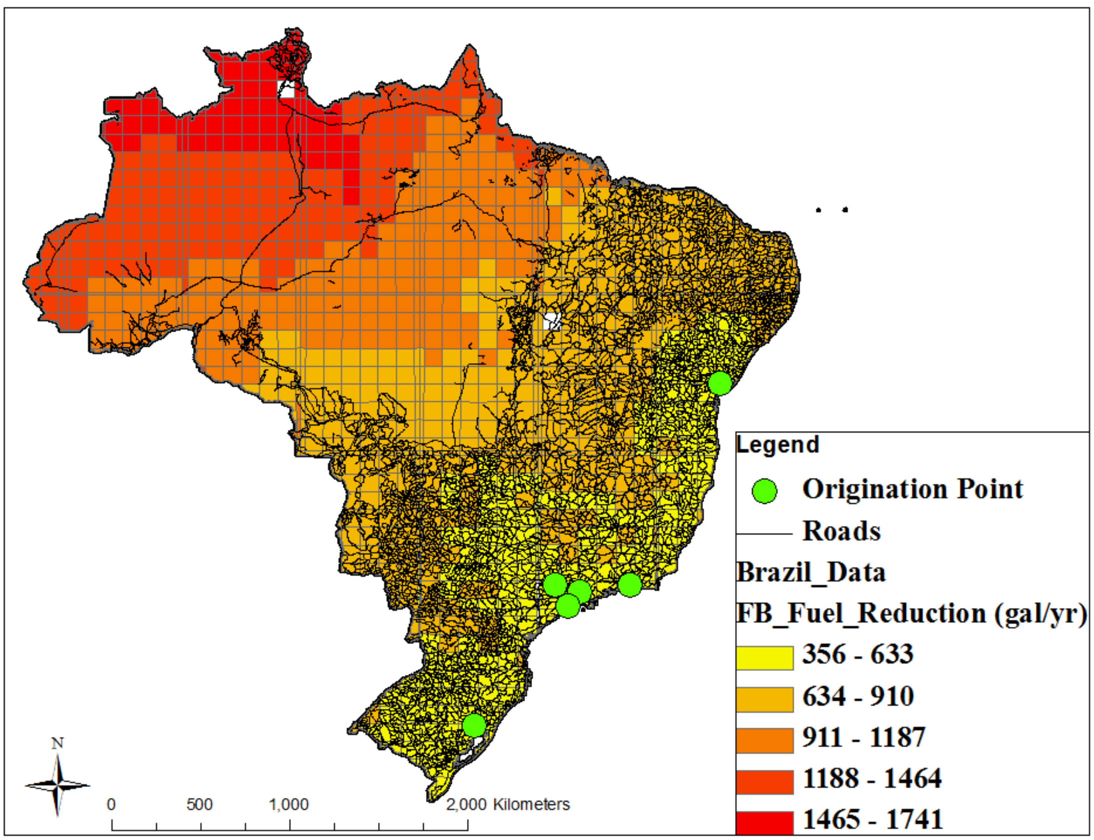


Figure 21. Annual Total Fuel Reductions in Brazil

The Brazil case study presented interesting results in that the percent reduction of fully burdened fuel consumption achieved through the application of solar flies was nearly uniform across the country at 15%. This characteristic is shown graphically in the histogram featured in Figure 22. The uniformity of the relative fuel reduction was attributed to the relative uniformity of the Brazilian climate relative to Afghanistan. With no major mountain ranges of the extent found in Afghanistan, the relative point-of-use cooling load reduction associated with solar fly use was more consistent across the country. Since the GIS transportation model used a linear fuel factor for analysis, this uniformity was found across the fully-burdened model.

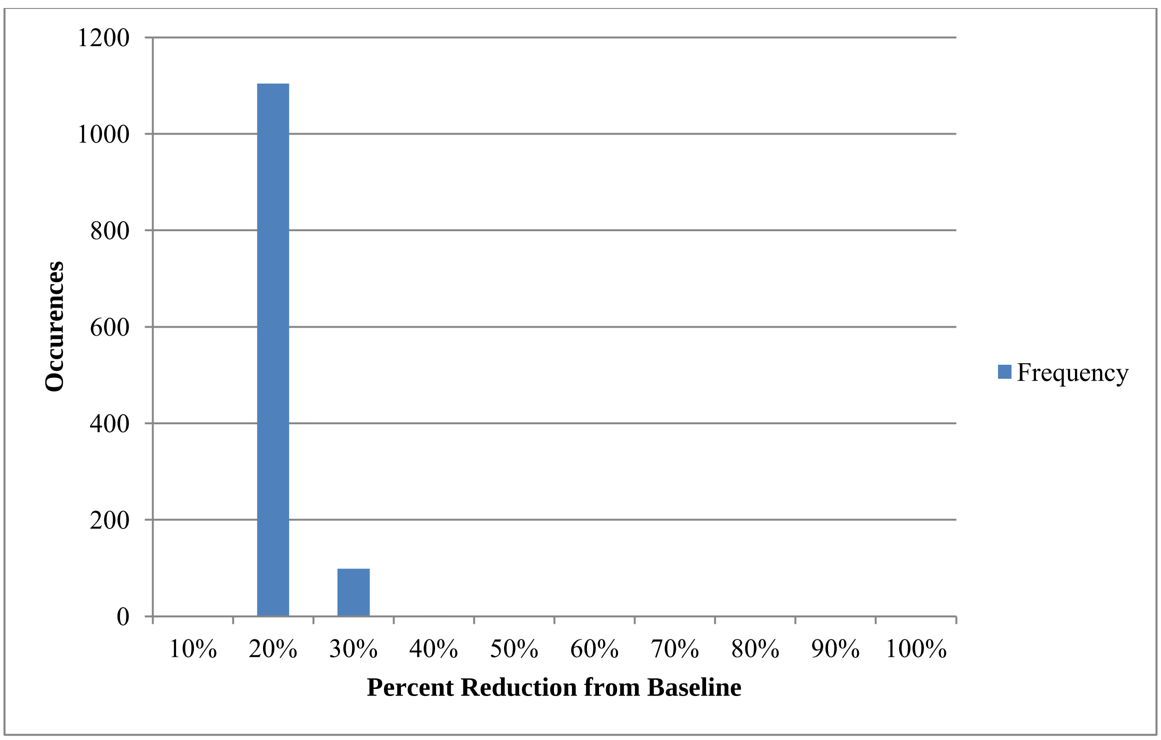


Figure 22. Relative Total Fuel Reduction by Grid Zone

However, this uniformity was not found in the analysis of the overall fuel consumption figures. Total reductions varied widely as seen in Figure 23. As mentioned earlier, fuel reductions varied from 406 gallons per year to 1,740 gallons per year across all grid zones. Since the climate was relatively uniform across the country, the majority of the variation can be attributed to the transportation costs of fuel. This is especially true due to the use of air transportation in the Brazil model. For purposes of comparison, the point-of-use fuel reductions due to solar fly implementation are shown in Figure 24. As described, these reductions are relatively uniform, confirming that the majority of the variation in total reductions is due to the distance between the Point of Origin and the point-of-use.

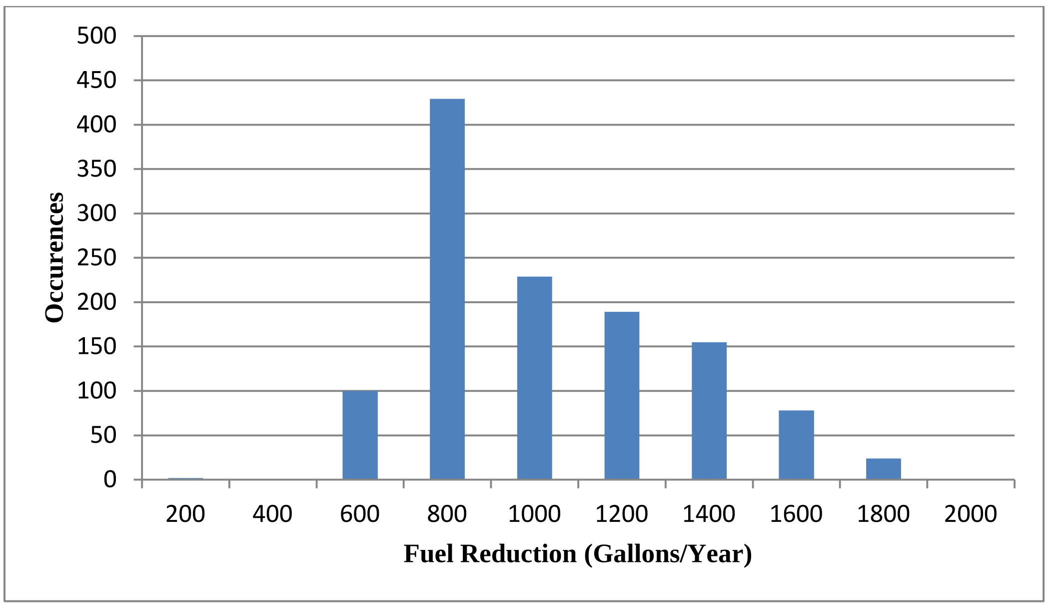


Figure 23. Annual Total Fuel Reductions for All Grid Zones.

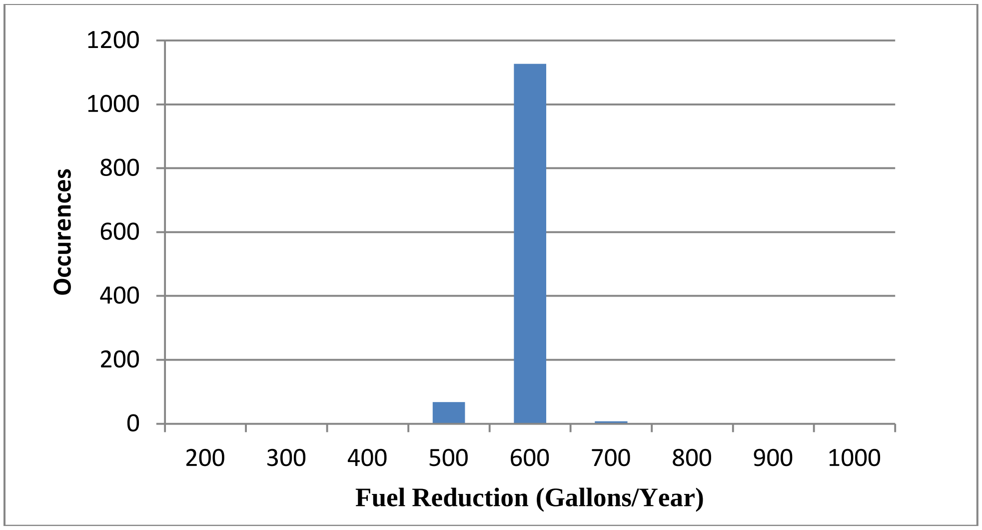


Figure 24. Annual Point-of-Use Fuel Reductions

Economic Analysis

An economic analysis was performed on the fuel reductions as described in Chapter 3. The distribution of discounted payback periods is shown by grid zone in Figure 25. Discounted payback periods ranged from 0.84 years to 2.61 years with a mean of 0.97 years and a standard deviation of 0.19 years. These values are based on the baseline costs of $5,000 per solar fly and $5 per gallon fuel. Results are shown geographically in Figure 26. The lowest payback periods were located in the northwest portion of the country. Payback periods tended to increase as the distance to the Point of Origin decreased. This confirms that distance and mode of transportation are the primary causes of the greater fuel reductions seen in the Brazil case study.

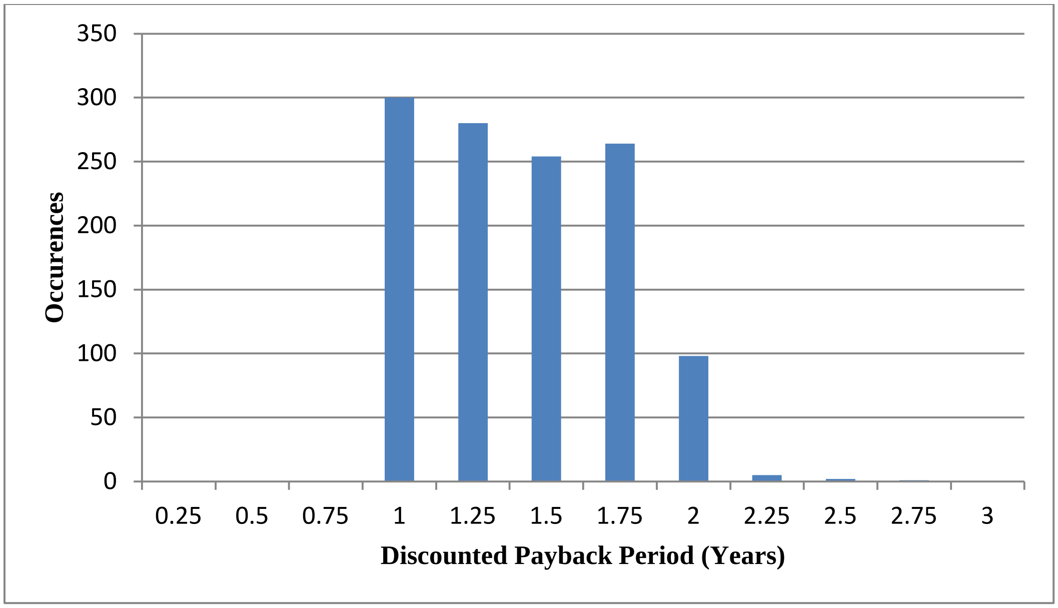


Figure 25. Distribution of Discounted Payback Periods by Grid Zone

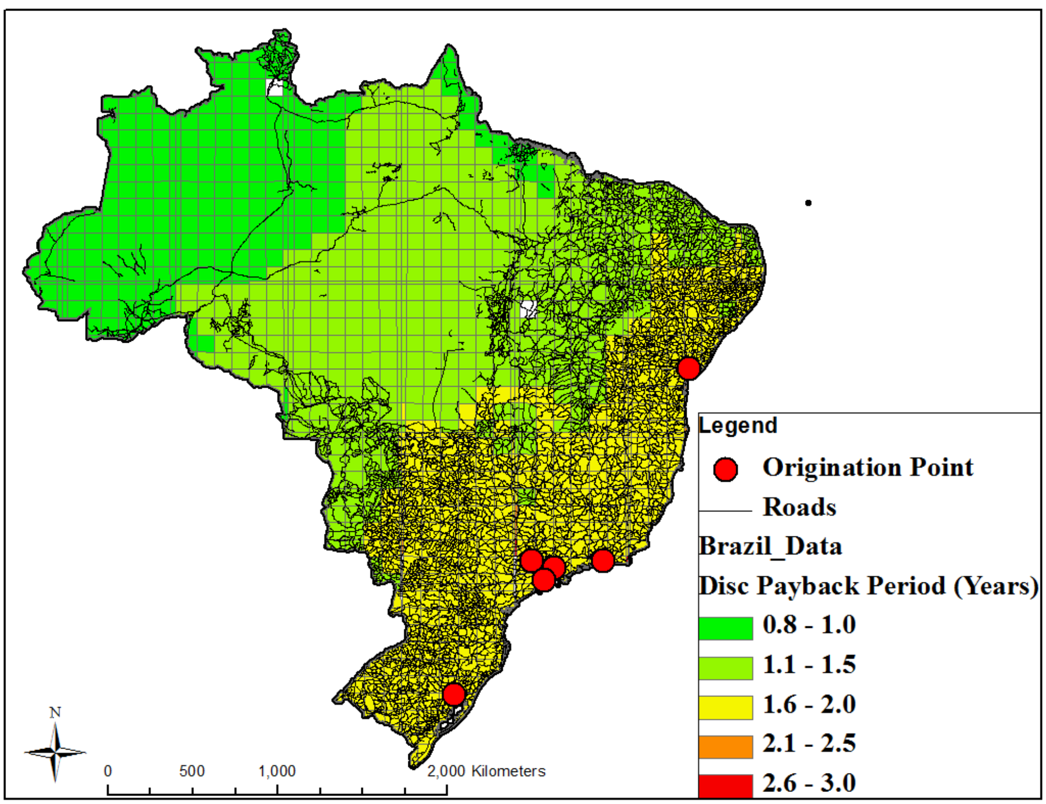


Figure 26. Discounted Payback Period map for Brazil.

Sensitivity Analysis

A sensitivity analysis was conducted on the average discounted payback period by varying the costs from -50% to +100% of the baseline. The resulting spider plot is shown in Figure 27. The analysis revealed that discounted payback periods remained relatively low despite large fluctuations in equipment and fuel costs. The discounted payback period remained less than 2 years even after the equipment cost was doubled from the baseline case. Similarly, the payback period remained less than 2 years after the baseline fuel cost was halved. This analysis provides high confidence that the solar flies would be economically justified throughout the country despite the uncertainty in the assumed fuel costs at the points of origin in the system model. Although each grid zone should be considered on a case-by-case basis if perfection is desired, this sensitivity analysis shows that solar flies are economically justified for the vast majority of grid zones. It is also significant that the payback period remains less than *The Sandbook* threshold of 2 years for temporary structures.

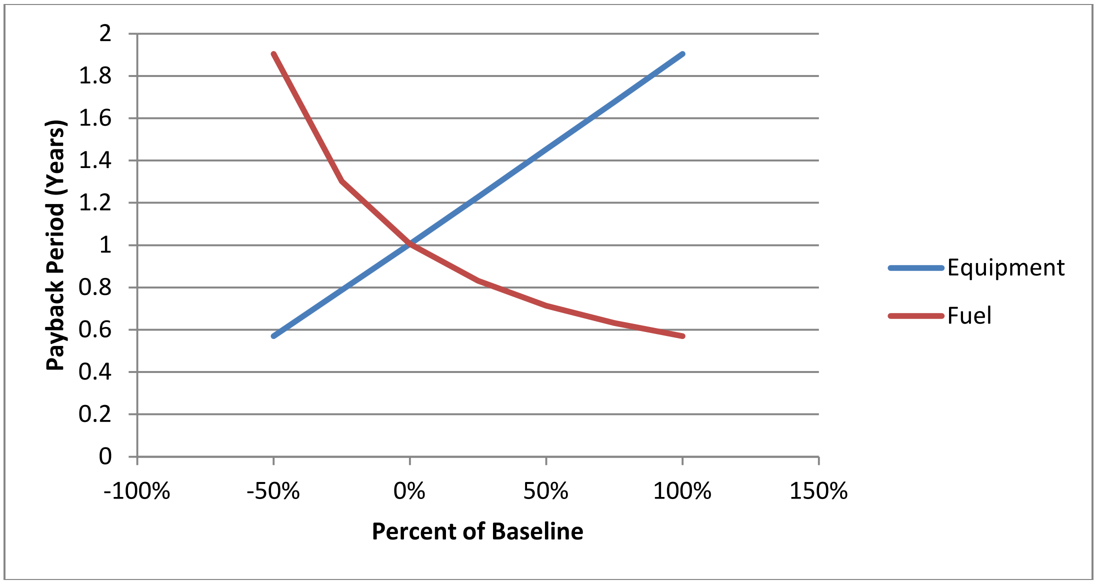


Figure 27. Sensitivity Analysis of Discounted Payback Period

Discussion

The definitive results achieved through both case studies confirm that the model is viable. The model achieves the overall research objective of creating a GIS model to evaluate the fully burdened impacts of installing solar flies on fabric shelters. The model successfully evaluated the vast majority of grid zones in both case studies and provided a discounted payback period estimate for use in decision-making. For military applications, these payback periods can be used in conjunction with engineer planning documents such as AFH 10-219, AFH, 10-222, and The Sandbook, to make decisions on when solar flies should be installed. For example, *The Sandbook* identifies fabric shelters as a "temporary facility" that should only be employed for 2 years. After 2 years, fabric shelters should be replaced with a semi-permanent shelter, such as a pre-engineering building. If projected payback periods exceed 2 years, planners may be justified in choosing to not install solar flies because the fabric structures may not be used through the end of the payback period.

Validation through Comparison with Contingency Planning Factors

The global HVAC model component was validated by comparing its results for baseline shelters to existing contingency planning factors. Air Force Handbook 10-219, Volume 5, states that each shelter ECU should consume approximately 4.5 kilowatts of power. Using this planning factor and assuming a 750-kilowatt generator that consumes 55 gallons per hour, a typical ECU will require approximately 2,885 gallons of fuel to cool a shelter in a location that requires year-round cooling. Since Brazil required year-round cooling in most grid zones, the mean annual fuel consumption was calculated at 3,295 gallons per year for comparison by averaging the annual fuel consumption across all grid zones. The resulting error is an over-prediction of 14.2%, which indicates a strong agreement between the model and contingency planning factors considering the error associated with extrapolating a daily load model across an entire year. For Afghanistan, the mean annual fuel consumption across all grid zones was estimated to be 1,374 gallons, which is approximately half of the expected full-time annual fuel requirement. This value seems reasonable since the cooling season is relatively short in many regions of the country.

Case Study Comparisons

Comparing the two case studies revealed some interesting characteristics. Payback periods in Brazil were significantly lower than payback periods in Afghanistan.

There are two primary reasons that explain this difference. First, most grid zones in Brazil experienced year-round cooling conditions within the model. Since both point-of-use and transportation consumptions depend on the climate, the length of the cooling season has a major impact on the economic effectiveness of solar flies. Secondly, the larger transportation distances and differing modes of travel within Brazil caused the transportation consumptions to exceed those found in Afghanistan. Admittedly, the transportation mode was driven by the ArcGIS ability to create road network connectivity. There are certainly places in Afghanistan that can only be reached via air despite the fact that the model simulated the entire country as accessible by ground. Likewise, there are likely locations in Brazil that can be reached by ground that were modeled using air transportation.

There was also much more variation of fuel reduction quantities across the country of Afghanistan than across Brazil. The larger variation is due to the more diverse climate and terrain found in Afghanistan. The northeastern part of the country features high mountains that pose high cooling loads only a few months out of the year. In contrast, the southwestern part of the country exhibits high cooling loads for the majority of the year. In comparison, Brazil presents a relatively constant high cooling load throughout the year in the majority of grid zones.

Conclusion

The model provided conclusive results in both case studies. The model and the available GIS data were used to calculate cooling loads and fuel consumptions for both the baseline and test shelters in grid zones throughout the case study countries. Differences between the test and baseline cases were calculated to reveal the fuel savings associated with solar fly implementation. The estimated fuel reductions in both point-of-use and transportation categories were substantial. The resulting discounted payback periods were compared to *The Sandbook* standard of a 24-month life for a fabric shelter. Sensitivity analysis results showed that the payback period is significantly dependent on equipment and fuel costs, which confirms that the decision to implement energy reduction equipment should be based on an economic analysis that considers geography and climate. Lastly, the overall fuel consumption estimates were validated using existing contingency planning factors. Major research conclusions are provided in Chapter 5.

V. Conclusions

This research developed a methodology to economically evaluate expeditionary energy reduction technologies. The methodology incorporated existing knowledge in cooling load modeling, fully burdened cost analysis, and geospatial analysis, and it was successfully applied to two case studies. This chapter concludes the findings of the research and recommends future actions and research in the field of expeditionary energy technology.

Conclusions

The economic benefits of implementing solar flies on fabric structures were examined within the context of varying climate and logistics networks. Results showed that the economic viability of implementation does, in fact, depend on geographic and climate characteristics of a region. The methodology was validated against field data and applied to two case studies as a proof of concept. The development and validation of this model fulfills the intended objectives of this research. Furthermore, the case study analysis shows that significant fuel reductions can be achieved at most locations by installing solar flies; however, it should not be universally accepted that solar flies are economically justified at all locations. A regional analysis should be conducted to determine if expeditionary equipment is economically justified before installation.

Several investigative questions were proposed at the beginning of research in order to guide model development. These questions and the answers discovered during research are reviewed below.

1) What is the proper method for modeling cooling loads of expeditionary fabric shelters?

The Radiant Time Series (RTS) method was determined to be the most appropriate method for modeling cooling loads. Its non-iterative nature and easy adaptation to GIS raster data made it the clear front runner when considering cooling load analysis techniques despite some level of known inaccuracy when considering low conductance surfaces. The RTS method overwhelmingly provided more accuracy than steady-state analysis. Although computational fluid dynamics (CFD) could likely provide more accurate results, the level of accuracy required for the analysis did not warrant the excessive level of time, knowledge, and experience required to develop a CFD model.

2) What are the most predictive, and most available climatic data for use in the GIS model?

GIS raster data from WorldClim (2012) was chosen to provide inputs to the worldwide RTS analysis on the fabric shelter models. The raster dataset was developed using a proven and academically accepted method of interpolating historical data between weather observation stations located around the world. Additionally, the WorldClim raster datasets provided all of the necessary data for RTS analysis except for relative humidity. Wet bulb temperatures were estimated by interpolating discrete humidity ratio data across each region of interest by using an Inverse Distance Weighting Method.

3) What is the optimum indoor air temperature point to ensure indoor air comfort, job performance, and minimal fuel consumption?

The indoor air temperature was set to 75 degrees Fahrenheit for cooling load analysis. This temperature falls within the ASHRAE defined comfort zone across a wide range of relative humidity. It is also near the upper limit of acceptable temperatures, and therefore requires less fuel than a lower thermostat setting. The ASHRAE comfort zone provides comfort in a wide range of activities and clothing types; however, it was determined that the examination of specific types of activities with regard to thermal comfort was beyond the scope of this research effort.

4) What factors should be considered when developing GIS based transportation networks? Where should the system boundaries be set?

It was determined that a GIS based network can become too complex to be meaningful. Therefore, it was decided that distance is the most important factor when considering the transportation cost of supply fuel. Likewise, the simplest form of boundaries should be used to define the system to examine the viability of the methodology and maintain a level of clarity in the results. Simple political boundaries were used to define the transportation networks in this research. However, regional boundaries could be equally applicable in some situations. Points of origin were determined to be where the majority of fuel enters the logistics system.

Significance of Findings

This research validated a methodology for estimating the fully burdened cost savings associated with improving the energy efficiency of expeditionary assets. Organizations seeking to quantify the fully burdened savings associated with any type of energy reduction opportunity can employ this methodology. The case studies showed that the fully burdened cost savings associated with energy reduction equipment installation can be significantly higher than the point-of-use savings; this validates the need to evaluate new technology on a fully-burdened basis. These fully-burdened evaluation methods were applied specifically to cooling load reductions of expeditionary structures. The cooling load analysis model component showed that there are significant opportunities to reduce the fuel consumption required to cool shelters in austere environments. While this model was aimed at fabric shelters, it could easily be adapted to accommodate any type of structure.

The application of the model to case studies supported the implementation of energy reduction equipment across the majority of regions studied. However, they also showed that energy reduction equipment in some regions is not economically justified, which validates the need to consider implementation on a regional basis. These findings and the developed methodology could be used to aid in decision making when considering the implementation of energy reduction equipment. Additionally, the cooling load model could be used to improve the design and implementation of expeditionary shelters of all types by enabling planners and designers to tailor shelter design and configuration to a specific environment.

Recommendations

Immediate recommendations can be made based on the research findings. First, any operations that have high vulnerabilities with respect to fuel dependency should receive immediate consideration for energy reducing initiatives, which should be evaluated on a fully-burdened basis to account for the total savings across the logistics system. Furthermore, the thermal efficiency of expeditionary shelters should be evaluated using the proposed RTS method, and the economic benefits of improving thermal efficiency should be considered on a fully-burdened basis. These evaluations should be accomplished at a regional level to ensure that variations in climate, geography, and transportation networks are considered during analysis. There is the potential to realize significant savings across several types of organizations by implementing these recommendations.

With respect to the SIPSS program, research supported immediate implementation of solar fly technology in most of the regions under study even though improvements are continuously in development. The most promising, fully developed technology that AFCEC research has produced should be analyzed on a regional basis by using the proposed methodology. If the resulting payback periods warrant action, then implementation should be discussed with current engineer commanders in theater. Specifically, the 577th Expeditionary Civil Engineer Group should be consulted regarding potential implementation in high vulnerability areas. While it is recognized that the current technology could be further improved, research has demonstrated that the current technology can have a significant impact if employed. Although the SIPSS program is focused on developing technology for the War Reserve Material (WRM) program, specifications could be developed to enable direct purchases from the field. This would require careful coordination between theater engineers and AFCEC researchers to ensure that procurement and implementation are executed in a methodical manner that makes the best use of funding and minimizes mission impacts. Direct purchasing could have an immediate impact on reducing the current fuel usage in operational theaters.

Direct purchases for existing sites are relatively easy to tailor because equipment is being purchased for a known location and climate. However, as attention turns to reconstituting the War Reserve Material program, the purchased equipment sets must be effective across a wide range of locations and environments. This requires careful planning regarding which equipment is purchased and how it is organized for deployment. For example, should solar flies be deployed with every shelter in future large-scale operations? Within the two case studies, deployment across the majority of regions studied would have been effective, but solar flies would have no economic benefit in some regions. Complicating the issue is the fact that there are no global models to estimate solar fly effects on the heating characteristics of fabric shelter. Since the cooling loads in this study were heavily dependent on solar irradiation, it is possible that the decrease in solar irradiation incident on the fabric during the winter could result in higher heating loads in certain locations. These issues highlight the need for further research to support WRM fielding decisions.

Future Research

Several opportunities exist for additional research. The evaluations presented in the current research represent a very small portion of the overall research opportunity related to evaluating deployable energy efficient technologies. The following areas represent only a portion of the available opportunities.

Improvements to the Existing Model

The existing model could be improved in several ways. First, better definition of the fabric shelter material properties would improve the accuracy of the model. Properties that were obtained through laboratory testing would also improve the perceived validity of the model. Additionally, further research into the application of Nigusse's (2007) findings related to low conductance materials for fabric shelters would also improve the model's accuracy. The incorporation of a heating load model would also be beneficial. Since lightweight shelters respond vigorously to solar irradiation, the solar flies could have a negative impact on heating load. This potential effect needs to be explored and accounted for in future research. Finally, the model could be expanded to incorporate a variety of structure types that can be used in austere environments.

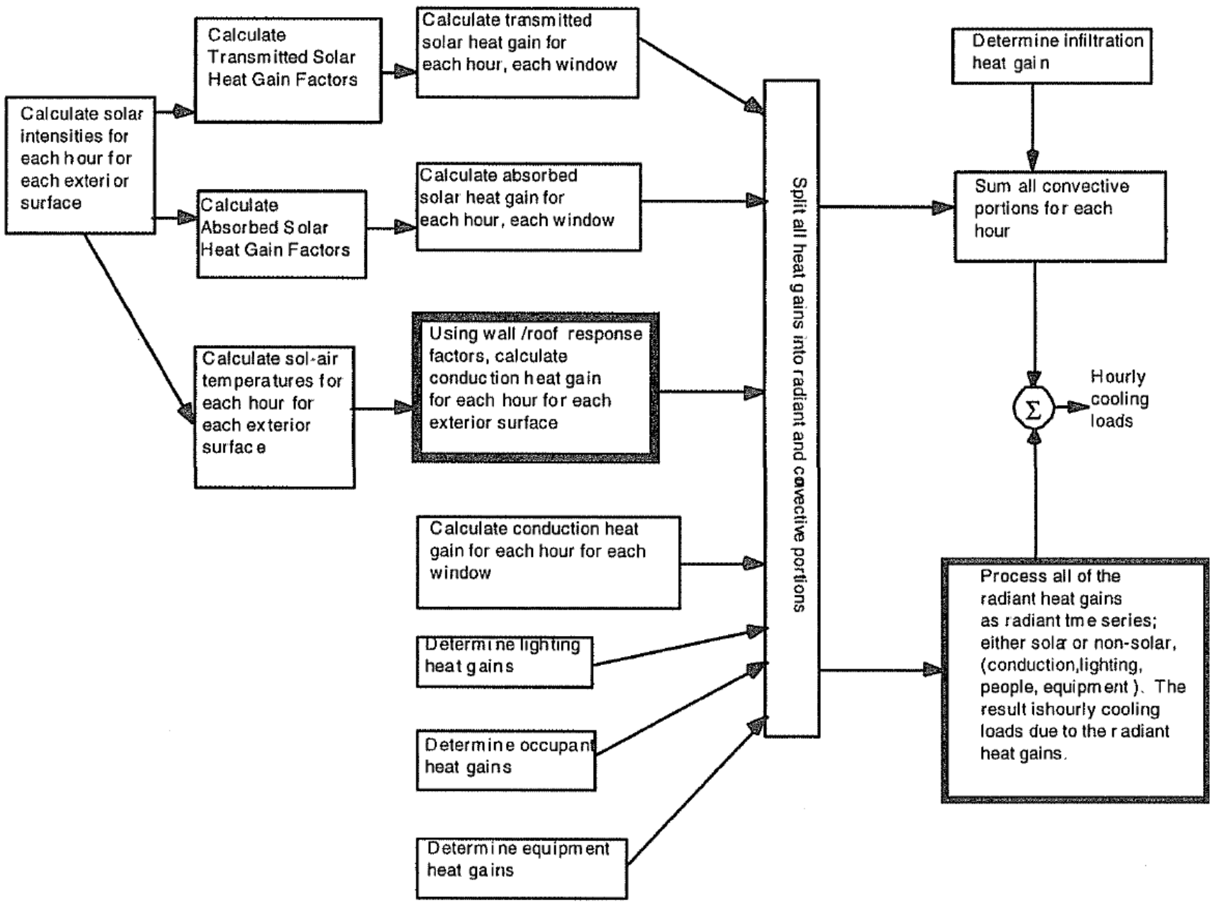
Applications to Newer and More Complex Technology

Researchers at the Air Force Civil Engineer Center are already working to capitalize on gains made by reducing shelter cooling loads by exploring the possibility of cooling multiple shelters with one ECU. The proposed methodology would be useful in examining different equipment configurations in a variety of climates to determine the most economic use of equipment for each operating environment. Other types of technologies could also be examined using the proposed methodology.

Final Remarks

Fuel dependency continues to be a major vulnerability for organizations operating in austere conditions. Technologies are being developed rapidly to reduce this vulnerability. The validated methodology discussed in this research provides a tool to evaluate the effectiveness of new energy efficient technology in a variety of operating environments. This capability will allow planners to decide when new technology will be implemented, and will also aid researchers in identifying new technologies in the future.

Appendix A – Radiant Time Series Process



Appendix B – Map Data for Afghanistan

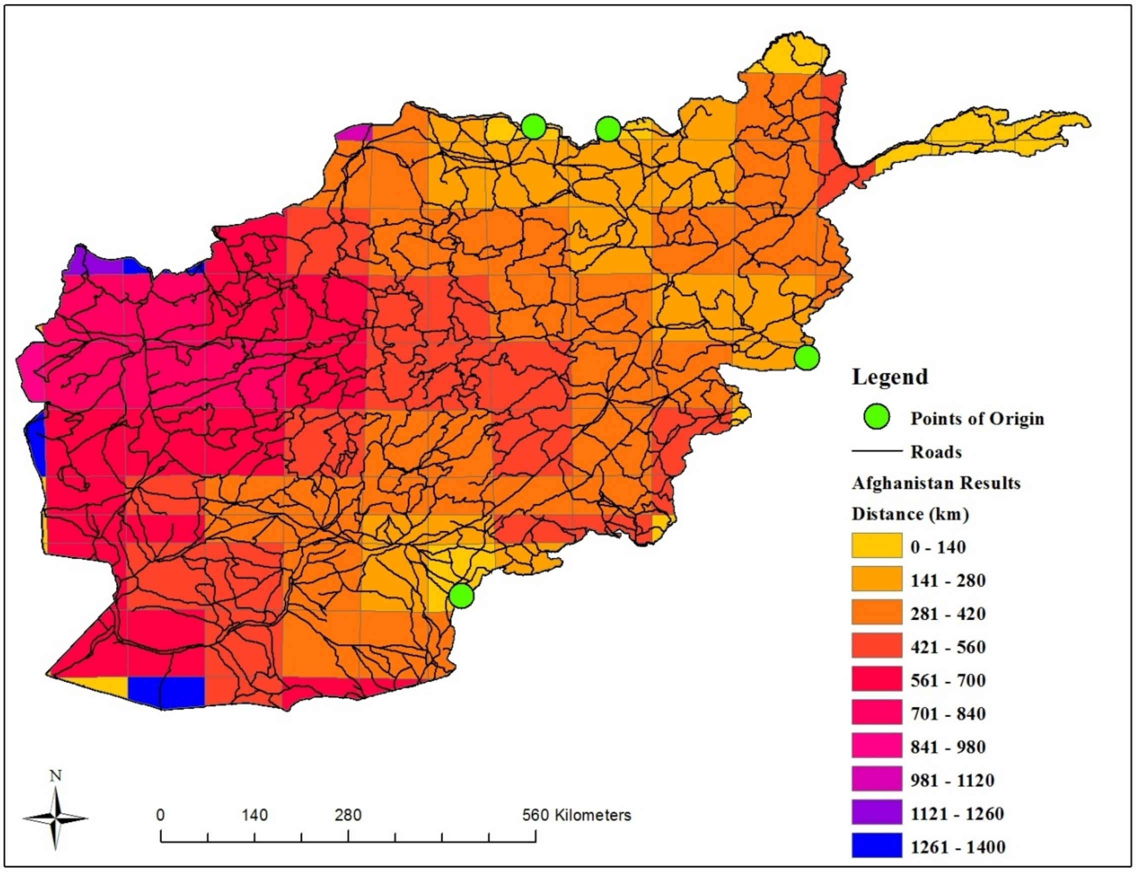


Figure 28. Distance from Point of Origin

Figure 28 shows the distance along the road network from the closest point of origin to each grid zone.

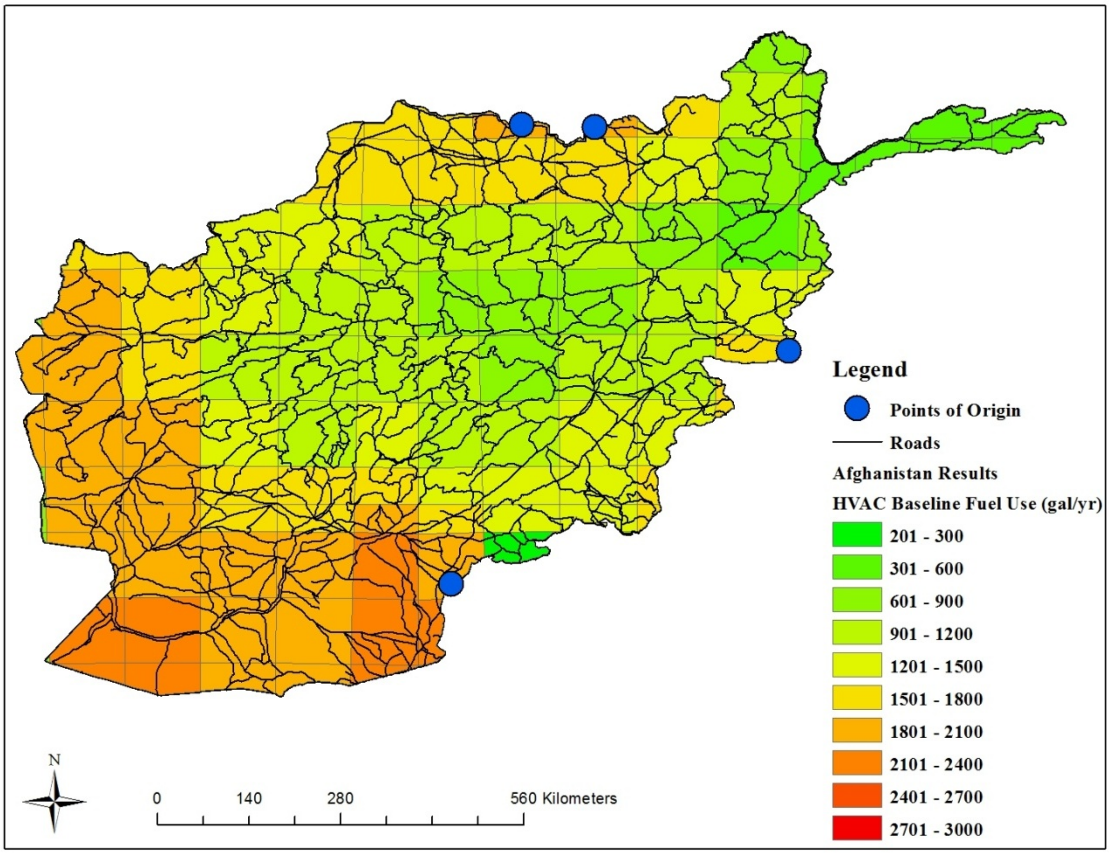


Figure 29. Baseline HVAC Point-of-Use Consumption

Figure 29 shows the estimated HVAC point-of-use consumption for fabric shelters without installed solar flies in Afghanistan. This value represents the annual fuel consumption required to power a single ECU in each grid zone.

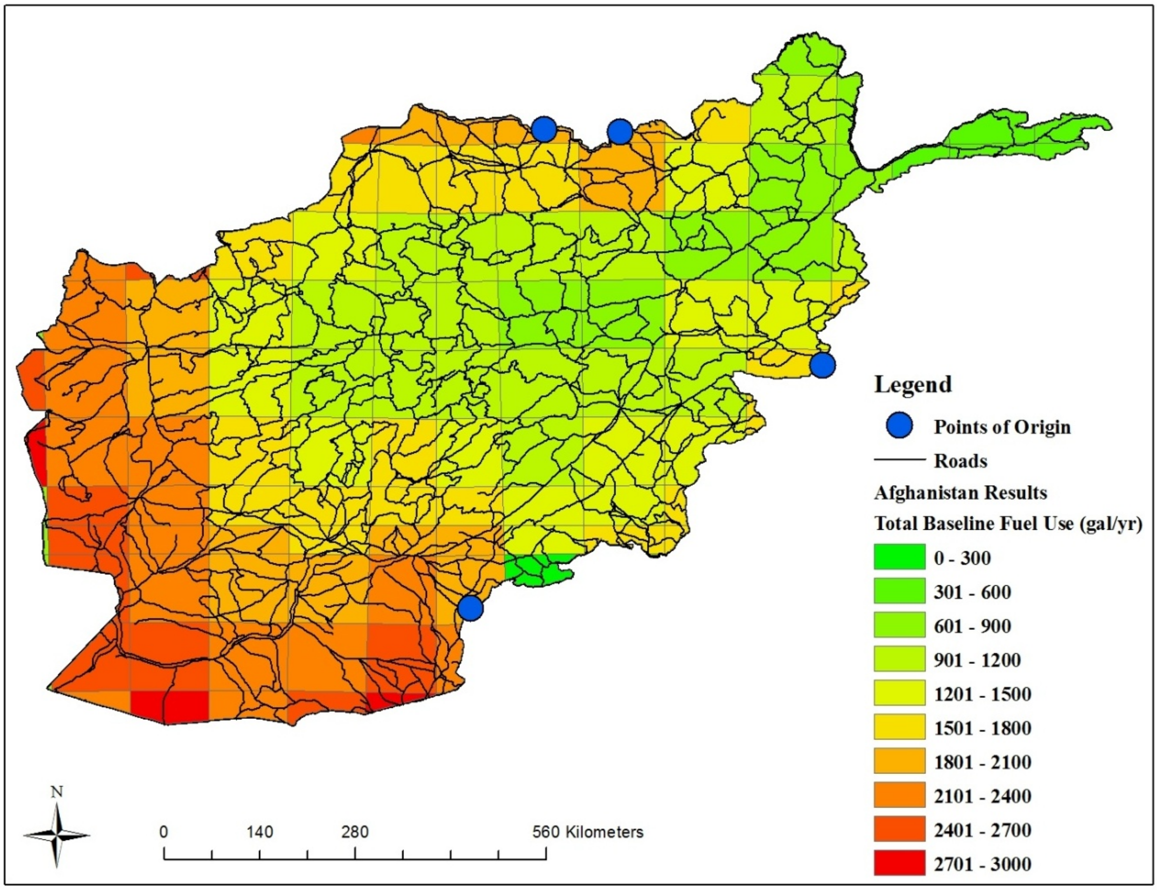


Figure 30. Baseline Total Fuel Consumption

Figure 30 shows the total annual fuel consumption to drive a single ECU in each grid zone without installed solar flies. This quantity includes both the HVAC point-of-use and transportation consumptions associated with powering the ECU.

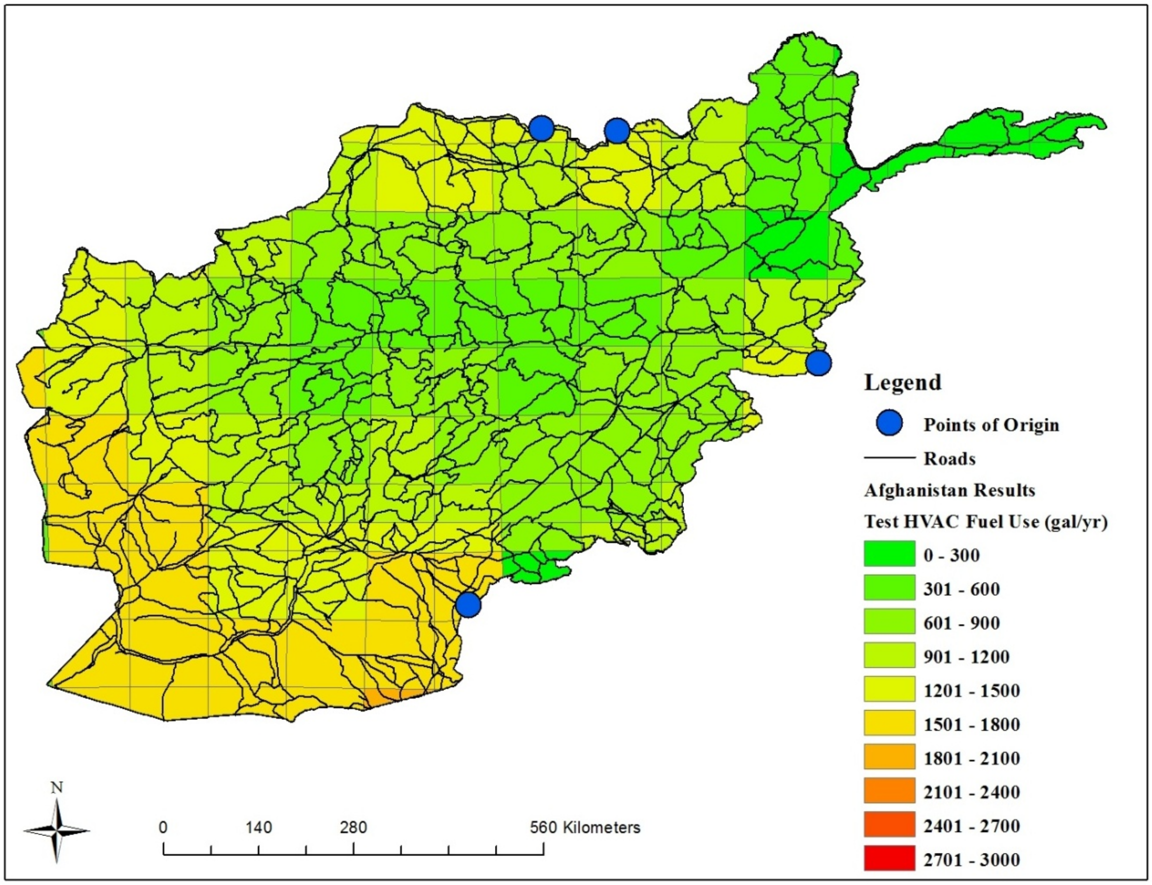


Figure 31. Test HVAC Point-of-Use Consumption

Figure 31 shows the estimated HVAC point-of-use consumption for fabric shelters with installed solar flies in Afghanistan. This value represents the annual fuel consumption required to power a single ECU in each grid zone.

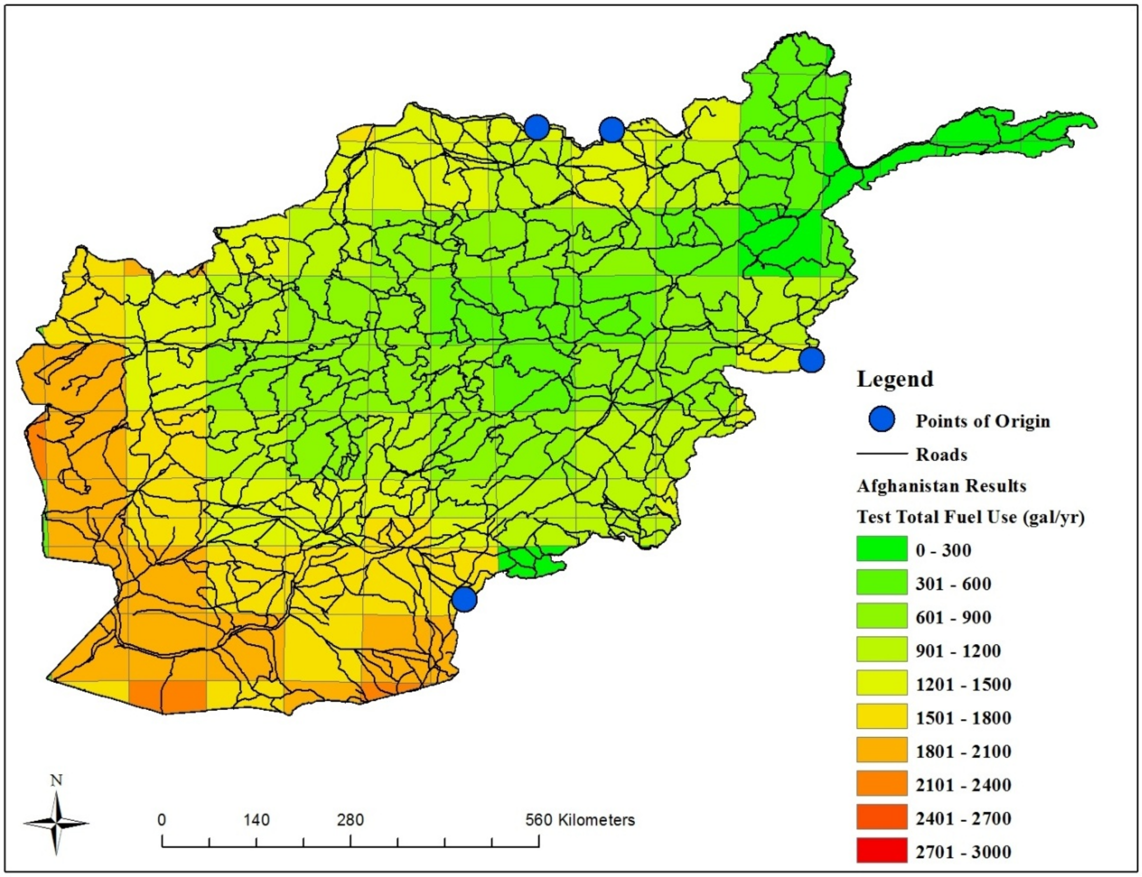


Figure 32. Test Total Fuel Consumption

Figure 30 shows the total annual fuel consumption to drive a single ECU in each grid zone with installed solar flies. This quantity includes both the HVAC point-of-use and transportation consumptions associated with powering the ECU.

Appendix C – Map Data for Brazil

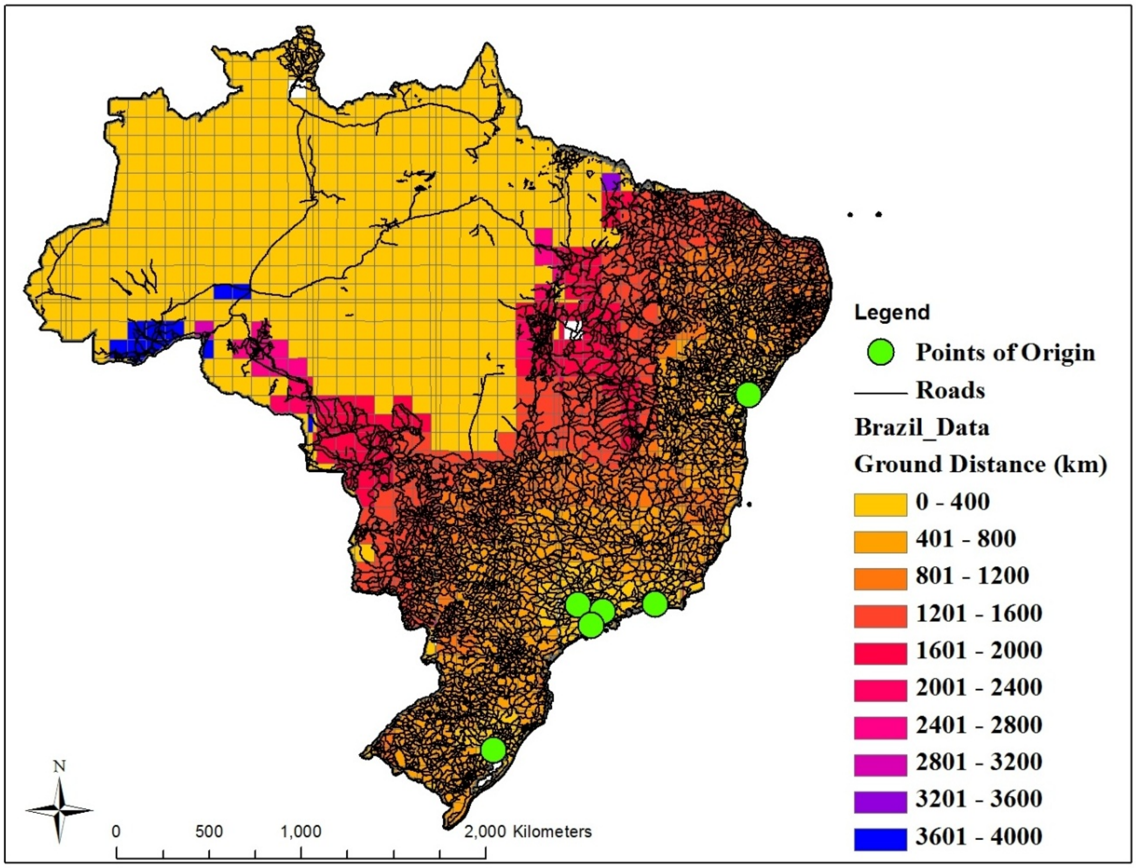


Figure 33. Ground Distance from Point of Origin

Figure 33 shows the distance along the road network from the closest point of origin to each grid zone. The areas denoted as 0-100 that are not adjacent to a point of origin are areas that are supplied by air for the purposes of the case study. The ground distance of the nearest grid zone with road service was used to calculate the total transportation consumption for these grid zones.

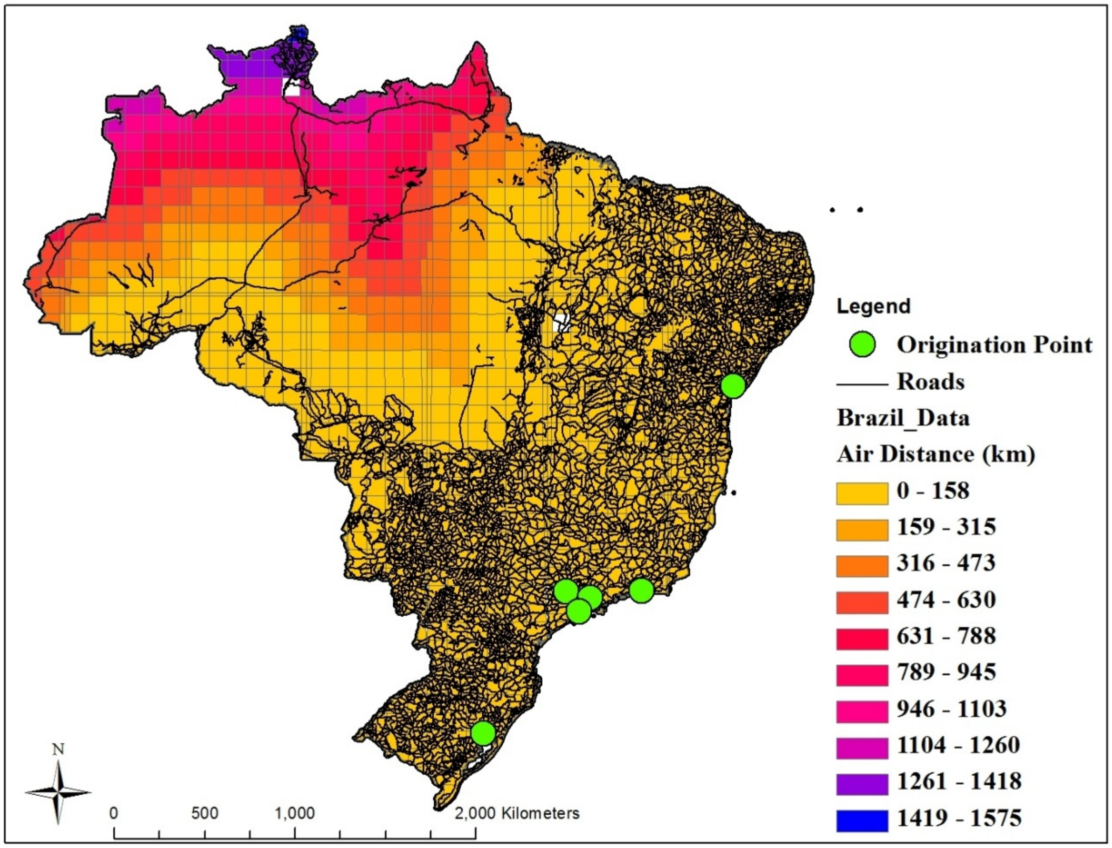


Figure 34. Air Distance from Point of Origin

Figure 34 shows the distance from each grid zone requiring air service to the nearest grid zone that can be serviced by ground. These values were combined with the ground distance to the nearest grid zone serviced by ground to develop a total transportation consumption.

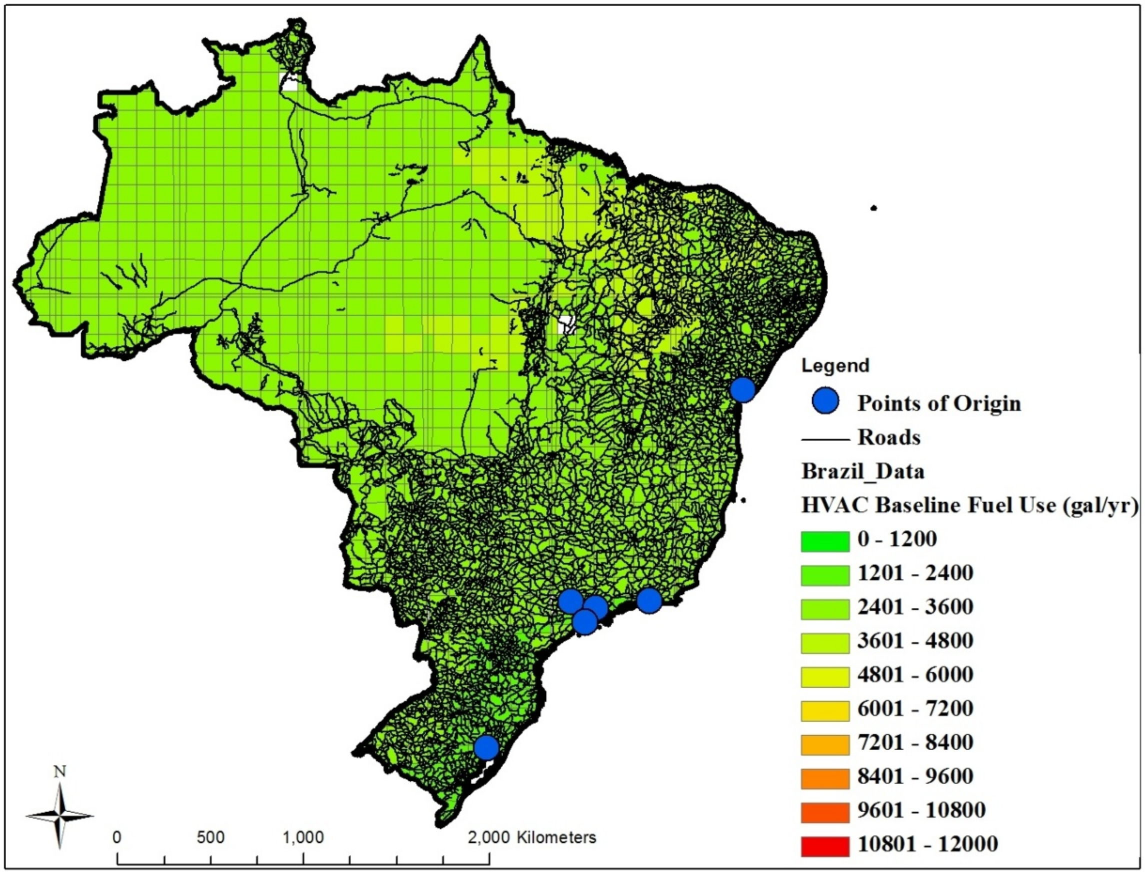


Figure 35. Baseline HVAC Point-of-Use Consumption

Figure 35 shows the estimated HVAC point-of-use consumption for fabric shelters without installed solar flies in Brazil. This value represents the annual fuel consumption required to power a single ECU in each grid zone.

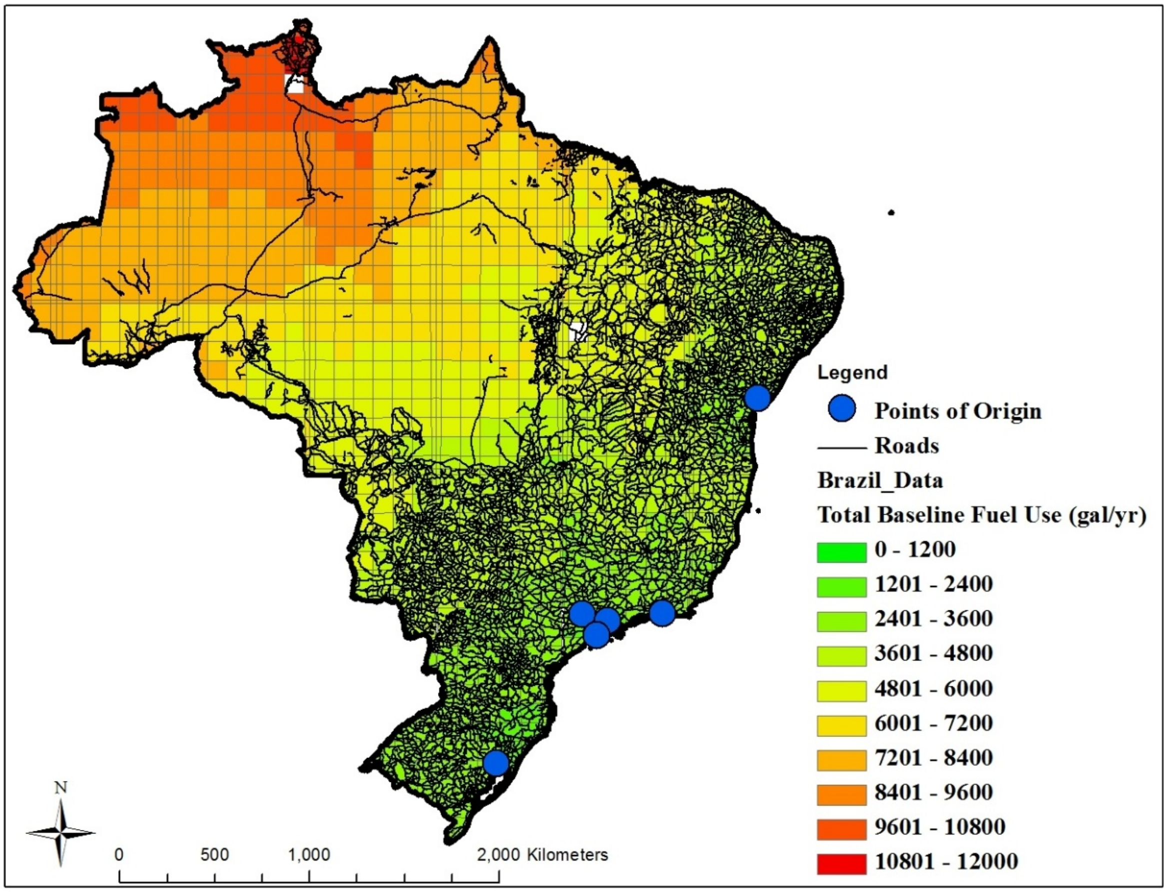


Figure 36. Baseline Total Fuel Consumption

Figure 36 shows the total annual fuel consumption to drive a single ECU in each grid zone without installed solar flies. This quantity includes both the HVAC point-of-use and transportation consumptions associated with powering the ECU.

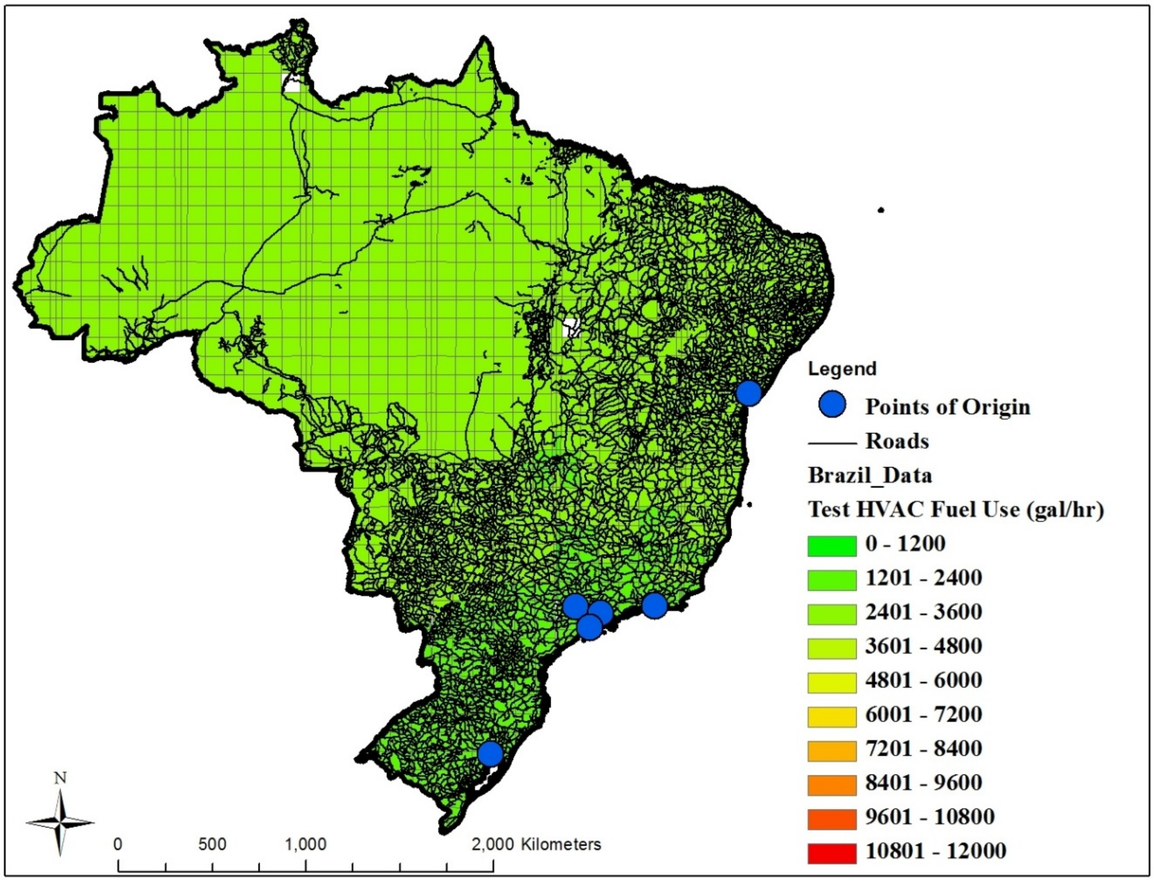


Figure 37. Test HVAC Point-of-Use Consumption

Figure 37 shows the estimated HVAC point-of-use consumption for fabric shelters with installed solar flies in Brazil. This value represents the annual fuel consumption required to power a single ECU in each grid zone.

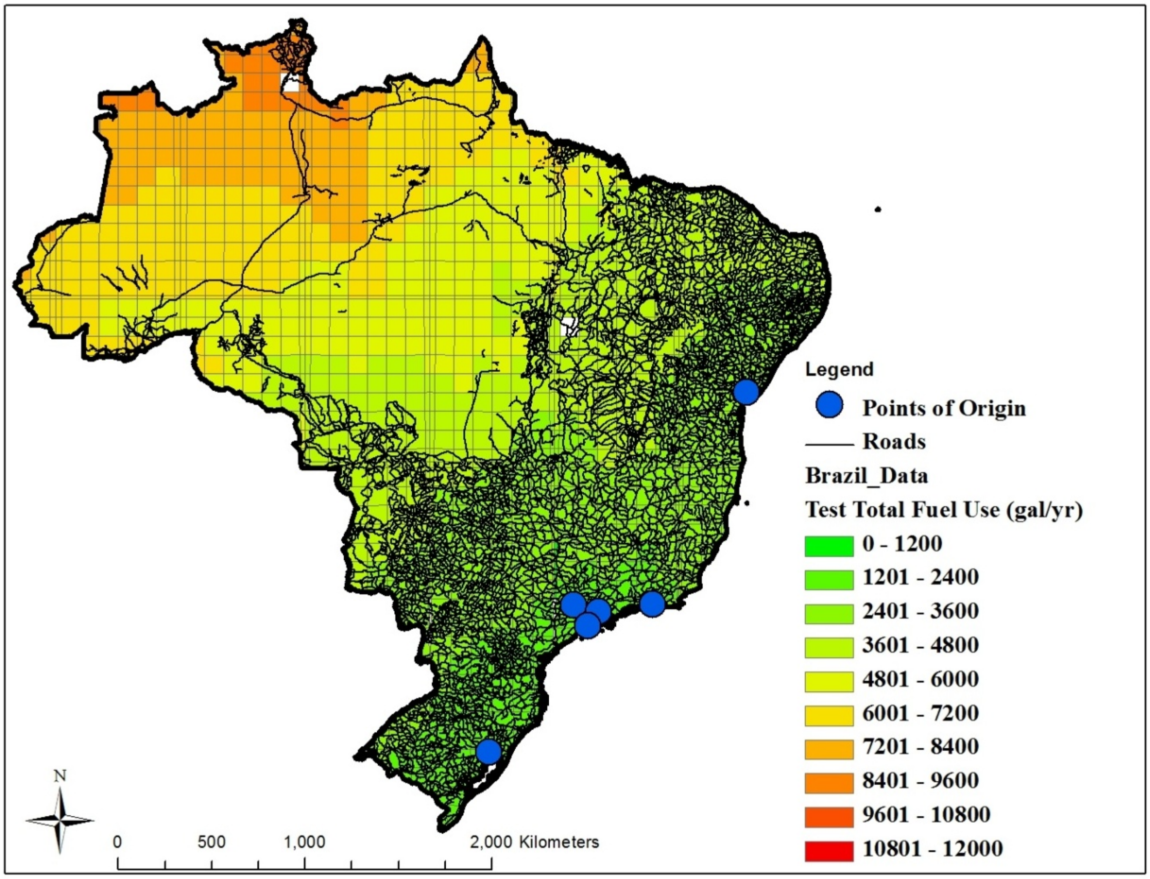


Figure 38. Test Total Fuel Consumption

Figure 30 shows the total annual fuel consumption to drive a single ECU in each grid zone with installed solar flies. This quantity includes both the HVAC point-of-use and transportation consumptions associated with powering the ECU.

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14. ABSTRACT
Organizations that operate in austere environments at the end of long logistics chains face significant energy challenges which often represent financial and security vulnerabilities. Reducing fuel consumption in these operations causes a proportional fuel reduction throughout the supply system as the need for transportation of fuel is reduced. Accordingly, the total fuel reduction across the supply system should be considered to capture the fully burdened cost savings when conducting economic analysis of energy reduction initiatives. This research examined the energy savings potential of improving the thermal properties of expeditionary shelters, and then evaluated these measures using a fully burdened cost savings technique. Geographic Information Systems, Radiant Time Series cooling load analysis, and fully burdened concepts were applied to develop a model that analyzes the economic effectiveness of various shelter improvements in any climate and location in the world. Specifically, solar flies developed through Solar Integrated Power Shelter System (SIPSS) program for installation on fabric shelters were examined. The model was validated against test data provided by the SIPSS program, and then it was applied to two case studies. Results indicated that the energy savings in transportation associated with point-of-use energy reduction initiatives can represent a substantial portion of the overall fuels savings, which validates the idea that cost savings should be evaluated on a fully-burdened basis. Additionally, the SIPSS solar flies were overwhelming economically justified in most regions studied, but a lack of effectiveness in certain regions validated the need for the developed methodology.

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