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OPTIMIZATION OF MICROGRIDS AT MILITARY REMOTE BASE CAMPS

by

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ABSTRACT

Energy savings both on the battlefield and at home are a high priority for the U.S. military. We present two mixed integer linear programs developed for a microgrid providing electrical power to a remote U.S. contingency base. The first program minimizes the total cost of electricity production and the second program minimizes the fuel consumption through the scheduling of generators, energy storage systems, and alternative energy production. Using the U.S. Army's Base Camp Systems Integration Laboratory as our baseline setup, we ran several different simulated microgrid scenarios through the model to determine possible fuel savings. The results showed varying levels of energy savings depending on the tested scenario. Installing different size generators instead of identical size generators produced fuel savings. Adding a battery storage system also increased the fuel savings. Finally, a photovoltaic solar array was evaluated in the microgrid and we found that it produced significant fuel savings.

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List of Acronyms and Abbreviations

ADCS Advanced Digital Control System

AMMPS Advanced Medium Mobile Power Sources

BCSIL Base Camp Systems Integration Laboratory

COTS commercial off-the-shelf

EXFOB Experimental Forward Operating Base

E2C Expeditionary Energy Concepts

GAMS General Algebraic Modeling System

kW kilowatt

kWh kilowatt hour

NPS Naval Postgraduate School

OEI Office of Energy Initiatives

SAGE Smart and Green Energy for Base Camps

TQG Tactical Quiet Generator

USMC U.S. Marine Corps

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CHAPTER 1:
Introduction

The warfighter's demand for energy has been steadily increasing since the dawn of conflict. Now, more than ever, success on the battlefield depends on the ready availability of energy. Without adequate energy resources and production, any modern war machine grinds to a halt. The research in this thesis led to the development of an optimization model for scheduling electricity production and distribution at remote contingency military base camps. This model makes the most efficient use of the energy available to a base camp and has the potential to reduce the amount of energy required on the battlefield.

1.1 Importance of Operational Energy

Energy has always been a critical component to successful warfighting. From hay for horses to petroleum for jeeps and fissile material for nuclear reactors, energy is the catalyst to sustaining operations in any wartime scenario. The importance of operational energy to the U.S. Army was underscored in 2012 when the Operational Energy Office was established under the Assistant Secretary of the Army for Installations, Energy, and Environment [7].

Operational energy is defined by U.S. Code as "the energy required for training, moving, and sustaining military forces and weapons platforms for military operations" [8]. This includes "the energy used by tactical power system and generators and weapons platforms" [8]. This energy has been identified as a target area for savings in the U.S. Army. The head of the Operational Energy Office in 2012, LTG Raymond V. Mason, described the costs associated with energy transportation in the battlefield: "It is a huge funding and resource requirement. So anything we can do to reduce that consumption is important to saving lives and money, and reducing the burden on the commanders" [7].

The importance of fuel consumption is only exacerbated during wartime operations. As seen in Table 1.1, the difference in fuel consumption between wartime and peacetime is significant, but not surprising [5]. What is notable, however, is the relative increase in certain categories. Wartime generator fuel consumption increases over 13 times the amount of peacetime consumption while the total U.S. Army fuel consumption increases less than

Table 1.1. Army Fuel Consumption as a Function of Operations Tempo. Adapted from [5, Table 1-1].

Energy Consumers	Wartime Optempo (millions of gallons)	Percent of Total	Peacetime Optempo (millions of gallons)	Percent of Total
Non-Tactical	51	5%	51	18%
Combat Vehicles	162	15%	30	10%
Tactical Vehicles	173	16%	44	15%
Combat Aircraft	307	29%	140	48%
Generators	357	34%	26	9%
Total	1,050	100%	291	100%

4 times that of peacetime [5]. Generator efficiency and fuel savings is the main focus area of our research.

1.1.1 Operational Energy Office Initiatives

Quickly after establishment, the newly formed Operational Energy Office developed a list of initiatives aimed directly at reducing the amount of energy used within the organization. Three of the top ten initiatives relate directly to our research. These initiatives include the acquisition and deployment of Advanced Medium Mobile Power Sources (AMMPS), the continued research and development at the U.S. Army's Base Camp Systems Integration Laboratory (BCSIL), and the development and deployment of electrical microgrids [7].

AMMPS Generator Sets

The U.S. Army started the acquisition of the AMMPS generators in 2011 (see Figure 1.1) to replace the aging Tactical Quiet Generator (TQG). These new AMMPS generators come in sizes ranging from 5 to 60 kilowatt (kW) and are smaller, lighter, and reduce fuel consumption by 21% when compared with the legacy power sources [9].

BCSIL

In order to test and evaluate new technologies in a simulated remote base environment, the U.S. Army established the BCSIL in 2011 under the management and operation of the Product Manager Force Sustainment Systems at Fort Devens, Massachusetts [10]. The primary mission of the BCSIL is to enable the U.S. and Joint Services to evaluate

Figure 1.1. Advanced Medium Mobile Power Source 60 kW Generator

future technologies while providing solutions to reducing the energy demands and logistical requirements of deployed contingency bases and non-traditional installations [1]. In the spring of 2017, the BCSIL was set up in a standard 150-troop base configuration as seen in Figure 1.2. Six 60 kW AMMPS generators were connected to an electrical power microgrid that provided electricity to all of the electrical loads in the camp. The loads included a kitchen and dining facility, berthing accommodations, an operations center, laundry facilities, latrines, and shower facilities. The microgrid provided power for lighting, heating, ventilation, and air conditioning for all of the temporary structures, as well as electricity for refrigeration, water heating, and waste-water treatment and recycling.

2014 Smart and Green Energy for Base Camps (SAGE) Project

Another initiative completed by the Operational Energy Office in 2014 was the SAGE project [5]. This project was completed by Pacific Northwest National Laboratory under contract by the Department of Energy at the U.S. Army's BCSIL [5]. The SAGE project was created to directly support one of the U.S. Army Operational Energy Office's primary missions. The project evaluated existing commercial off-the-shelf (COTS) products and demonstrated their ability to directly reduce fuel consumption at remote contingency bases [5]. The project demonstrated fuel savings of 49% to 84% depending on the simulated size and location of the contingency bases [5].

Figure 1.2. Aerial View of Simulated Base Camp at Fort Devens, Massachusetts. Source: [1].

Advantages of Electrical Microgrids

The preferred method of power distribution for contingency base camps is through a self-contained microgrid [11]. A self-contained microgrid is a “localized grouping of electricity generation, energy storage, and loads” that normally operate connected together in a centralized grid [11]. Microgrids are generally more efficient and may provide electrical power storage for emergency supply of electricity to mission-essential equipment. An example of a typical tactical microgrid setup in the field is shown in Figure 1.3 [2].

The advantages of electrical microgrids to the U.S. Army have been proven in many studies. The SAGE project confirmed the benefits of establishing a microgrid at a remote contingency base when testing at the BCSIL [5]. The project found that a microgrid setup saved up to 34% annual fuel savings over the traditional spot-generation setup [5]. The U.S. Marine Corps (USMC) also started developing and implementing microgirds. They created the USMC Experimental Forward Operating Base (EXFOB) in 2009 to demonstrate COTS energy and water technologies that can be fielded to increase the operational reach of the force [12]. This program continues today as the Expeditionary Energy Concepts (E2C) where one of the four primary technology areas for 2016 was “energy storage technology for mobile electric micro-grid applications” [12].

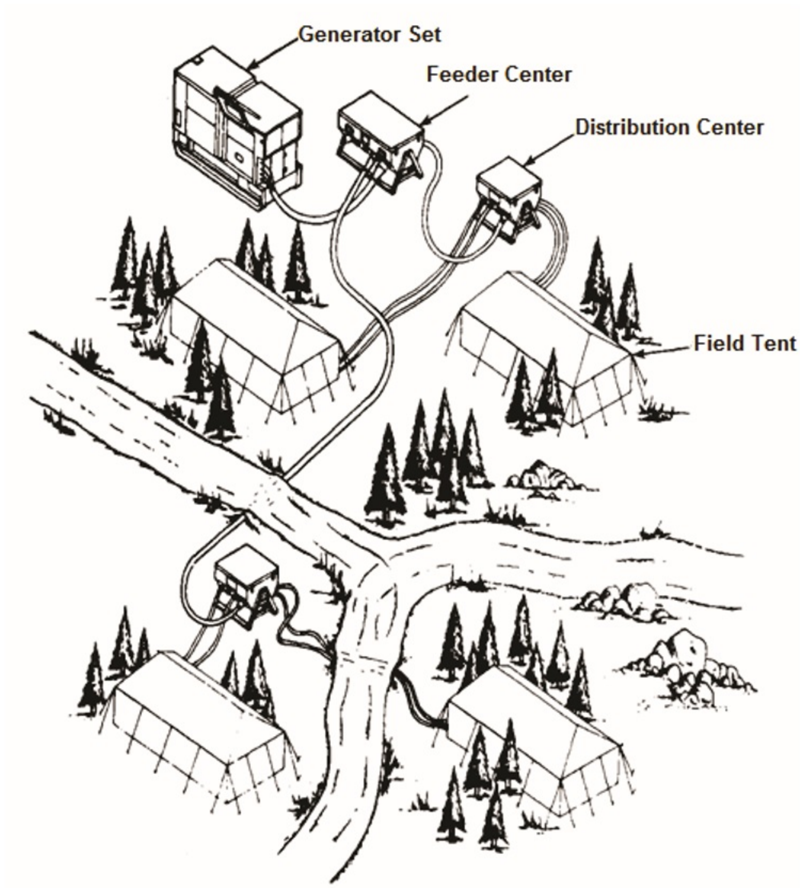

Figure 1.3. Typical Field Placement of a Microgrid. Source: [2].

1.2 Contingency Bases and Non-traditional Installations

In the ever evolving world of warfighting, the U.S. Army developed tactics and procedures for operating contingency bases in all environments throughout the world. Contingency bases are locations used to support and protect deployed forces conducting military operations during a temporary period [6]. These contingency bases are critical to meeting the strategic objectives of U.S. military forces as they directly support the ability to rapidly deploy and support military forces in any environment [6].

1.2.1 Contingency Base Camp Classifications

The U.S. Army classifies contingency base camps by their size and expected duration. Contingency base camps vary from the Platoon size which supports a force of approximately

50 personnel up to the Support Area size which supports 6000 or more personnel as shown in Table 1.2 [6]. Contingency base camps are also classified according to their expected service length which varies from a few weeks up to several years [6].

Table 1.2. Base Camp Sizes and Approximate Populations. Adapted from [6, Table 1-3].

Base Camp Size	**Approximate Population**
Platoon	50
Company	300
Battalion/Battalion Landing Team	1,000
BCT / RCT	3,000
Support Area	6,000 or greater
Legend: BCT / RCT - brigade/regiment combat team	

This thesis mainly focuses on smaller bases classified as Platoon or Company size which support under 1,000 personnel. Additionally, the camp duration timeframe addressed by this thesis is the "Temporary" duration of not more than 5 years.

1.2.2 Contingency Base Camp Electrical Power

Smaller sized base camps are usually located in remote locations away from commercial power generation infrastructures. In most cases, it is necessary for base camps to produce their own electrical power. For the U.S. Army, electrical power in the field is produced almost exclusively using mobile electric generator sets [13]. These generator sets create electricity by driving a generator with a diesel engine. They have an internal fuel supply and all necessary accessories to make them an independent and mobile source of tactical power generation [13].

1.3 Future Technologies

1.3.1 Renewable Sources

As microgrid distribution of electrical power on contingency base camps becomes increasingly common, so too does the research into alternative generation sources. The most common research into alternative generation sources involves wind power generators and solar photovoltaic power generation.

The U.S. Army Office of Energy Initiatives (OEI) manages “cost-effective, large-scale renewable and alternative energy projects on Army installations” [14]. These large projects provide excellent research data for small-scale microgrid implementation. Currently, OEI manages alternative energy projects at U.S. Army installations across the country. Several energy security projects are fully operational providing solar and wind power to U.S. Army installations and the local power grid [14]. Several additional projects have been approved and are under construction for islandable microgrids that use renewable energy production with energy storage systems to provide electricity to the installations [14].

In 2014, the SAGE project tested two renewable energy systems at the BCSIL [5]. The project tested the efficiency of a solar-heated hot-water system that produced hot-water in conjunction with traditional boilers to reduce the use of fossil-fuels [5]. The project also tested two photovoltaic arrays that supplemented the traditional diesel-generators [5]. Both projects helped reduce the consumption of fossil-fuels during the evaluation period and can easily be implemented in the field [5].

1.3.2 Energy Storage

With the increase of renewable and alternative energy generation at contingency base camps, the requirement for energy storage has become increasingly important. Energy storage systems supplement renewable generation sources by storing excess energy during low demand periods and/or high generation periods [15]. When the energy demand is high and/or the renewable generation is low, the energy storage system can discharge electricity to meet the required energy demand [15]. This significantly increases the usability of energy generated using renewable sources by aligning the production of electricity with the actual energy demand. Without an energy storage system, the production of electricity using renewable sources and the load demand must be treated as two disjoint and uncontrollable inputs [16].

Several energy storage technologies are currently being researched for integration into remote microgrids such as batteries, supercapacitors, compressed air, and thermal energy storage. Currently, batteries are the most commonly used energy storage device for microgirds, with Lithium-ion and lead-acid batteries as the two most common types. Lithium-ion is becoming the preferred battery type due to their high energy density and lack of detrimental memory effect [15]. Lead-acid batteries are used when initial purchase cost is a significant driver because they cost less than lithium-ion batteries.

Supercapacitors are electricity storage devices that store energy in an electrode–electrolyte interface with no chemical reactions involved [17], [18]. Because of this, they are able to charge and discharge very rapidly and maintain a longer life span than most batteries. The downside of supercapacitors is that they have a low energy density, which means that their storage capacity per weight is lower than most batteries [17]. In order for a supercapacitor to have the same electricity storage capacity as a battery, the supercapacitor would have to weigh significantly more. In addition, supercapacitors are typically more expensive than a similarly sized battery [18].

Compressed air and thermal energy storage are two additional alternatives for energy storage systems. Compressed air systems work similar to batteries and supercapacitors in that they store energy from excess generation and/or low demand and use it to power the microgrid during periods of low generation and/or high demand. Their excessive size and weight along with relatively inefficient operation relegate this type of system to use in only special circumstances. Thermal energy storage is excellent for capturing excess heat from generation and redirecting it to hot-water heating or building heating tasks.

1.3.3 Rigid Wall Force Provider Base Camp System

Currently, the U.S. Army uses the Force Provider Module system to provide all necessary accommodations for a 150-soldier expeditionary base camp [1]. It is a containerized, highly deployable city with the basic necessities for living conditions [1]. The system includes showers, latrines, laundry, kitchen, and air-beam-supported living tents [1]. The tents are built on wooden platforms and are supported by the inflated beams [1].

The Product Manager for Force Sustainment Systems is currently evaluating rigid-wall camps as seen in Figure 1.4 [3]. These camps are quicker to setup and more energy efficient [3]. In addition, the rigid roof provides a perfect location for photovoltaic solar panels.

Figure 1.4. Prototype Rigid-wall Force Provider System. Source: [3].

1.4 Thesis Organization

There have been countless articles written about the formation and control of electrical microgrids. A literature review of related topics is presented in Chapter 2. This chapter simply highlights some of the more relevant topics and articles with respect to our model.

The mixed integer linear program is developed in detail in Chapter 3. Indices, parameters, constraints and the objective function are presented and thorough explanations of each are provided. The assumptions necessary to maintain linearity and keep the solve times low are explained. Additionally, some of the more common approaches for optimizing the fuel use of a diesel generator are discussed along with the approach taken in our model.

The results of several different scenarios are presented in Chapter 4. First, the current BCSIL setup is run through the model to determine a baseline fuel usage. Then, the model is used to determine if there is any effect on fuel usage by using different sized generators to power the microgrid. A battery storage system is added to the model and finally a photovoltaic solar array is added to determine fuel savings.

Chapter 5 presents the conclusions of our research. In addition, it contains recommendations for future work and research areas.

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CHAPTER 2: Motivating Examples

In the past 20 years, significant military research and development into operational energy efficiency has been conducted. In addition, there has been extensive academic research into increased energy efficiency through microgrid optimization. This section focuses on the academic research and achievements related to microgrid optimization, military microgrids, and increases in energy efficiency.

2.1 Microgrid

In the context of electrical power supply, microgrids are defined as "small power systems with enough local power generation to supply entirely a local load demand (or at least a significant portion of it) and have the ability to work in grid-connected or islanded modes of operation" [19]. The exception to this definition for contingency base camp microgrids is that they almost always operate in an islanded mode because there is rarely the opportunity or availability to be grid-connected.

Using microgrids to supply electrical power to contingency base camps has been proven to produce up to a 34% annual fuel savings when tested at the BCSIL [5]. On a larger scale, the U.S Army replaced thirteen 60 kW TQGs at Bagram Airfield in Afghanistan with a 1-megawatt microgrid [20]. The U.S. Government Accountability report found that a 17% fuel savings resulted during a 4-month test period in 2011.

The efficiency of a microgrid was proven in a laboratory setting by R. Kelly of the Department of Computer and Electrical Engineering at the Naval Postgraduate School in [21]. In the test, the fuel consumption of a traditional generator setup at a contingency base camp was calculated. This result was compared with the fuel consumption of the same generators and electrical load demands setup in an energy management system-enabled microgrid. The 24-hour simulation definitively concluded that connecting available generators and electrical loads to an energy management system-enabled microgrid produced a fuel savings of over 50% [21].

2.2 Fuel Consumption Minimization

In [19], an optimization model was developed to minimize the cost of fuel consumed in a theoretical microgrid containing two reciprocating gas-engine generators, a combined heat and power plant, photovoltaics, and wind generators. The research compared four strategies for defining how two gas-engine generators of different sizes work together to share an electrical load. The power curve is an important part of determining fuel consumption of a generator and is generally a graph that plots the power output of a generator versus the fuel consumed to produce that power output. First, a simple linear power sharing strategy was analyzed where the power curve is assumed to be linear and both generators equally share all loads. The second strategy was a nonlinear power sharing scheme that used piecewise-linear power curves. The third strategy used dynamic power sharing where the power curves are linear, but the load sharing between the generators is not fixed. The final strategy optimized the sharing of power on a highly nonlinear power sharing scheme [19].

The analysis determined that the optimized strategy was superior to both the linear and piecewise-linear (nonlinear) strategies [19]. Both the linear and nonlinear strategies have both generators running and producing at least some amount of power under all scenarios. The optimized strategy attempts to minimize the amount of fuel used, therefore minimizes the number of generators running under all scenarios. This leaves a single generator running and the other generator off for all loads from 0 up to the maximum output of the largest generator. There is a handover point at the maximum load for the smaller generator where that generator turns off and the second generator starts up and takes the full load [19].

In order to complete a fuel consumption comparison, data for two specific generators were curve-fitted and interpolated by a fourth-order polynomial [19]. The results for the nonlinear power sharing model produced a noticeable fuel reduction between a 15%-60% power demand. Moving to the optimization strategy increased the fuel savings an additional 20% over the nonlinear strategy with a power load between 30%-60% [19].

This model included a penalty function and a security margin [19]. The penalty function charged a penalty for any excess heat produced above that which is required by the microgrid. The penalty factor is scalable to permit an impact that ranges from minimally significant to highly significant. The security margin insured that the microgrid is able to respond to fluctuations in the power demand. The security margin is a user-defined factor that can be covered by any combination of the installed electricity generators.

C. Hernandez-Aramburo et al. suggested the following list as several options for determining a security margin:

1. cover the largest available load in a ready standby mode but not currently connected to the grid;
2. cover the potential loss of the highest output generator currently providing power;
3. provide an additional specified percentage of power (reserve energy) [19].

After developing and testing the model for the theoretical microgrid, the authors found that it was difficult to present the results as there was a large number of selectable settings and parameters. Without a real-world scenario with actual data, a theoretical optimization problem can adjust all of the parameters from the penalty factor and security margin to the simulated solar irradiation and wind speed conditions [19]. This causes an overwhelming amount of potential results.

One important takeaway from the experimental model developed in [19] was the importance of a communication infrastructure that updates governor settings to achieve optimal performance. The authors hypothesized that a communication infrastructure would help coordinate power plants with predictable outputs such as photovoltaic and wind power, increase the power sharing ability of all power generation sources, and significantly minimize operating costs. Although this seems like a more obvious conclusion, in 2005, the cost of a communication network linking a microgrid was not insignificant. However, C. Hernandez-Aramburo et al. realized that a communication network was necessary to maximize the benefits of a cost minimization model for a microgrid.

2.3 Lifetime Characteristics of a Battery in Energy Storage Systems

A significant amount of research has been conducted into increasing the energy efficiency of islanded microgrids. Although most microgrid systems have some sort of energy storage capacity, many of the models and problems that attempt to quantify the outputs and costs of these microgrids make wide-sweeping assumptions about the costs and lifecycle of the batteries used to store the electricity.

China's easternmost inhabited island of Dongfushan Island has a microgrid that includes wind, solar, and diesel generation to supply electrical power, lead-acid batteries to store electricity, and an electrical distribution system to connect the island's electrical loads. In [22], B. Zhao et al. developed a model of this electrical microgrid with the goal of analyzing a battery energy storage system in a microgrid to determine the effects of minimizing fuel usage on the lifetime characteristics of lead-acid batteries. The authors made the argument that simply minimizing fuel does not produce a complete and true calculation of savings due to the significant cost of batteries. They suggested the need for a model that both increases the use of renewable electrical generation and maximizes the preservation of the battery life.

The two goals of minimizing power generation cost while also maximizing the useful life of the batteries end up being contradictory when subjected to most scenarios. This led to the need to develop and solve a multi-objective optimization problem using the nondominated sorting genetic algorithm [22].

In another study of lead-acid batteries, D. Jenkins et al. found that in order to optimize the life expectancy of batteries, it was best to operate them at a high state of charge [23]. In [24], R. Kaiser developed a list of the largest stress factors on a battery system:

1. operating at a low state of charge for an extended period;
2. partial cycling at a low state of charge;
3. rarely achieving full charge;
4. operating at higher temperatures.

Using these previous studies, B. Zhao et al. assumed a minimum battery state of charge of 0.5 and assumed that the weighting factor was linear to the state of charge [22]. This linear weighting factor was used to express the battery loss of life cost. The model was run using actual historical data from Dongfushan Island for 2 scenarios, abundant renewable resources and limited renewable resources. Both scenarios produced significant cost savings with the abundant resources reducing cost by 37.6% and the limited resources scenario reducing cost by 23.6%. The proposed method was able to achieve the objectives of reducing the electrical generation cost and increase the expected lifetime of the battery [22].

2.4 Energy Storage Sizing for Microgrids

The sizing of energy storage systems for different applications involving renewable energy resources has been widely researched as evident by [25]–[29]. In [15], S. Chen et al. focused their effort on determining the appropriate energy storage system size for both a grid-connected microgrid and an islanded microgrid.

In a grid-connected microgrid, external power can be used to supplement local generation during periods of peak load. Then, when excess power is produced by the renewable energy generation sources, it can be sold to the external grid. Careful consideration of the electricity market prices must be made in order to maximize the market profit in the grid-connected objective function [15].

The islanded microgird does not have the added complication of managing the electricity market prices, but does require that the self-contained microgrid generate all of the electricity necessary to operate. Energy storage can be used to store excess energy produced during periods of lower demand and then use that stored energy to supplement the normal generation sources during periods of high demand [15]. S. Chen et al. developed an objective function that minimizes the total cost of an islanded microgrid.

The system model used in [15] analyzed a microgrid containing multiple types of electrical generation including photovoltaic, wind turbines, microturbines, fuel cells, and a connection to the utility grid. To calculate the maximum power output, p_s, of the solar photovoltaic system, Equation (2.1) is applied:

$$p_s = \eta S I(1 - 0.005(t_o - 25)), \tag{2.1}$$

where η is the solar cell array conversion efficiency in percentage, S is the area of the solar array (m^2), I is the solar radiation (kW/m^2), and t_o is the temperature of the outside air (° C) [15].

Lithium ion batteries were used as the energy storage system in this model [15]. Supercapacitors, compressed air energy storage, flywheel energy storage, and other types of chemical batteries were considered for the model. However, lithium ion batteries were chosen because they have "one of the best energy-to-weight ratios, no memory effect, and have a slow loss of charge when not in use" [15].

The model developed by S. Chen et al. included several cost factors used to determine the total cost of the energy storage system. The one-time initial purchase and installation costs were considered in addition to the cost of annual maintenance. These costs all vary proportionally to the size and capacity of the energy storage system. Additionally, S. Chen et al. claimed their model considered the interest rate for financing the energy storage system. All of these costs were combined to determine the total cost per day in dollars [15].

In order to determine the optimal size and capacity of the energy storage system, S. Chen et al. first determined the minimum size required for the islanded microgrid. The minimum size energy storage system should be able to lower the peak demands by providing previously-stored excess energy. It should also be able to store any excess energy produced by renewable sources and provide previously-stored excess energy when the amount of renewable generation is low such as at night or on calm wind days. The energy storage system may also be used to provide spinning reserve. The spinning reserve is the total amount of available generation in the system and all available energy stored in the energy storage system, minus the current demand and all energy losses [15].

Once the minimum size of the energy storage system was calculated, the optimal size was determined by minimizing the total cost [15]. Then, the total costs of each size system between the minimum and maximum size were calculated. From these costs, the authors proposed that the optimal size energy storage system is determined by finding the minimum cost point.

During the cost-benefit analysis of the islanded microgrid, S. Chen et al. found that by using the previously generated excess energy from the batteries, there were some time periods where generators in the microgrid could be shutoff to save cost. Without the energy in the energy storage system, it would have been required to run those generators to meet demand. Due to the waste of energy caused by using charge and discharge efficiencies of 90%, the model minimized the use of the batteries. For a majority of the time periods, the energy storage system was kept at a constant full charge to maximize the availability of a spinning reserve. The energy storage system only discharged electricity to the microgrid when doing so prevented an additional generator from being required to operate [15].

In [15], it was determined that it is possible to calculate the optimal size of a energy storage system in a microgrid. The energy storage system can be used to store surplus energy generated by renewable sources and distributed to the microgrid at more usable times. It can also be used to operate the generators in a more stable condition and decrease the amount of times generators are started and shutdown. With an optimally sized energy storage system, the model reduced the total cost of the microgrid by 8.64% per day [15].

2.5 Optimizing the Data Rate of a Hybrid Microgrid

When developing and applying microgrid optimization models with renewable power generators such as photovoltaic and wind turbines, most research uses lower frequency data sampling. In [30], Shadmand and Balong developed their optimization model with significantly higher temporal resolution data using a 10-second sampling rate. In addition, the authors developed an optimization model that blends an economic assessment with a technical assessment to both maximize the availability of renewably generated electricity and minimize the investment cost for the system.

This optimization problem was developed using an existing apartment complex that uses a photovoltaic and wind-power generating system to provide electrical power to the buildings in addition to the regular utility grid [30]. The microgrid also has a battery system to store excess energy produced by the renewable power systems. No dedicated reliability analysis was completed for the model, however, the authors included the maintenance cost for each system in addition to inflation, interest, and escalation factors. The total system cost was calculated using the initial, operational, and maintenance costs for each system which were all assumed to be linear. Since the battery system has a significantly shorter life cycle than the other systems, the replacement cost for batteries was added in to the operational and maintenance cost of the system [30].

The hybrid system model was optimized using the Multi Objective Genetic Algorithm which finds a set of equally good solutions called the Pareto Frontier [30]. This solution is not necessarily the only solution, but it is one of many possible feasible solutions that are not dominated by any other solution.

The model was used to determine the results both with and without uncertainty scenarios [30]. The authors found that when solar radiation, wind speed, and demand data uncertainties were accounted for, the system availability remained nearly constant, but the system cost was significantly increased. Shadmand and Balong further pointed out that the optimized design does not guarantee system availability for all scenarios as that would significantly increase the cost. What their research did develop, was a model that can optimize the scale of a hybrid microgrid system to both maximize availability of renewable energy production and minimize the total cost of the system. This was made possible by increasing the resolution of the data to prevent oversizing of the microgrid [30].

2.6 Mixed Integer Linear Programs

In [31], H. Morais et al. developed a mixed integer linear program to minimize the total marginal cost of producing electricity for a microgrid. The model aggregates all distributed generation plants into one combined Virtual Power Producer. The main benefit of the Virtual Power Producer concept is that it controls all of the generation sources and the distribution of electricity. All of the generation sources in the microgrid are optimally operated which reduces maintenance and operating costs of the isolated microgrid. The Virtual Power Producer also disconnects non-critical loads when necessary to maintain the balance of generation and demand [31].

The model was tested on a small-scale microgrid system built for experiments and demonstrations at the Budapest University of Technology and Economics [31]. The system consists of a wind turbine, photovoltaic panels, a fuel cell, and a battery storage system. The microgrid has a centralized management system used to measure and control all of the generation sources, battery storage system, and electrical demands. The tested model used the battery storage and fuel cell to maintain a minimum reserve of 10% [31].

In order to preserve low execution time in the General Algebraic Modeling System (GAMS)[1], H. Morais et al. developed their model as a mixed integer linear program. The model contains a linear objective function and linear constraints with binary variables directing the system to charge or discharge the batteries. All costs used in the case study were fixed costs per kilowatt hour (kWh) and the time interval was set to one hour. Using IBM's

[1]According to [32], "GAMS is high-level modeling system for mathematical programming and optimization. It consists of a language compiler and a stable of integrated high-performance solvers. GAMS is tailored for complex, large scale modeling applications, and allows you to build large maintainable models that can be adapted quickly to new situations. GAMS is specifically designed for modeling linear, nonlinear and mixed integer optimization problems."

CPLEX[2] mathematical programming solver applied in the GAMS platform, H. Morais et al. were able to optimize the small-scale microgrid in the case study by minimizing the total cost of the system.

2.7 Optimization Using a Knowledge-Based Expert System

There are other methods used to optimize the efficiency of a microgrid besides developing a mixed integer linear program. M. Ross et al. tested a knowledge-based expert system on an isolated microgrid containing diesel and wind generation with an energy storage system in [16]. The microgrid maintained the generator within operating limits by applying a dump load that balanced the power demand during low loads or high renewable energy generation. The goal was to minimize the use of the dump load in the microgrid by using the knowledge-based expert system to optimize the scheduling of the diesel generator and charge/discharge cycles of the energy storage system in one hour discrete time steps.

The model treated the wind and load data as uncontrollable inputs and assumed the energy storage system was properly sized prior to installation [16]. The model was then applied to a continuously operating diesel generator and also to a scenario where the diesel generator could be turned on and off. This was made possible through the use of a binary variable which identified if the diesel generator was running or shutdown. The model did not consider the inefficiencies and additional costs caused from starting and stopping a diesel generator. The battery used a constant 85% charge and discharge efficiency [16].

M. Ross et al. found that the knowledge-based expert system controller tended to discharge the energy storage system whenever possible. This maximized the available storage capacity in the energy storage system to accept the excess energy provided by the diesel generator instead of wasting it as a dump load. The dump load was only utilized when the energy storage system was fully charged [16].

[2] According to [33], "the CPLEX Optimizer provides flexible, high-performance mathematical programming solvers for linear programming, mixed integer programming, quadratic programming, and quadratically constrained programming problems. These include a distributed parallel algorithm for mixed integer programming to leverage multiple computers to solve difficult problems."

The results of the analysis proved that using the knowledge-based expert system minimized the cost of operating a diesel generator in the microgrid in both scenarios [16]. However, in the scenario where the diesel generator could be started and stopped, the inefficiencies caused by the charging and discharging of the battery reduced the overall effectiveness of the minimization. M. Ross et al. found that for some scenarios, it was more efficient to keep the generator running and use the dump load than to use the energy storage system. They noted that "one cannot neglect the efficiency of energy storage when performing analysis" [16].

CHAPTER 3: Methodology and Problem Formulation

This chapter describes the mixed integer linear program developed to minimize the total cost of producing electricity to meet the demand of a remote U.S. contingency base. First, the model assumptions are explained. These assumptions were required to maintain linearity and keep the solve times low. Next, some of the more common approaches for optimizing the fuel use of a diesel generator are discussed along with the approach taken in our model. Finally, the indices, parameters, constraints, and the objective function are presented with thorough explanations.

3.1 Assumptions

Part of the challenge with developing a model of a complex system is determining which factors to make assumptions about. If the model incorporates all factors and limits of the physical system, it may become unnecessarily complex, resulting in unreasonable solve times for optimality. Conversely, a model that makes too many broad assumptions of the physical system will produce inaccurate results significantly limiting its usefulness. Our model attempts to strike the best balance of assumptions by considering the most important factors as determined by previous research and our collective experiences.

3.1.1 Electrical Engineering Theory

Our research focus was on a macro-level of contingency base camp microgrid electrical systems. We did not delve in to the electrical engineering or physics levels of the microgrid system. We did not consider wiring details or limitations, electrical resistance losses, load balancing, or phase balancing. We assumed that all loads and generation sources were balanced. In general, our research focus was on the total load of the microgrid, not on individual component loads.

3.1.2 Transmission Losses

Most electrical power system models attempt to minimize the operating costs. These operating costs are broken down into the operating efficiency of generators, fuel cost, and transmission losses [34]. For a microgrid model, the generators are positioned very close to the electrical loads, so transmission losses were not factored in to our model.

3.1.3 Time Period

We selected a time period of 15 minutes. Decisions made at the second and microsecond level are beyond the scope of this research. We assumed that all decisions at that level were successfully managed by properly programmed and fully operating microcontrollers.

As seen in Section 2.5, many optimization models use one-hour time periods. However, using a higher-resolution data rate produced better results and prevented the oversizing of microgrids. We picked 15-minute periods to increase the accuracy of our model from the one-hour rate, while still keeping the computational solve time well under the time period rate. Using a time period under 15 minutes would have made it difficult to solve the model and adjust the microgrid in real-time.

3.1.4 Battery Modeling Assumptions

We selected lithium-ion batteries as the energy storage system to be used in our model. As discussed in Section 1.3.2, this type of battery has many benefits and as such is utilized in the vast majority of microgrids. Although supercapacitors are an intriguing alternative, their position as a currently-developing technology limited their ability to be immediately implemented in the field.

For the lithium-ion battery storage system, we assumed a constant charge and discharge efficiency. This is a broad assumption that becomes increasingly inaccurate as the state of charge of the battery reaches 100% capacity. Research shows that a battery's charge efficiency is relatively constant at lower states of charge. However, as the state of charge increases over 80% to 85%, the charging efficiency significantly decreases [35], [36]. This means that at higher states of charge, a significantly greater amount of energy will be required to charge the battery.

The operating cost and maintenance cost for the battery storage system are assumed to be linearly dependent on the amount the battery charges or discharges in each time period. This operating and maintenance cost constant is based on the initial purchase and setup cost and the cost of scheduled maintenance.

The battery will also provide the spinning reserve for the microgrid within each 15 minute time period. Since the load will not be perfectly constant for the entire period, the battery will be required to absorb the load inconsistencies.

3.1.5 Generator Modeling Assumptions

The total cost of generating electrical power with a diesel generator includes the cost of fuel, labor, supplies, and maintenance. The fuel cost is considered nonlinear because fuel efficiency of a diesel generator increases non-linearly as a percentage of electrical output [34]. During low load operations, a diesel generator is very inefficient. As the percentage of rated load increases to 100%, diesel generators become more efficient.

While the fuel cost is nonlinear, often times the labor, supplies, and maintenance costs are assumed to be linearly dependent on the fuel cost [34]. These costs can even be tied directly to the fuel cost to form one incremental fuel-cost curve [34].

Our model also calculates the cost of starting a generator. This is a fixed-cost that will be directly dependent on how many (if any) generators are started in a period. It is assumed that the cost is only for starting a generator and there is no cost for shutting down a generator.

3.2 Single Generator Optimization

A major hurdle in optimizing fuel cost for a diesel engine is determining the best approximation to use. For most cases, there are a very limited number of fuel efficiency data points actually measured for a specific diesel generator. Many diesel generators have only proprietary test data or no test data at all. The best cases have a few sample points collected at specific generator power settings. The fuel efficiency at the untested intermediate power settings are then estimated using different "best-fit"curves. The following sections contain different estimation techniques for developing an approximate fuel efficiency curve for diesel generators.

3.2.1 Quadratic Approximation

In most instances, a diesel generator's nonlinear fuel cost can be estimated as a quadratic approximation of the power generated

$$C_i = \alpha_i + \beta_i P_i + \gamma_i P_i^2, \tag{3.1}$$

where C_i is the cost of fuel for generator i, P_i is the power output of generator i, and α_i, β_i, and γ_i are constants [34]. This is a very common approximation for the fuel cost of a diesel generator.

Using this approximation technique with the available data for an AMMPS 60 kW generator gave us Figure 3.1. The quadratic approximation of this plot is

$$G_i = \frac{E_i}{6.183 + 0.260 \cdot P_i - 0.002 \cdot P_i^2}, \tag{3.2}$$

where generator i is producing P_i kW (rate) and G_i is the amount of gallons used per hour by generator i to produce E_i kWh (energy) of electricity. This approximation is valid when the generator is running above a 25% load. Most internal combustion generators become very inefficient at lower power ratings and thus are kept from operating in this range.

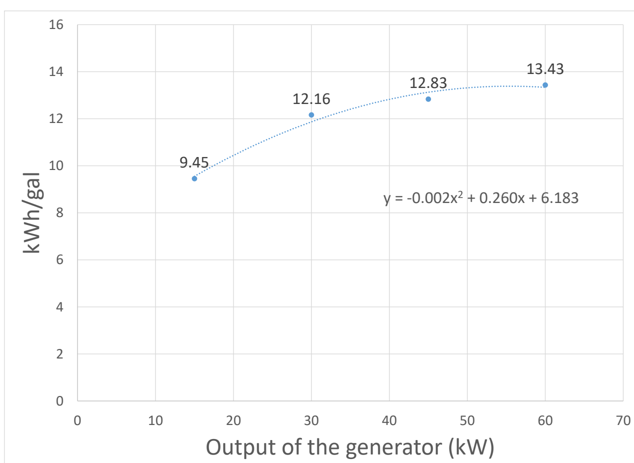

Figure 3.1. Quadratic Approximation of 60kW AMMPS Fuel Efficiency.

3.2.2 Exponential Fit Using Golden Search

Another approximation for diesel generator efficiency that we researched was an exponential curve. We used the golden search function in MathWorks' MATLAB program to find the best fit to the curve

$$y(x) = c_0 + c_1 e^{-c_2 x}, \tag{3.3}$$

where c_0, c_1, and c_2 are constants and x is the power output of the generator. Using AMMPS generator fuel efficiency data obtained from testing at the BCSIL, the golden search function returned the fuel efficiency curve approximations displayed in Figure 3.2. The left graph displays the 30 kW AMMPS fuel efficiency at generator output levels of 15% to 100% of the rated output. The right graph of Figure 3.2 displays the fuel efficiency of the 60 kW AMMPS in the same operating range. As seen in both graphs, the fuel efficiency drastically increases from 15% to about 50% rated load. Above 50%, the fuel efficiency increases at a much smaller rate.

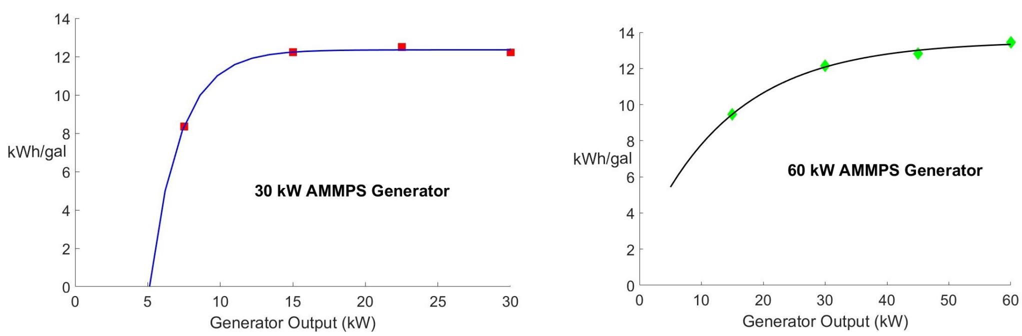

Figure 3.2. Exponential Approximations of AMMPS Fuel Efficiency.

3.2.3 Piecewise-Constant Approximation

After developing the exponential curve approximation of generator fuel efficiency, we used those curves to approximate the rest of the AMMPS generator fuel efficiency at specified intervals. Initially we broke the generator curve into 4 piecewise-constant step function zones. This proved to be a very coarse estimation. Twelve piecewise-constant steps provided a much finer estimation of the generator curve with a maximum deviation from the exponential approximation of 28% as seen in Figure 3.3. Above 33% generator output, the error decreases significantly to below 5%. Increasing the number of steps to 60 provided one kW step sizes for the 60 kW generator. This provided a very close approximation of

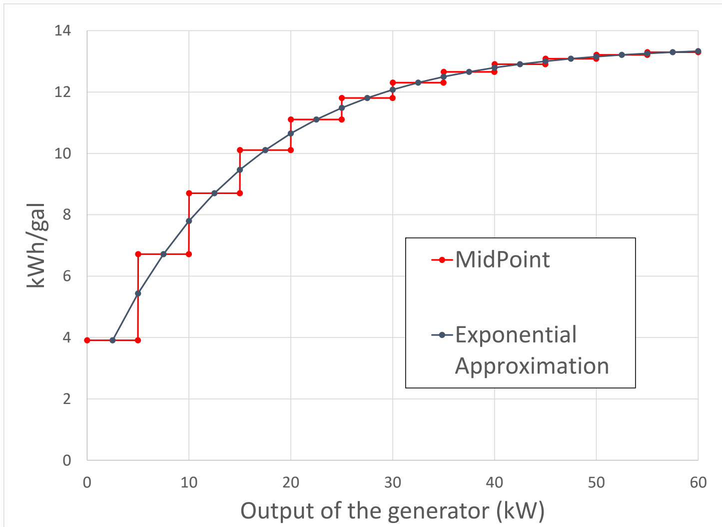

Figure 3.3. Piecewise-Constant Approximation of 60kW AMMPS Fuel Efficiency Using 12 Steps.

the exponential curve with a maximum deviation of 5% and an error of under 1% for all generator output levels above 33%.

The primary benefit of the piecewise-constant approximation of the generator fuel efficiency curve is to maintain linearity. Section 3.3.1 discusses the benefits of a linear program versus a nonlinear program.

3.3 Why a Mixed Integer Linear Program?

Many different types of optimization models exist from simple linear programs to extremely complex mixed integer nonlinear programs. Determining which model type to apply to each instance depends on several factors including system complexity, desired accuracy, and model solve time. Frequently, the goal in creating an optimization model is to create a model that is very accurate and useful without being so overly complicated that it cannot be solved in a reasonable amount of time. The following section will highlight some of the optimization model features and definitions applicable to our model.

3.3.1 Linear versus Nonlinear Programs

One of the fundamental optimization modeling considerations is determining whether or not the model is linear or nonlinear. In order for a function to be linear, it can only have variables to the first power and terms with constants [37].

A **linear program** is defined as "an optimization model in functional form when the (single) objective function f and all constraint functions $g_1, ...g_m$ are linear in the decision variables. Also, decision variables should be able to take on whole-number or fractional values" [37].

A **nonlinear program** is defined as "an optimization model in functional form when the (single) objective function f or any of the constraint functions $g_1, ...g_m$ is nonlinear in the decision variables. Also, decision variables should be able to take on whole-number or fractional values" [37].

As described in [37], linear programs are always preferred to nonlinear programs if they are appropriate. Each nonlinearity reduces tractability in a program when compared with a strictly linear program. This increases the difficulty and time it takes to solve a program. However, sometimes linear programs are not appropriate. They are limited to equal returns to scale because they are restricted to constants and first power variables only [37].

3.3.2 Discrete Programs

Discrete optimization models are mathematical programs that use discrete variables to make logical decisions [37]. Discrete variables are different from the quantitative decisions of linear and nonlinear continuous variables. Discrete variables are defined as variables "limited to a fixed or countable set of values" [37].

Although there are many types of discrete variables, two common types are binary variables and integer variables. Binary variables have an output limited to the values of only 0 or 1 [37]. This type of variable is frequently used for on/off or yes/no types of decisions. Integer variables have an output limited to integer values [37]. These variables can be modified by further restricting their output to non-negative integers, positive integers, etc. Integer variables are frequently used in manufacturing models where fractions of a product cannot be produced [37].

Optimization models that contain only continuous variables with no discrete variables are called continuous optimization models [37]. Models that have one or more discrete variables are called discrete optimization models [37]. Mixed integer programs are discrete optimization models that contain both continuous and discrete variables [37].

Our model is a mixed integer linear program. The objective function and all of the constraints are linear. We have no integer variables, but we do have several binary decision variables that change the model from continuous to discrete.

3.4 Optimization Model

Our optimization model is a discrete-time mixed integer linear program developed to minimize the total cost of producing electricity to meet the varying load of a remote U.S. Army contingency base.

3.4.1 Sets and Indices

$t \in T$	Set of all time steps
$g \in G$	Set of all generators
$k \in K$	Set of all generation zones
$h_1 \in H_1$	Set of all critical loads
$h_2 \in H_2$	Set of all sheddable loads
$h_3 \in H_3$	Set of all deferrable loads

3.4.2 Parameters

l	Length of time steps [hours]
ρ_{h_2}	Cost factor for shedding load h_2 [$/kWh]
ζ_t	Amount of deferrable load met during time t [%]
M	Arbitrarily large number

Batteries:

η_c	Battery charge efficiency [%]
η_d	Battery discharge efficiency [%]
Bl_{min}	Minimum battery charge level [kWh]
Bl_{max}	Maximum battery charge level [kWh]
Bl_{start}	Starting battery charge level [kWh]
Bl_{final}	Final battery charge level [kWh]
Br_c	Maximum battery charge rate [kW]
Br_d	Maximum battery discharge rate [kW]
C_b	Battery operating cost constant [$/kWh]

Generators:

$Grmin(k)$	Minimum generator output in zone k [kW]
$Grmax(k)$	Maximum generator output in zone k [kW]
$fuel(k)$	Fuel efficiency in zone k [gal/kWh]
C_f	Generator fuel cost constant [$/gal]
C_g	Generator operating cost constant (maintenance and purchase cost) [$/hr]
C_{SU}	Generator start-up cost constant [$/start-up cycle]
$G(k)$	Number of generators running in zone k
$Z_g(t)$	Auxiliary variable for number of generators started in time step t

3.4.3 Continuous Decision Variables

$u_1(g,k,t)$	Output of generator g in zone k during time step t [kW]
$u_2(t)$	Charging rate of battery during time step t [kW]
$u_3(t)$	Discharging rate of battery during time step t [kW]
$f(g,k,t)$	Gallons per hour of fuel used by generator g in zone k during t [gal/hr]

$TF(g,t)$	Total gallons of fuel used by generator g during time step t [gal]

All of the continuous decision variables are non-negative.

3.4.4 Binary Decision Variables

$$v_1(g,k,t) = \begin{cases} 1, & \text{if generator } g \text{ is operating in zone } k \text{ during time step } t \\ 0, & \text{otherwise} \end{cases}$$

$$v_b(t) = \begin{cases} 1, & \text{if charging battery during time step } t \\ 0, & \text{if discharging battery during time step } t \end{cases}$$

3.4.5 Reference Trajectory

$w_1(h_1,t)$	Critical electrical load h_1 during time step t [kWh]
$w_2(h_2,t)$	Sheddable electrical load h_2 during time step t [kWh]
$w_3(h_3)$	Deferrable electrical load h_3 [kWh]

3.4.6 State Dynamics

$x_1(t)$	Total electrical demand during time step t [kWh]
$x_2(t)$	Energy stored in battery at the end of time step t [kWh]]

3.4.7 Objective Function

$$\begin{aligned} \text{min: } \sum_g \sum_t \left[C_f \cdot TF(g,t)\right] \quad &+ \quad \sum_g \sum_k \sum_t \left[C_g \cdot v_1(g,k,t) \cdot l\right] + \sum_t C_{SU} Z_g(t) \\ &+ \quad \sum_t \left[C_b\Big(u_2(t) + u_3(t)\Big) \cdot l\right] + \sum_{h_2} \sum_t \rho_{h_2} w_2(h_2,t) \end{aligned}$$

Our objective function seeks to minimize the combined cost of fuel consumed by the generators, operating and start-up costs of the generators, battery operating costs, and a cost penalty for sheddable loads not met across all time periods.

3.4.8 Constraints

The objective function described in Section 3.4.7 is subject to the following constraints:

$$\sum_g \sum_k \Big[u_1(g,k,t) \cdot l\Big] - \frac{1}{\eta_c} u_2(t) \cdot l + \eta_d u_3(t) \cdot l = x_1(t) \quad \forall t \tag{3.4}$$

$$\sum_k v_1(g,k,t) \leq 1 \quad \forall g, t \tag{3.5}$$

$$Grmin(k) \cdot v_1(g,k,t) \leq u_1(g,k,t) \quad \forall g,k,t \tag{3.6}$$

$$Grmax(k) \cdot v_1(g,k,t) \geq u_1(g,k,t) \quad \forall g,k,t \tag{3.7}$$

$$f(g,k,t) = fuel(k) \cdot u_1(g,k,t) - M\Big[1 - v_1(g,k,t)\Big] \quad \forall g,k,t \tag{3.8}$$

$$TF(t,g) = \sum_k \big[f(g,k,t) \cdot l\big] \quad \forall g,t \tag{3.9}$$

$$u_2(t) \leq v_b(t) \cdot br_c \quad \forall t \tag{3.10}$$

$$u_3(t) \leq \Big[1 - v_b(t)\Big] \cdot br_d \quad \forall t \tag{3.11}$$

$$Bl_{min} \leq Bl_{start} + l \cdot \sum_s \Big[\eta_c u_2(s) - \frac{1}{\eta_d} u_3(s)\Big] \quad \forall t \tag{3.12}$$

$$Bl_{max} \geq Bl_{start} + l \cdot \sum_s \Big[\eta_c u_2(s) - \frac{1}{\eta_d} u_3(s)\Big] \quad \forall t \tag{3.13}$$

$$x_2(t) = Bl_{start} + l \cdot \sum_s \Big[\eta_c u_2(s) - \frac{1}{\eta_d} u_3(s)\Big] \quad \forall t \tag{3.14}$$

$$x_1(t) = \sum_{h_1} w_1(h_1,t) + \sum_{h_2} w_2(h_2,t) + \zeta_t \sum_{h_3} w_3(h_3) \quad \forall t \tag{3.15}$$

$$Z_g(t) \geq \sum_k \Big[G(k) \cdot v_1(g,k,t) - G(k) \cdot v1(g,k,t-1)\Big] \quad \forall t \tag{3.16}$$

$$Z_g(t) \geq 0 \quad \forall t \tag{3.17}$$

Equation (3.4) ensures that the combined output of all operating generators and batteries meets the total net electrical demand.

Equation (3.5) ensures that each generator g is not operating in more than one generation zone k at any time step t.

Equations (3.6) and (3.7) define the operating zone k that each operating generator will operate in during any time step t. $Grmin(k)$ and $Grmax(k)$ constrain each operating zone k on the lower and upper bound respectively.

Equation (3.8) determines the gallons of fuel used in each of the possible operating zones k by each operating generator g during any time step t. Due to constraint (3.2), each generator will be operating in a maximum of one zone, leaving the rest of the zones using 0 gallons of fuel.

Equation (3.9) adds up all of fuel used in the possible operating zones k of each generator g for each time step t. This gives you the total gallons of fuel used by each generator during each time step.

Equations (3.10) and (3.11) set the maximum limits for the charge and discharge rate of the battery. The minimum limits for the charge and discharge rates are zero.

Equations (3.12) and (3.13) set the limits for the maximum and minimum charge level of the battery.

Equation (3.14) determines the amount of energy stored in the battery at the end of time step t.

Equation (3.15) determines the amount of power to distribute to the three different types of loads (critical, sheddable, and deferrable) at each time step t given the total electrical demand at each time step t.

Equation (3.16) defines the auxiliary variable for the number of generators started in time step t. If n generators are started, Z_g will return a positive integer n. If a generator is turned off, Z_g would attempt to return a negative number, but Equation (3.17) will make Z_g zero. This ensures that only generator starts will be considered as part of the total cost.

3.5 The Subjectivity of Cost Minimization

The mixed integer linear program developed in Section 3.4 is modified in this section to minimize fuel use instead of cost. In an attempt to minimize cost in the optimization model, we found that cost is an extremely subjective factor. Calculating the fully burdened cost of fuel is a complex research topic of its own. Determining a single cost constant for generator operating cost and generator start-up cost depends on several factors including type of generator, level of preventative maintenance, and environmental operating conditions. Calculating a fixed battery operating cost constant depends on initial purchase and installation costs, approximated life expectancy, and environmental operating conditions.

The subjectivity of all of these cost factors compound to form an optimization model that could be widely inaccurate when attempting to run nonspecific scenarios. If all cost factors are known and the cost savings for a specific scenario are desired, the optimization model in Section 3.4 is ideal. However, for this research, removing the subjectivity of cost allows for more accurate comparisons of general conditions.

3.6 Fuel Minimization Model

This alternative optimization model builds directly off the model developed in Section 3.4. The objective function and constraints are modified while maintaining the same sets, indices, parameters, and variables described previously. This optimization model is a discrete-time mixed integer linear program developed to minimize the fuel used to produce electricity to meet the varying load of a remote U.S. Army contingency base.

3.6.1 Objective Function

This objective function seeks to minimize the total amount of fuel consumed by each generator in each time period.

$$\text{min: } \sum_{g} \sum_{t} \left[TF(g,t) \right]$$

3.6.2 Constraints

The objective function described in Section 3.6.1 is subject to the same constraints as the cost model described in Section 3.4. However, Equations (3.15–3.17) are cost specific constraints that do not apply to the fuel minimization model. Those constraints can be ignored in this model.

CHAPTER 4: Results

The results of several different scenarios are reported in this chapter. Using the Fuel Minimization Model developed in Section 3.6, we ran a scenario with the current microgrid setup at the BCSIL. We compared the baseline results with several potential scenarios based on the addition of COTS components and systems to the original microgrid.

4.1 Application of Model Using BCSIL

All scenarios in this chapter are based on the microgrid set up at the BCSIL in May of 2017. This microgrid setup is described in detail in Section 1.1.1.

4.1.1 BCSIL Load Profile

The load data we used for this research was from a training exercise in March of 2016 at the BCSIL. Soldiers occupied the simulated base camp using the tents, kitchen and dining facility, showers, bathrooms, and laundry facility as they would at a remote contingency base camp.

The load profile provided by the BCSIL had 1-minute time interval recordings of the energy used by each tent and structure. All of the loads for each 1-minute time period were added to obtain a total system electricity demand for that minute. To obtain 15-minute time interval demand data, all 1-minute total system electrical demands in each 15-minute period were averaged to produce one total system electrical demand value for each 15-minute period. The total load profile in 15-minute time steps is seen in Figure 4.1. This is the load profile that is used for all optimization simulations in this chapter.

4.1.2 Baseline Results

We ran the model using the equipment actually installed at the BCSIL. This included six 60 kW AMMPS generators supplying a microgrid setup. The generators were controlled and balanced using an Advanced Digital Control System (ADCS) that started and stopped generators according to programmable parameters. The preset parameters start an additional

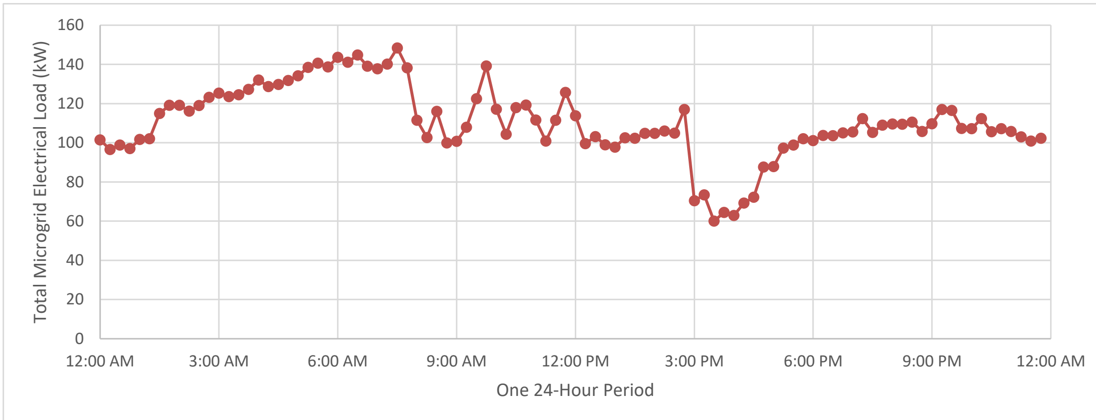

Figure 4.1. 24-hour Electrical Load Profile at BCSIL.

generator if the load goes above 80% of the total capacity of running generators and shuts down a generator if the total capacity of the remaining generators is below 60% [38].

Using the 12-zone piecewise-constant generator efficiency approximation returned a total fuel burn for the 24-hour period of 812.7 gallons. This is the baseline fuel consumption that we compared the results of all system modifications to.

Different Amounts of Generation Zones

The number of zones in the piecewise-constant approximation of the AMMPS generator efficiency can make a substantial difference in the accuracy of the model's output. Selecting a large number of zones will result in more accurate results, but increase the calculation time. A small number of zones will reduce the calculation time, but also have the detrimental effect of reducing accuracy. We ran the baseline scenario using several different efficiency zone sizes to determine the best balance of reduced calculation time and increased accuracy.

As discussed in Section 3.2.3, the first approximation we used divided the generator efficiency curve into 4 piecewise-constant zones. We also ran the model using 12, 60, and 120 piecewise-constant zones to approximate the generator efficiency curve. Table 4.1 displays the results for the different piecewise-constant zones.

Table 4.1 confirms that as the step size increases the accuracy increases and the solve time decreases. The solve time and accuracy using the 60 piecewise-constant zones is satisfactory for this research. The accuracy gain when increasing from 60 to 120 piecewise-constant

Table 4.1. Baseline Results Varying Piecewise-Constant Zone Size.

Zones (#)	Zone Size (kW)	Fuel Burned (Gallons)	Percent Error	Solve Time
120	0.5	816.1	-	1 minute 25.5 seconds
60	1.0	816.3	0.01%	26.5 seconds
12	5.0	812.7	0.42%	5.7 seconds
4	15	810.8	0.66%	1.2 seconds

zones is not significant to overcome the solve time that is nearly three times as long. We used 60 piecewise-constant zones to approximate the generator efficiency curve for the remainder of our research.

Adjusting the Relative Optimality Criterion in GAMS

The Relative Optimality criterion in GAMS is a user-defined set point percentage away from the optimal solution [32]. When a feasible solution is found within that range, the solver will stop [32]. The benefit of this option is that finding the exactly optimal solution in complex problems can be prohibitively time-consuming.

For the initial baseline scenario, 1%, 0.5%, 0.1%, 0.01%, and 0.001% optimality criterion settings were checked. The relative optimality criterion was set at 0.001% as this setting did not result in an unreasonable solve time. This set point stopped the solver when the difference between the solved feasible solution and the best possible solution was no more than 0.001%.

As the model became more complicated with the addition of an energy storage device and solar arrays, the relative optimality criterion was reduced to 0.01%. This still returned a fuel consumption solution that was no more than one gallon of fuel away from optimal over the 24-hour period.

4.2 Different Sized Generators

The current BCSIL setup only utilizes 60 kW AMMPS generators. However, the U.S. Army currently has several differently sized AMMPS generators in its inventory. We tested different sized generators powering the microgrid to determine the effect on fuel consumption. Does running a smaller generator at a more efficient setting save fuel? What if there were several different sized generators?

4.2.1 30 kW and 60 kW Generators

In Section 4.1.2, we determined that the best approximation for the generator efficiency curve was to use 60 piecewise-constant zones. The baseline setup was modified to include one 30 kW AMMPS generator and was tested using the fuel minimization model.

The results showed that replacing one 60 kW AMMPS generator with a 30 kW AMMPS generator in the microgrid led to a 1.7% fuel savings. Although this does not seem significant, over a one year operating period, this equates to a 5000 gallon fuel savings at a single 150-man contingency base camp. This fuel savings comes with very little additional cost to the government as these generators are already part of the U.S. Army's inventory. Additionally, 30 kW generators are part of the same AMMPS family, so maintenance and spare parts allowance would be very similar which also avoids additional costs.

4.2.2 15, 30, and 60 kW Generators

Following the results in Section 4.2.1, we determined that it would be worthwhile to investigate the fuel savings potential of using one 15 kW, one 30 kW and four 60 kW AMMPS generators to power the microgrid. Replacing an additional 60 kW AMMPS generator with a 15 kW generator in the microgrid led to an additional 0.65% fuel savings. This resulted in a total fuel savings of 2.3% when two 60 kW generators were replaced with one 30 kW generator and one 15 kW generator. Over a one year operating period, this equates to almost 7000 gallons of fuel savings. As with the single generator replacement in Section 4.2.1, replacing two 60 kW generators with smaller output generators of the same AMMPS family adds only a minimal cost to the U.S. Army.

4.2.3 Other Generator Combinations

As the output size of the generator gets smaller, the efficiency at maximum power also decreases. For this size microgrid, adding generators smaller than 15 kWs did not contribute to any significant fuel savings; there were simply too few load profiles were running a smaller and less efficient generator was economically advantageous. Only one each of the smaller sized generators were included in the microgrid because operating more than one did not make economic sense. Due to the lower fuel efficiency of smaller generators, there is no load profile where operating two identically sized smaller generators is more efficient than operating one larger generator.

4.3 Battery Storage System

As discussed in Chapter 1 and 2, including an energy storage system into a microgrid can significantly increase efficiency. An energy storage system can store extra energy during periods of low demand and supply the microgrid during periods of high demand. It can also absorb extra energy to keep a generator running at a higher efficiency. This is a similar concept to the dump load utilized in [16] and described in Section 2.7. The benefit of an energy storage system over a dump load is that the energy is not wasted. The stored energy can be used to supply the microgrid at a selected time that may permit a generator to shutdown. Without the energy storage system, the generator would be required to provide power at a low and inefficient power setting.

An additional benefit of an energy storage system is that it can be used as the spinning reserve for the microgrid. In the current BCSIL, the ADCS keeps the generators below 80% of their total capacity to maintain a spinning reserve. The downside to this spinning reserve is that it keeps the generators from running in their most efficient zones. Allowing the generators to run up to 100% of their rated load by using an energy storage system to provide the spinning reserve has the potential for significant fuel savings.

4.3.1 Tesla Powerwall 2

After the background research completed in Section 2, lithium-ion batteries were selected for use in our model in Section 3.1.4. As an example, we decided to use Tesla's Powerwall 2 lithium-ion battery packs as seen in Figure 4.2. These battery packs can charge and discharge at a rate of 5 kW and store 13.2 kWh of energy [4]. In order to provide a similar spinning reserve, two Powerwalls would be required for each 60 kW generator.

We ran our model keeping the energy storage system completely full and allowing the generators to operate at full capacity instead of the ADCS-limited 80% capacity. Removing the spinning reserve requirement from the generators setup in the configuration described

Figure 4.2. Tesla, Inc. Powerwall 2 Lithium-ion Battery System. Source: [4].

in Section 4.1.2 resulted in a 3% fuel savings that equated to saving over 9000 gallons of fuel in one year at a single 150-man remote contingency base camp. When combining the benefit of a lithium-ion energy storage system with the most efficient setup in Section 4.2, the fuel savings reached just over 4%. Powering a base camp microgrid with a lithium-ion energy storage system and one 15 kW, one 30 kW and four 60 kW AMMPS generators resulted in an annual savings of over 12,000 gallons of fuel.

4.3.2 Tesla Powerpack

Due to the smaller storage capacity and limited charge and discharge rate, Tesla's Powerwall 2 is best suited to provide the microgrid with the spinning reserve. This permits the generators to operate through their full operating range, including up to maximum output.

Tesla also produces a much larger lithium-ion energy storage system called the Powerpack as seen in Figure 4.3. This energy storage system is designed for commercial applications that require peak shavings, load shifting, or emergency backup. It is scalable, microgrid-ready and can charge and discharge at a rate of 50 kW and store up to 210 kWh of energy with a round-trip efficiency of 88% [4]. The round-trip efficiency of an energy storage system is the ratio of energy sent in to storage versus the amount of energy sent back to the electrical grid from storage [39]. A high round trip efficiency indicates that very little energy is lost to waste during the transfer to and from the storage system.

The Tesla Powerpack is well suited for integration into a remote contingency base camp microgrid. If installed, it could provide spinning reserve, peak shavings, and load shifting.

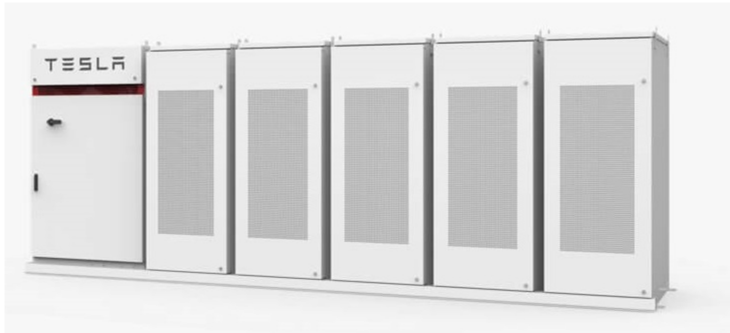

Figure 4.3. Tesla, Inc. Powerpack Lithium-ion Commercial Energy Storage System. Source: [4].

In the application of our model, we did not allow the Powerpack to go below a 25% charge in order to preserve an appropriate spinning reserve. Additionally, we assumed the energy storage system started and ended the 24-hour period with a 50% charge. This prevented the model from simply discharging the battery over the 24-hour period and leaving no charge for the next day which would have produced an artificial fuel savings.

Unfortunately, running the model with the 60 kW generators and the above assumptions produced nearly identical energy savings compared with the model using the Powerwall 2. In fact, running the model with an infinitely large battery with an infinite charge and discharge rate produced similar results. This is due directly to the 88% round-trip efficiency. The possible savings achieved through gains in generator efficiency using the energy storage device for peak shavings and load shifting are negated by the loss of energy due to the inefficiency of the charging and discharging cycles. The difference in efficiency between an AMMPS generator running at 50% load and 100% load is less than 10%. This limited increase in efficiency is not enough to overcome the inefficiency of charging and discharging the battery.

4.3.3 Battery Storage with High Efficiency

Battery technology is always evolving and improving. Although current round-trip efficiency for Tesla's Powerpack is only 88%, future advances are likely to continue improving it. Additionally, the Powerpack is but one example of a battery energy storage system.

We next looked at how a future-technology battery storage system in a remote base camp could reduce fuel usage. We used the same model assumptions as we did with the Powerpack with increased round-trip efficiency. We were looking to see if increasing the battery efficiency led the model to use peak shavings and load shifting.

As the round-trip efficiency of the charge and discharge cycle increased, the model made use of the battery more and more as seen in Figure 4.4. The model made very little use of the battery when the efficiency was 88%. Each step up in efficiency increased the use of the battery and decreased the fuel used in the 24-hour period.

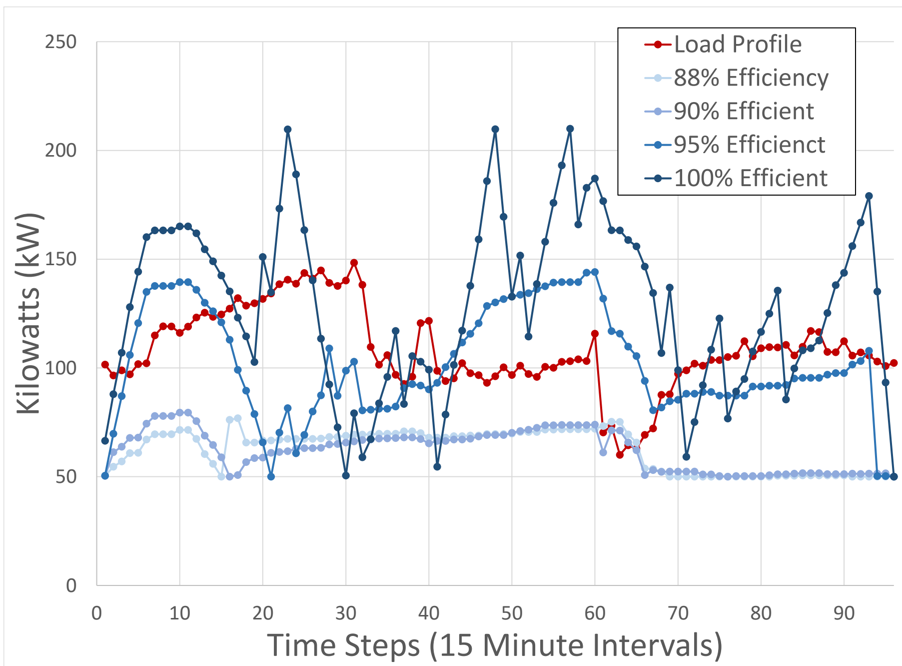

Figure 4.4. Battery Level for Various Battery Efficiencies.

Using a battery that returned a theoretical 100% round-trip efficiency made the most use of the battery. The minimum amount of fuel was used to meet the demand by either running the generator(s) at maximum output or having them shut off at each time interval as seen in Figure 4.5.

During the beginning of the 24-hour time period, the model runs two generators at maximum

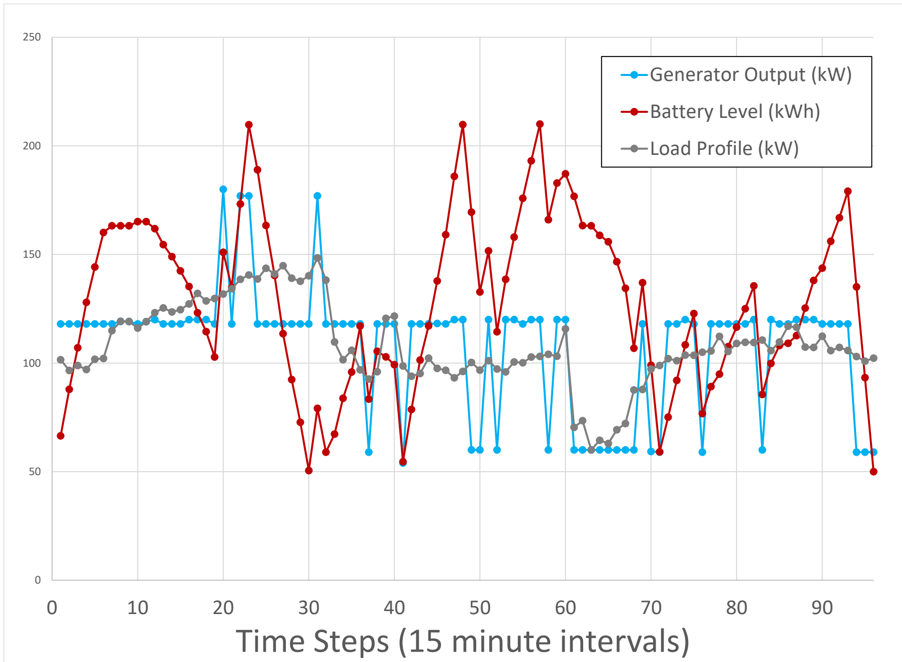

Figure 4.5. Generator Output Versus Battery Level With a 100% Efficient Battery.

output. This output is more than the demand, so the battery is charged. After time period 10, the load demand is above the output of two generators, so the model discharges the battery instead of starting another generator. At time period 20, the model starts to follow the Bang-Bang Theorem of control systems as described by Krener in [40] where a controller will generally tend to operate a generator a full power or shut it down. At time period 20, the model jumps between running one, two, or three generators at full power while charging or discharging the battery to meet the demand load. Each generator is run at full power or shutoff as seen in Figure 4.5. This leads to a maximum amount of fuel savings at 4.6%. We believe this to be the maximum savings obtainable by just adding an energy storage system to a microgrid powered solely by AMMPS generators and equates to a nearly 14,000 gallon fuel savings at a single 150-man remote contingency base camp.

4.4 Photovoltaic Solar Array with Battery Storage System

With the U.S. Army deploying regularly to low-latitude locations, incorporating photovoltaic solar generation into the electrical microgrids of remote contingency base camps could prove to be another step towards significant fuel savings. Our model requires only one modification to accept and apply the benefits of solar generation. The objective function in Section 3.6.1 remains the same with a minor change to the constraint defined by Equation (3.4). To incorporate solar generation, Equation (3.4) changes to

$$\sum_{g}\sum_{k}\left[u_1(g,k,t)\cdot l\right] + \sum_{s} u_4(s,t) - \frac{1}{\eta_c}u_2(t)\cdot l + \eta_d u_3(t)\cdot l = x_1(t) \quad \forall t \qquad (4.1)$$

where $u_4(s,t)$ is the output of solar array s during time t in kW.

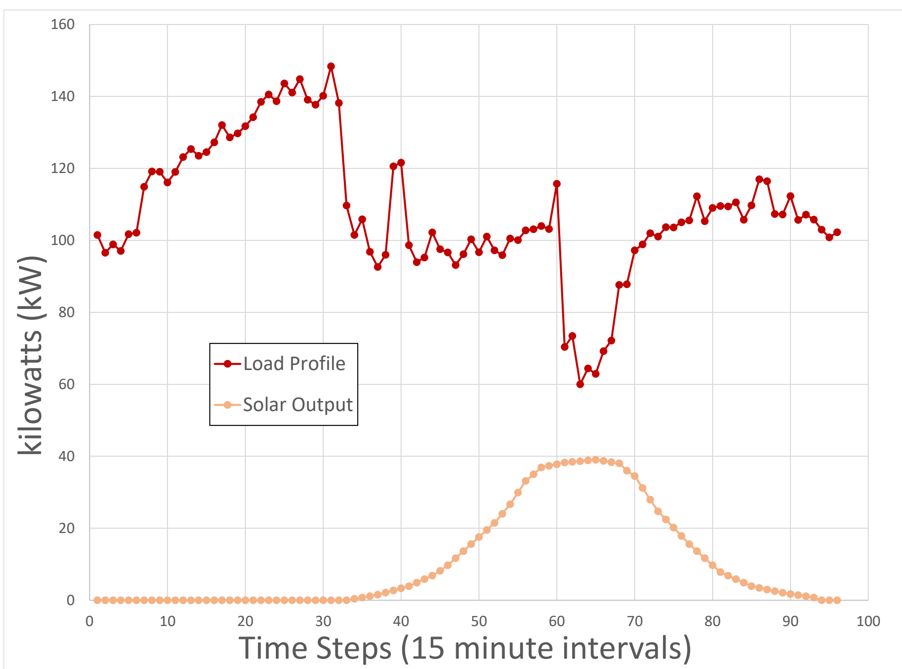

Figure 4.6. Predicted Total Solar Generation Versus Electrical Demand.

The output of each solar array is determined by Equation (2.1) as defined in [15]. For our research, we assumed each of the rigid buildings discussed in Section 1.3.3 were equipped with roof-top photovoltaic solar panels. Using an average daily radiation profile adopted from [41], we applied Equation (2.1) to calculate the total output of solar generation for each time step t. This resulted in a total solar generation output displayed in Figure 4.6, where load demand and solar output are plotted versus each time step.

Using the updated model constraint described in Equation (4.1), we ran the model to determine the amount of fuel savings the solar arrays would achieve on an average day of solar radiation. We used the solar arrays described in this section, the exact specifications of Tesla's Powerpack as described in Section 4.3.2, and four 60 kW AMMPS generators. The results showed that the theoretical microgrid produced a fuel savings of over 12% which equates to over 35,000 gallons of fuel a year. When the battery efficiency was adjusted to 100%, the microgrid produced a savings of 14%, or nearly 42,000 gallons of fuel saved.

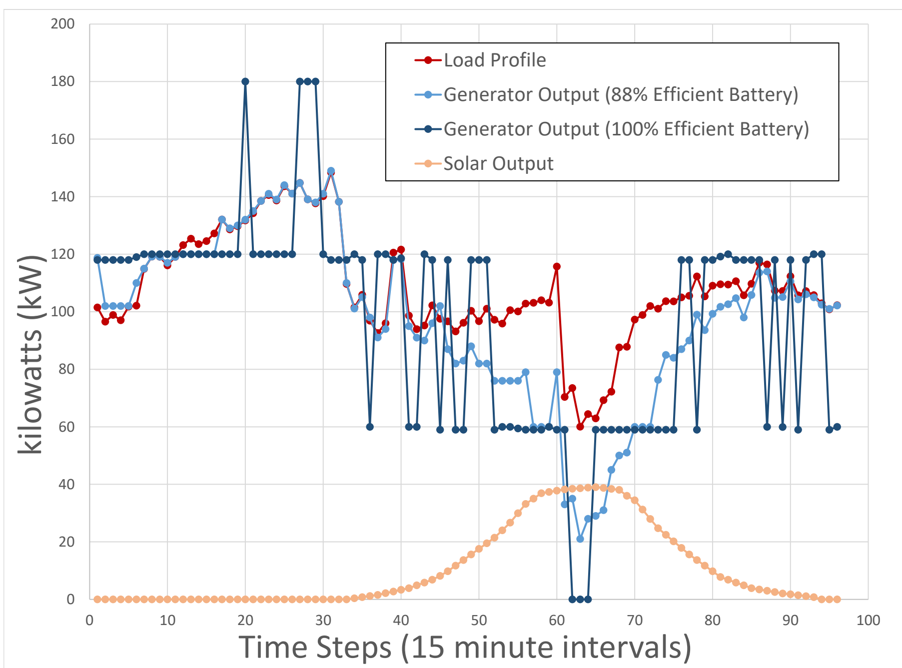

Figure 4.7. Generator Output Levels With Photovoltaic Solar Array Inputs to the Microgrid.

As seen in Figure 4.7, the total generator output for the microgrid with an 88% efficient battery mostly follows the demand curve until the solar output picks up in the afternoon. Once the solar output increases, that power directly feeds the microgrid reducing the diesel generator requirement. The model still does not make much use of the battery due to the relative inefficient charging and discharging rates as seen in Figure 4.8.

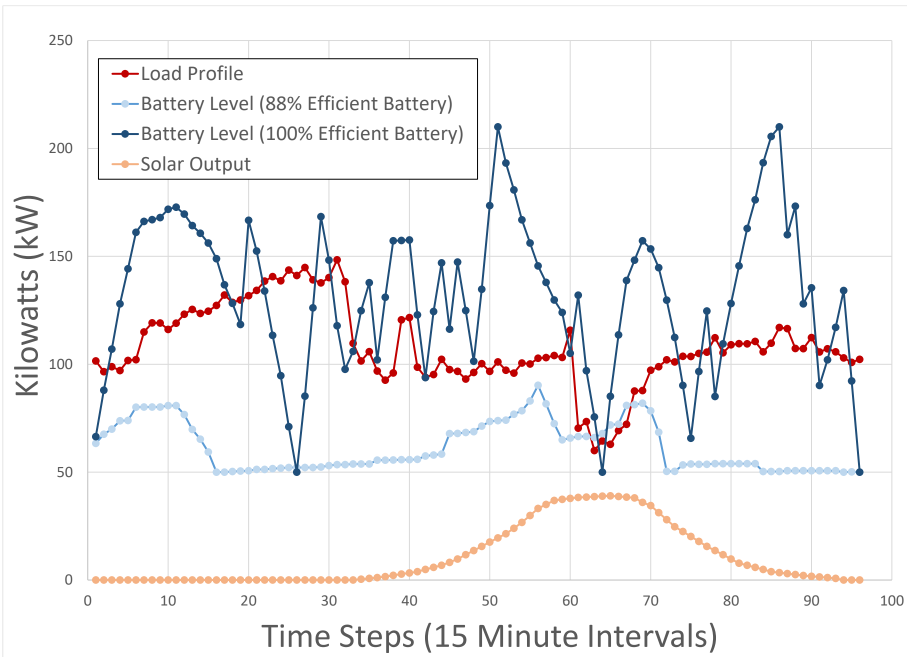

Figure 4.8. Battery Levels With Photovoltaic Solar Inputs to the Microgrid.

An important distinction is that the solar output under these specific conditions and assumptions is always below the microgrid demand for all time steps. In different scenarios with different assumptions and parameters, it would be possible for the solar output to be larger than the microgrid demand at certain time steps. This would result in energy flowing to the energy storage system regardless of the round trip efficiency because otherwise the produced electricity would be wasted. Micrograms with high solar generation capacities are therefore more likely to make greater use of an energy storage system.

When a battery with 100% round-trip efficiency is used in the microgrid model, the model again follows a Bang-Bang theorem of control systems similar to the results in Section 4.3.3.

As the solar output increases in the afternoon, the model turns off all generators and just powers the microgrid on the battery and solar arrays alone as seen in Figure 4.7 for three time steps (45 minutes). The total possible savings over a year period for this microgrid setup could exceed 40,000 gallons of fuel at just one 150-man remote contingency base camp.

4.5 Chapter Conclusions

This chapter compiled the results of several different theoretical microgrid setups run through the model defined in Chapter 3. Fuel savings in percentages and yearly savings of fuel in gallons were determined for several different cases.

4.5.1 Baseline Results

In order to determine a baseline fuel usage, we ran the model using the current BCSIL setup. We determined the optimal step-size for piecewise-constant approximation is 60 zones. Following that, we tested several different relative optimality criterion in GAMS and determined that 0.001% optimality worked for most scenarios. Once the solar arrays were added with the battery storage systems, the optimality criterion was dropped to 0.01% to avoid excessive calculation times.

4.5.2 Battery Storage System

Next, the model was run testing different battery capacities with different charge and discharge efficiency values. We ran the model using two existing COTS battery storage devices and several theoretical efficiency values. The result was a significant fuel savings with the current technology by transferring the spinning reserve from the generators to the batteries. Additional savings through the use of peak shavings and load shifting were possible with battery charge and discharge efficiency values above 95%. However, the maximum fuel savings with a 100% efficient battery was only another 5 gallons per day. This small savings would likely not justify the significant jump in cost of a much larger and more efficient battery.

4.5.3 Solar Array

Finally, we calculated the results of adding a photovoltaic solar array to the microgrid. With the current battery technology available today, the model predicted a 12% savings in fuel which saves over 36,000 gallons of fuel a year at a single 150-man remote contingency base camp.

CHAPTER 5:
Conclusion

Energy savings both on the battle field and at home are a high priority of the U.S. military. This thesis presented a mixed integer linear program developed to minimize the fuel consumption of a microgrid providing electrical power to a remote U.S. contingency base. We ran several different simulated microgrid scenarios through the model to determine possible fuel savings. Although the model thoroughly considers all factors for accurate fuel minimization in a microgrid, there are several areas for future improvement.

5.1 Future Work

This thesis focused on developing and presenting a linear program to minimize fuel used in the production of electricity for a microgrid. There is a significant amount of potential future work using this optimization model.

5.1.1 Improved Load Data

We made several assumptions when compiling the load profile. We took the 15-minute average of the one-minute time increment data recordings we received from the BCSIL. Additionally, the data we received was from just one weekend exercise. Obtaining and comparing several similar datasets from different exercises at the BCSIL would likely produce a different load profile. Future work could run different load profiles through the model to confirm or refute the predicted fuel savings. Different load profiles from different times of year could also be analyzed to examine the effects heating versus cooling have on the microgrid fuel consumption.

5.1.2 Varied Time steps

Our analysis only used 15-minute time steps. Although one-minute time steps seem unreasonable due to GAMS calculation times, future work could determine if smaller or larger time steps produce better results. Five minute time steps would be possible with the current calculation times, but does it produce better results? Future work could also determine what granularity is lost by increasing to 30 or 60 minute time steps.

5.1.3 Sheddable and Deferrable Loads

Sheddable and deferrable loads were included as part of the total cost minimization model, but not the fuel minimization model. Future work could include deferrable loads into the fuel minimization model to determine if there is any fuel savings by moving certain electrical loads to different time periods. This could be modeled similarly to charge and discharge decisions of the battery storage system. Moving deferrable loads from high demand periods to low demand periods may smooth out the demand profile and decrease fuel consumption. Incorporating sheddable loads into the fuel minimization model may prove more challenging as it is difficult to assign an objective fuel cost penalty for shedding a load that would keep the model from just shedding all available loads to save fuel.

5.1.4 Model Predictive Control

The two models described in this thesis minimize fuel consumption or total cost based on a known demand profile. Incorporating model predictive control into a future model would allow the model to adjust to a constantly changing demand profile. This type of model would allow for better control of a microgrid in a realistic scenario and likely increase fuel and cost savings.

5.1.5 Further Research into Battery Options and Parameters

This thesis analyzed the impact of Tesla's Powerwall and Powerpack battery storage systems on the fuel consumption of a microgrid. However, there are numerous other options for COTS battery systems and future battery technologies. Future work could research other battery storage systems and analyze the results using the optimization models developed in this thesis. These results could be compared with our results to determine if our projected fuel savings are accurate.

Although this thesis analyzed the results of different battery charge and discharge efficiency values, we assumed that the charge and discharge efficiency and rates were constant. This assumption does not hold true for any existing battery. Future work could modify the optimization model to include variable charge and discharge rates and efficiency values. Both of these parameters are non-linear, but future research may be able to make linear approximations similar to the generator efficiency approximations we made.

5.1.6 Further Research into Photovolatic Solar Arrays

The analysis of photovoltaic solar generation effects on fuel savings in a microgrid is a complete research topic of its own. In this thesis, we only analyzed one solar configuration with an average daily solar radiation profile at one location. Several different types, sizes, and efficiencies of photovoltaic arrays could be tested in future work. Different locations for installation could be analyzed with varying levels of solar radiation profiles. It would be entirely possible to devote a complete thesis to analyzing the effects of adding solar generation to a microgrid.

5.1.7 Further Research into Additional Alternative Energy Options

This thesis did not delve into alternative energy production options other than photovoltaic solar generation. The models presented can easily be modified to include other types of energy production. We recommend that other types of energy production be analyzed to determine if there is a better technology to increase fuel savings in a microgrid.

We also recommend that additional research be conducted into alternative energy storage systems. This thesis only researched battery storage systems as they are the most prevalent. However, it is possible that another current or future energy storage system could produce increased fuel savings.

5.2 Conclusions

The fuel minimization model was modified from our original mixed integer linear program that was developed to minimize the total cost of electrical production at a contingency base. The total cost minimization model is still valid and can be easily implemented if the cost factors for fuel, maintenance, operations, and initial purchase price are readily available for a given system. Fuel minimization provides a less subjective measure to compare scenarios and systems that do not have all of the cost factors clearly defined.

The main purpose of the fuel minimization model is to determine an optimal generator setting for each generator in a given microgrid at each time step. There are many other systems and models already developed that determine the best equipment to consider when designing and building a new microgrid. This model takes the already installed equipment, considers all operating parameters, and optimizes electrical production with the goal of minimizing fuel consumption.

Although determining the best equipment for a microgrid is not the primary purpose of this model, it is possible to use this model to compare different scenarios to determine potential fuel savings. Our research compared different potential microgrid setups with the existing microgrid at the BCSIL. We found that simply replacing two of the six 60 kW AMMPS generators with one 15 kW and one 30 kW resulted in a 2.3% fuel savings. We also analyzed the effect of adding a battery storage system to the baseline microgrid. Our model predicted that adding a battery storage system to absorb the spinning reserve requirement of the generators could result in a 4% fuel savings. Finally, we analyzed the potential results of adding photovolatic solar generation to the existing microgrid. We found that by adding rooftop solar panels to each of the buildings that are part of the rigid wall Force Provider Base Camp System, the microgrid could save an estimated 12-14% of fuel. Although none of these percentages are exceptionally large, the amount of gallons saved over a year per facility are worth further research and potential upgrades to the existing and future electrical microgrids at remote U.S. contingency bases.

APPENDIX: GAMS Code

The optimization model to minimize fuel consumption was run in GAMS using the CPLEX Optimizer. Contained in this chapter is the code used to run that model.

A.1 GAMS Code

This section contains the GAMS Code used to solve the optimization model for a microgrid with AMMPS generators, a Tesla Powerpack battery storage system, and a photovoltaic solar array. It can be modified for less complicated scenarios without certain inputs by simply setting those affected parameters to 0. For example, if there is no battery storage system, all the battery parameters can be set to 0.

```
SETS
k       generation zone       / k1*k60 /
t       time periods          / t1*t96 /
g       generator             / g1*g5 /
e       demand                / 1 /
a       solar output          / 1 /
;

PARAMETER
Brc     maximum battery charge rate       / 50 /
Brd     maximum battery discharge rate    / 50 /
Blmin   minimum battery level             / 50 /
Blmax   maximum battery level             / 210/
Blstart starting battery level at time 0 / 50 /
Blfinal final battery level               / 50 /
Beffc   battery charging efficiency       / 1 /
Beffd   battery discharging efficiency    / 1 /
l       length of time period (in hours) / 1 /
M       arbitrarily large number          / 1000000 /
```

```
;

TABLE d(t,e) electrical demand d during time t
$ondelim
$INCLUDE BCSIL_Load_Profile.csv
$offdelim
;

TABLE u4(t,a) solar output a during time t
$ondelim
$INCLUDE solar_output.csv
$offdelim
;

TABLE eff(k,g) efficiency of generator g in zone k
$ondelim
$INCLUDE efficiency_60_zones.csv
$offdelim
;

TABLE outputmin(k,g) minimum output of generator g in zone k
$ondelim
$INCLUDE min_output_60_zones.csv
$offdelim
;

TABLE outputmax(k,g) maximum output of generator g in zone k
$ondelim
$INCLUDE max_outpu_60_zones.csv
$offdelim
;

POSITIVE VARIABLE
u1(t,g,k)      Output of generator g during time t in operating zone k
TF(t,g)        Total gallons of fuel used by generator g during time t
```

```
f(t,g,k)       Gallons per hour of fuel used by generator g
               during time t in operating zone k
u2(t)          Charging rate during time t
u3(t)          Discharging rate during time t
x2(t)          Level of battery at the END of time t
;

BINARY VARIABLE
v1(t,g,k)      one if the output of generator g during time t is
               in operating zone k
vb(t)          one if charging zero if discharging during time t
;

VARIABLE
Fuel
;

EQUATIONS
OBJ
EFFICIENCY(t,g,k)
EFFPOSITIVE(t,g,k)
EFFALLZONES(t,g)
ALLZONE(t,g)
LOWERZONE(t,g,k)
UPPERZONE(t,g,k)
TOTALOUTPUT(t,a,e)
CHARGERATE(t)
DISCHARGERATE(t)
BATTMINLEVEL(t)
BATTMAXLEVEL(t)
FINALBATTLEVEL
BATTERYLEVEL(t)
;
```

```
OBJ..
Fuel =E= sum((t,g), TF(t,g))
;

EFFICIENCY(t,g,k)..
f(t,g,k) =G= ( eff(k,g) * u1(t,g,k) ) - (M*(1-v1(t,g,k)))
;

EFFPOSITIVE(t,g,k)..
f(t,g,k) =G= 0
;

EFFALLZONES(t,g)..
TF(t,g) =E= sum(k, ( (f(t,g,k)) *l ) )
;

ALLZONE(t,g)..
sum(k, (v1(t,g,k)) ) =E=
;

LOWERZONE(t,g,k)..
( v1(t,g,k)*outputmin(k,g) ) =L= u1(t,g,k)
;

UPPERZONE(t,g,k)..
outputmax(k,g) * (v1(t,g,k)) =G= (u1(t,g,k))
;

TOTALOUTPUT(t,a,e)..
(sum( (g,k), ( u1(t,g,k) ) ) ) + (u4(t,a)) -
( (1/Beffc) * u2(t) ) + ( Beffd * u3(t) ) =E= d(t,e)
;

CHARGERATE(t)..
u2(t) =L= (Vb(t))*Brc
;
```

```
DISCHARGERATE(t)..
u3(t) =L= (1-Vb(t))*Brd
;

BATTMINLEVEL(t)..
Blmin =L= Blstart + l * sum(s$(ord(t)>=ord(s)),
(Beffc*u2(s)-(1/Beffd)*u3(s)))
;

BATTMAXLEVEL(t)..
Blmax =G= Blstart + l * sum(s$(ord(t)>=ord(s)),
(Beffc*u2(s)-(1/Beffd)*u3(s)))
;

FINALBATTLEVEL..
Blfinal =E= Blstart + l * sum(t, Beffc*u2(t)-(1/Beffd)*u3(t))
;

BATTERYLEVEL(t)..
x2(t) =E= Blstart + l * sum(s$(ord(t)>=ord(s)),
(Beffc*u2(s)-(1/Beffd)*u3(s)))
;

MODEL FuelMin/ALL/;

SOLVE FuelMin USING MIP MINIMIZING Fuel;
```

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