Mobile Hybrid Power System Theory of Operation

Timothy M. Pierce Jr.

Thesis submitted to the faculty of the Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of

Master of Science
In
Electrical Engineering

Alfred L. Wicks, Chair

Rolando Burgos

Steve C. Southward

July 22, 2016
Blacksburg, VA

Keywords: mobile hybrid power system, fuel consumption, energy storage, load profile, power factor correction

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Abstract

Efficiency is a driving constraint for electrical power systems as global energy demands are ever increasing. Followed by the introduction of diesel generators, electricity has become available in more locations than ever. However, operating a diesel generator on its own is not the most energy efficient. This is because the high crest factor loads, of many applications, decrease the fuel efficiency of a hydrocarbon generator. To understand this, we need to understand how an electrical load affects a generator.

Starting with a load profile, a system designer must choose a generator to meet peak demand, marking the first instance where a load profile has influence over a generator. This decision will insure that brownouts do not occur, but, this will lead to poor energy efficiency. We say this because a generator is most energy efficient under heavier loads, meaning, during lighter loads, more fuel will be consumed to produce the same amount of energy.

While this may be fine if the peak load was close to the average load, however, the actual crest factor for a typical residential load profile is much higher. This gap between peak and average load means that a generator will spend most of its time operating at its most inefficient point. To compensate for this, and reduce fuel consumption, the Mechatronics Lab at Virginia Tech has developed a mobile hybrid power system (MHPS) to address this problem. The solution was to augment a diesel generator with a battery pack. This allowed us to constrain the generator so that it only operates with fixed efficiency. It is the theory behind this system that will be covered in this thesis.

Acknowledgements

I would like to take the time and recognize my committee for the guidance that they have given me throughout my matriculation as a graduate student and towards the completion of my thesis. Dr. Wicks, who created the foundation for my graduate work and invested the time in me so that I could reach my potential, Dr. Burgos, who provided support as I conducted research abroad, and Dr. Southward who supported my interest in controls. It is because of their efforts, and through the funding of the Bradley Fellowship, that have made it possible for me come this far in my graduate studies.

Outside of my formal committee, I would like to recognize my personal committee who helped me to navigate the intricacies of graduate school and help keep me on track. Dr. Amelink, who pushed me in the right direction, Dr. Lesko who insured that I integrated well into the university, and Dr. Pendleton who looked after my well-being. It was with their support, along with the New Horizons Graduate Scholars Program, that I was able to maintain my mental stability.

To my parents Tim and Tina, my brother Trey, and all of my extended family, I would like to say thank you for being the best family that anyone could have hoped form. It was your upbringing that established my foundation as a person and is a reflection of your great integrity and morals. I attribute my success and maturation in life to your nurturing and love.

Finally, I would like to thank the Mechatronics Lab, the HEIT Team, Hampton University, and Hampton City Schools. It was your work that established a positive learning environment that allowed me to grow as both a student and a person.

Contents

List of Figures

List of Equations

List of Acronyms

A	amperes	23
gal	gallon	15
hr	hour	15
IC	internal combustion	10
kW	kilowatt	16
kWh	kilowatt-hour	16
MHPS	mobile hybrid power system	ii
mins	minutes	3
sec	seconds	27
SoC	state of charge	8
SoH	state of health	8
V	volts	23

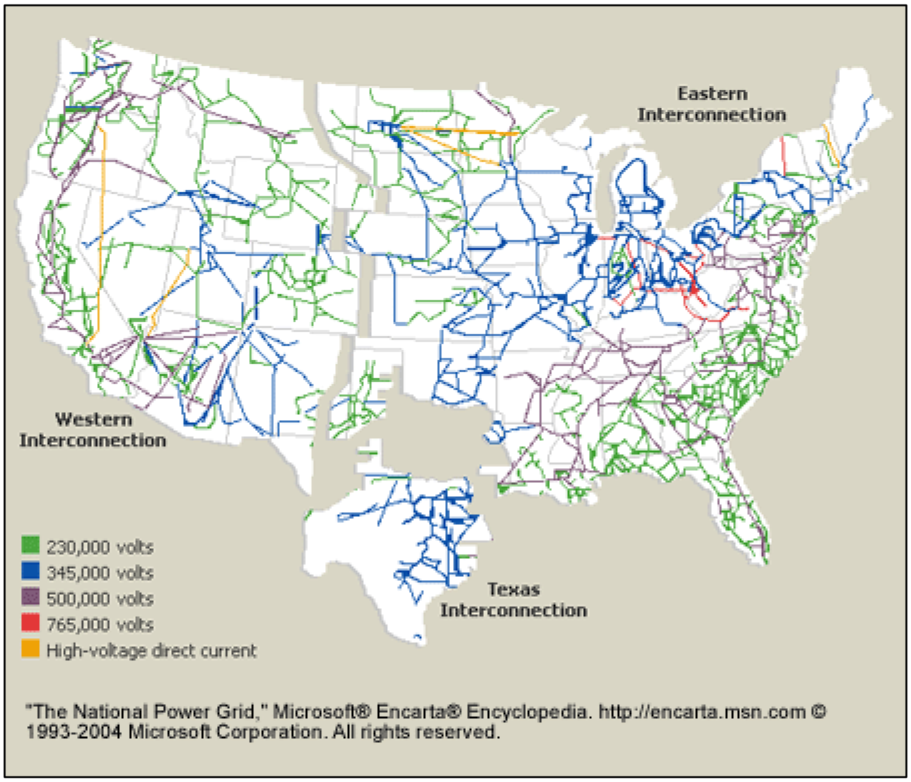
List of Tables

Chapter 1 Introduction

1.1 Introduction
1.2 Humans and Energy
1.3 The US Power Grid
1.4 Generation Capacity
1.5 The Smaller Issue
1.6 Literature Review

Section 1.1 Introduction

The US power grid is a dynamic organism that is comprised of over 7,000 power plants [1], 200,000 circuit miles of transmission lines, and over 677 transformers [2]. All of which supply millions of consumers with electricity, from the residential and industrial level all the way up to cities such as New York. However, as power demands continue to change, our nation's outdated infrastructure begins to show its age. To fully appreciate its complexity, we have to start with the basics and understand why the grid exists and then we can discuss its problems and ways to improve it. A map of the US power grid is show below in Figure 1.



"The National Power Grid," Microsoft® Encarta® Encyclopedia. http://encarta.msn.com © 1993-2004 Microsoft Corporation. All rights reserved.

Figure 1 - The US Power Grid [3]

Power. That is why the US power grid exists, to provide US citizens the ability to do work. This makes living easier, and, looking at power over time we get energy. We start with the US power grid because it demonstrates the traditional design of how to take power from an energy source and harness it to supply a load. Starting with a load profile a system designer will determine a peak output requirement and from there a power system will be designed around that requirement. However, a problem arises when this metric is applied to various energy sources. This is because different sources of energy (i.e. diesel, solar, and wind) have different costs associated with the production of energy. For a diesel generator this means that the maximum output of a generator will need to meet peak load. However, this is only half the story.

For a typical residential load profile the peak power can be many times larger than the average power. It is this gap that creates a problem for diesel generators, because they are less energy efficient under light load. This means that the diesel generator will be spending most of its time under light load, wasting fuel as its idling away. It is this wasting of fuel, which we will try to reduce through the course of this thesis.

To accomplish this we will have to departing from the traditional peak power design and turn our attention to a design method that focuses on average power. This will become clearer as we delve deeper into the subject and explore some of the inherent inefficiencies of the traditional design methods. Additionally, what makes a hybrid power system particularly attractive is that it does not have to rely on one source of energy, pulling from other sources such as solar and wind. To start we will use the following section to understand the role that energy has played throughout the course of human history, specifically, how to deliver energy efficiently.

Section 1.2 Humans and Energy

Since the days of cave men, humans have been in search of energy. However, instead of using energy to fuel our bodies, we now use energy to power our computers, run our cars, light our homes, and condition the air we breathe. This energy is called electricity, and it has now become an important resource as we move forward into the Anthropocene epoch [4]; but, there is one fundamental concept that we have yet to apply to this new form of energy, and that is storage.

The earliest forms of humans were hunter gatherers, following food, or, “energy”, wherever it may be. While this may have been one way to live, it was not always efficient. This is because it was not reliable, being highly susceptible to weather, disease, famine, drought, and a variety of other maladies. During such times humans would have had to travel farther to obtain food. This is costly, as they would have had to expend more energy to get that same amount of food, making the journey highly inefficient, along with the increased risk of injury. However, that changed around 10,000 BC with the Neolithic Revolution [5]. It was then that humans started to grow and store their own food [6].

Changing from a hunter gatherer to a settled lifestyle provided humans a reliable and sustainable way to live that could withstand large fluctuations in available energy. The key here being the storage, as it allowed energy to be produced when it was most efficient and then consumed as needed. Now humans had a method to survive harsh winters and sweltering summers. Specifically this means that they can gather a minimal amount of food and still survive because of the stores of energy that they have accumulated. Along with the ability to endure energy fluctuations, storage created the ability to combined different sources of food, allowing early humans to choose what to eat. This is equivalent to hybridizing a power system. Moving forward about 12 millennia we stand at the beginning of another revolution, this time for electrical energy.

Section 1.3 – The US Power Grid

To set the stage we look at the US power grid and see how its elements are connected. Starting with generation, the US produces energy from a variety of sources, including: nuclear, water, solar, wind, and most importantly fossil fuels, also known as hydrocarbons (e.g. coal, natural gas, diesel, gasoline, etc.). From there is it stepped up to high voltages and sent over transmission lines to surrounding areas. Nearing the end of its journey the electricity is stepped down at local distribution centers supplying industries, businesses, and residential neighborhoods, Figure 2 [7].

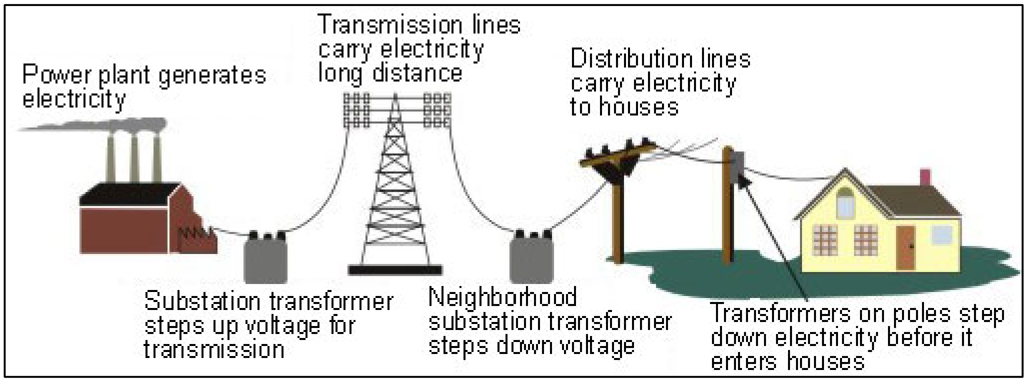


Figure 2 – US Power Grid Transmission [7]

Now that we have painted the larger picture, we can delve deeper into the intricacies of how the US power grid behaves. Starting with the consumer’s needs, shown in Figure 3, we can see that over the course of a week a consumer’s load demand fluctuates greatly. To characterize this we recall the concept of average power, peak power, and crest factor. Together this information is known as a load profile. The data for Figure 3 was provided by [8].

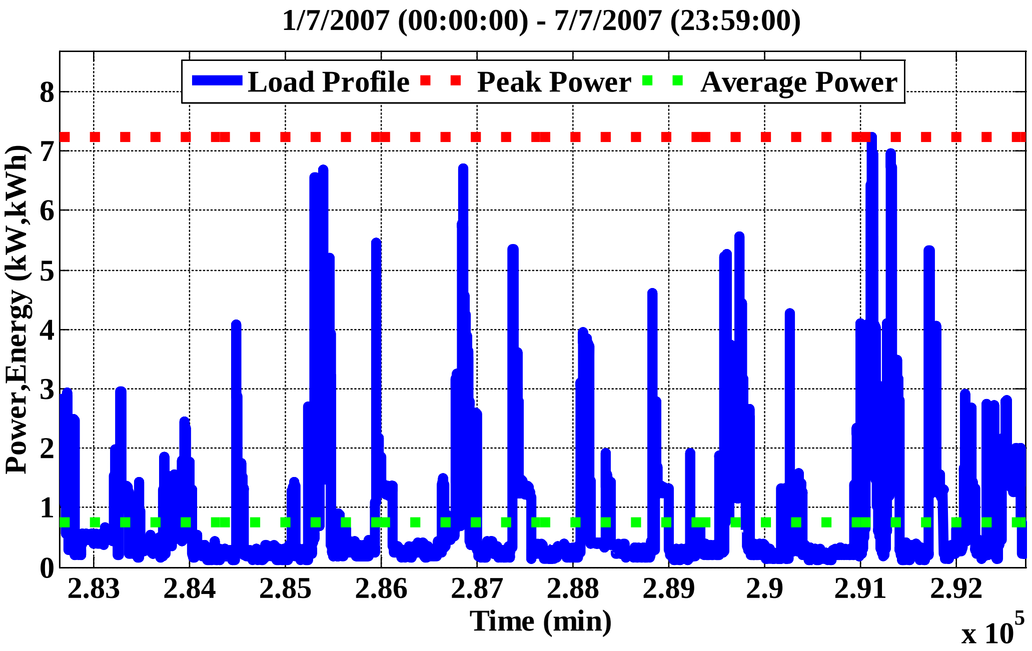


Figure 3 – Residential Load Profile (1 Week)

The load profile is important because it is what power companies use to determine how power should be generated, transmitted, and distributed. Without this data the power company could end up in a bad situation where they produce too much power which will be wasted or not enough where power outages will occur. This can be related back to early hunter gatherers, where, if they gathered more than they could bring back, it would spoil and be wasted. At the other end of the spectrum too little food would mean that the community would starve. Both are less than ideal situations, however, this is where we are at, in 2016, as we search for ways to improve the power grid.

Section 1.4 Generation Capacity and Efficiency

Now that we can see what the demands of a consumer are we can turn our focus to how the grid behaves as it tries to supply a varying load. To understand this we have to look at the other end of the grid where power is generated and introduce another term, called capacity. In the context of power, capacity is the maximum amount of power that the US power grid can supply at a given time and, for the US power grid, that is about 1TW [1]. Looking at [9] we can see why that number is so large and that is because US power grid is sized to meet a peak demand of 768,943MW.

While this makes sense it is inefficient for the more than 7,000 power plants across the country. This is because a large portion of US' energy still comes from fossils fuels which are most efficient when operated at higher loads. To understand this we can recall the load profile of a consumer. If we were to try to supply the consumer with power we would select a generator based on their peak load, and be done. However, this would be inefficient as a generator's efficiency will change based upon the load. To understand this we can compare the load profile histogram of Figure 4 to the efficiency curve of a 10kW generator in Figure 5.

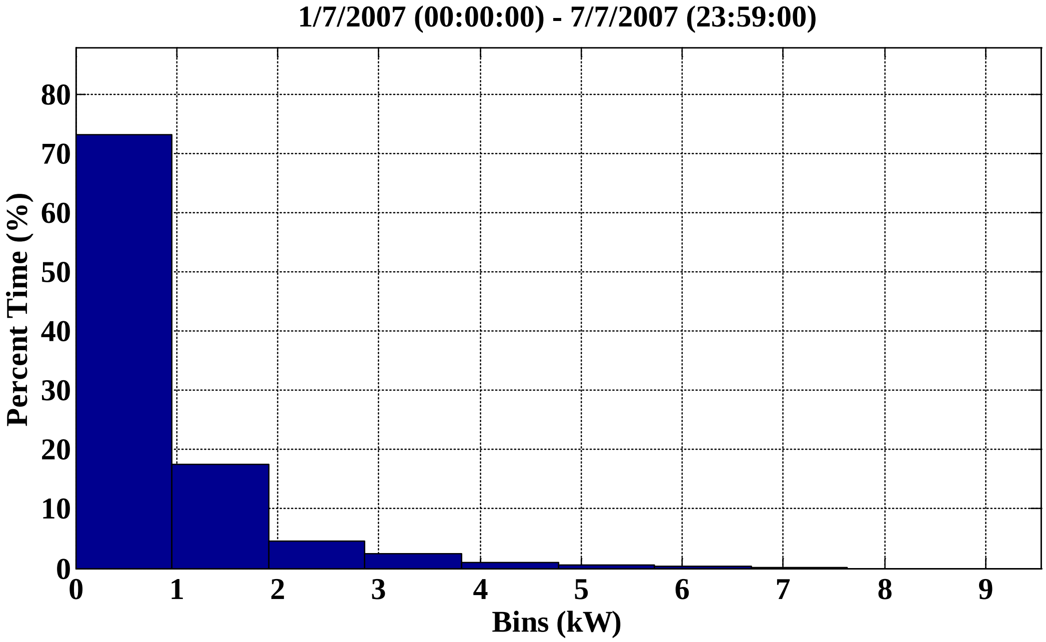


Figure 4 – Residential Load Profile Histogram (1 Week)

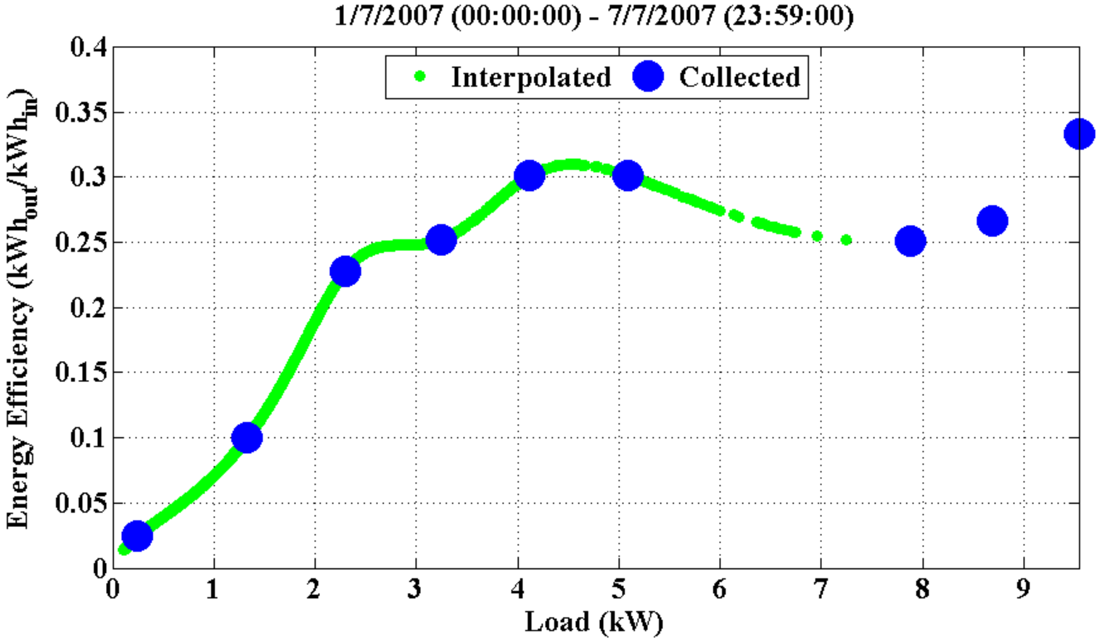


Figure 5 – Arbitrary Diesel Generator Energy Efficiency

Looking at the curve of Figure 5 we can see that under light loads the generator will burn more fuel per kWh than at higher loads. This is a problem because if the generator was selected to supply power to the consumer of Figure 3, it would spend most of its time operating at lower efficiency levels, burning more fuel and costing more money. We say this because the peak power that it was sized for only makes up a small percentage of the load profile.

This example represents how the US power grid behaves every day, using more fuel than necessary. The question now is, can we operate the US power grid in a way that meets the load profile of the country while always operating at its most efficient point? To answer this question we go back to the first agricultural revolution to see what we are missing, and the answer, as mentioned previously, is storage.

If we add a storage element we can decouple load fluctuations from the generator's operation allowing us to constrain its efficiency. Additionally it allows us to combine energy produced from a variety sources and then store the excess. This allows the grid to build up a surplus of energy that can respond to transient load changes while simultaneously reducing hydrocarbon fuel consumption. Ultimately this will allow the US to go further with the same amount of fuel, in addition to reducing financial cost, emissions, and the required output of generators. This is where the work of the Mechatronics Lab began but, on a much smaller scale.

Section 1.5 The Smaller Issue

The motivation for this research is to reduce the fuel consumption of a hydrocarbon generator. This began with the development of a mobile hybrid power system (MHPS) by the Mechatronics Lab at Virginia Tech. Through this work much was learned about what determines fuel consumption such as how generator efficiency varies as a function of load, and how it can be improved. This thesis will serve as an addition to existing and a foundation for future work by exploring other ways to reduce fuel consumption. To support this research a background in applied controls and power electronics was developed as a way to gain intuition about the system's dynamics.

What makes this project so unique is that it minimizes fuel consumption by maximizing the efficiency of power delivery. To understand this we must recall again that generators are most efficient when operated at higher load. This means that a generator burns more fuel per kilowatt-hour under light load than heavy load, Figure 5. This would be acceptable, except that traditional methods select generators for peak, not average load. From there we then pose the question, what if we could always run a diesel generator at its most efficient point? This led to the realization that normal loads vary, and to operate a generator at full load, when only a light load is needed, would produce surplus energy. To compensate for this the MHPS incorporates a battery pack to store the surplus energy. A simple block diagram of the system is shown in Figure 6.

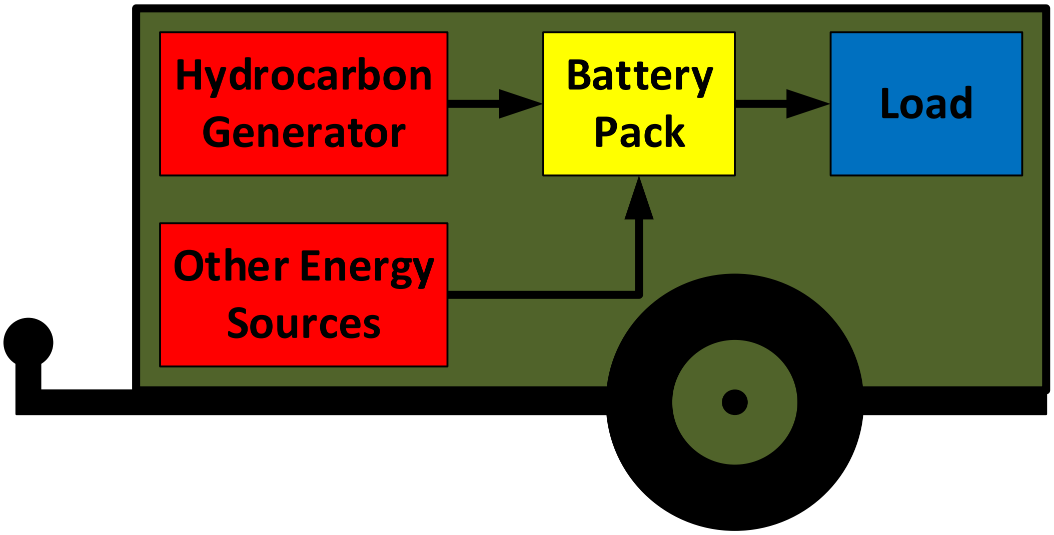


Figure 6 – Hybrid Power System High Level Block Diagram

The concept of storing energy is nothing new, and history shows us that humans used this concept when we transitioned from living as hunter gatherers to living in settlements. It would be very inefficient to go hunting in the middle of winter when the weather was bad and food was scarce. So, to make it through hard times, stores of food were created. This added capability is what the battery pack brings to the MHPS allowing it to produce power from multiple of sources when it is most efficient and then use it on demand.

This reasserts the fact the power should not be provided from the source but, rather a storage medium. Now a MHPS can be used to address the gap between peak and average load, and provide power efficiently to any load. Ultimately this system can be applied to situations such as the US power grid but, what makes it particularly attractive is its mobility. This allows the system to be extended to even more applications such as rural electrification, the military, and disaster relief areas where grid power may not be available.

Section 1.6 Literature Review

Naturally a MHPS is a large system made of many smaller subsystems arranged in such a way that allows them to work together and augment a diesel generator. This means that in order to understand the big picture we must review the many smaller pictures that form our collage. It is from this concept, which we will build our literature review.

At the highest level MHPSs have been studied for years as summarized by [10], where much progress has been made in the way of “system configurations, generation unit sizing, storage needs, and energy management and control”. From this we are able to delve into the details of a MHPS. Taking the source to load approach we can study the dynamics of how energy is transformed along the way, starting with the transformation of mechanical to electrical energy.

Referring to [11], we can see how alternators can be used to couple mechanical and electrical energy. From this we are able to utilize energy from hydrocarbon fuels. However, there is still plenty of work to be done in maximizing their power output as explored by [12], and as more advances are being made, MHPSs become all the more attractive. There is also more work to be done to improve power factor as suggested by [13].

Moving past the alternator we need to build an intuitive understanding of the current technologies employed using power electronics. To cover this [14] provides a thorough background. It is because of power electronics that we are able to transfer power at various voltage and current levels. They, along with the alternator, are important in coupling energy between components within a MHPS.

Getting to the heart of our system we then need establish an understanding of batteries beyond the ideal case, which many simulations consider. This area of research actually goes back quite a ways, dating to 1947 with Randles' investigation into the "Kinetics of Rapid Electrode Reactions" [15]. Over the years his work as led to many advances in battery modeling with the most current methods accounting for changes in battery run time performance, state of charge (SoC) and state of health (SoH) [16].

It is the culmination of theses separate research endeavors that have made this an appropriate point in time to conduct more research in the field of MHPSs and, as we continue into the future, we will be able to create an even more efficient system as more technological advance are made.

Chapter 2 Theory

2.1 Introduction
2.2 System Overview
2.3. Load Profile Analysis
2.4 Generator Efficiency Analysis
2.5 Energy Flow
2.6 Experimental Needs

Section 2.1 Introduction

Hybrid power systems are an effective way to improve energy efficiency, as introduced in Chapter 1. This is made possible by coupling multiple energy sources with a battery pack, helping fill the efficiency gap between energy production and usage. However, designing such a system is complex and encompasses a significant amount of theory. To make this more comprehensible, Chapter 2 breaks down the underlying concepts of hybrid systems, batteries, conversion equipment, and efficiency so that a deeper understanding can be obtained. Ultimately this research will be used to design a system that improves efficiency and reduces hydrocarbon fuel consumption. Figure 7 shows a more detailed block diagram of the necessary equipment.

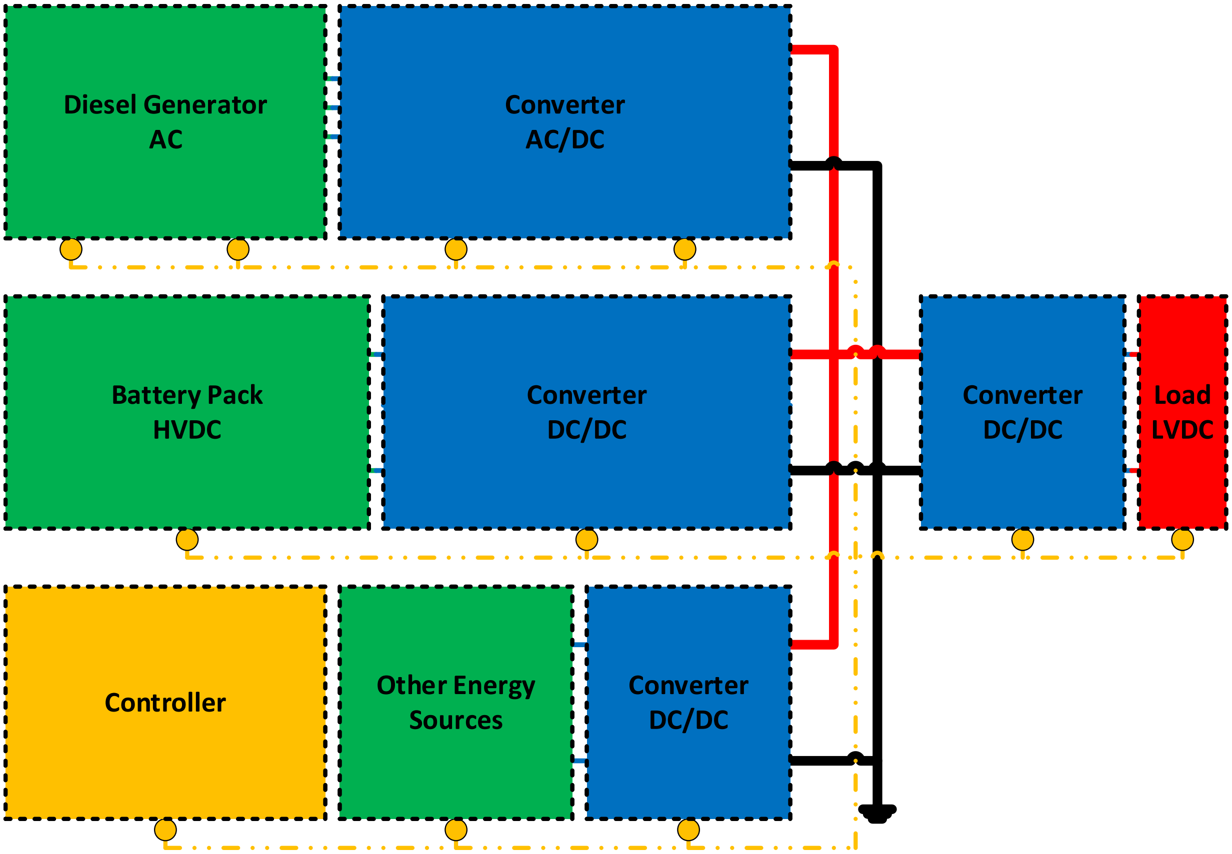


Figure 7 – Hybrid Power System Low Level Block Diagram

Section 2.2 System Overview

To begin we start at the source of energy hydrocarbon fuels are considered a valuable resource because of their energy density, or, the ability to do work per unit volume. This is why hydrocarbon generators are still a predominant way to generate electrical energy. However, hydrocarbons are a nonrenewable resource, making it desirable to minimize a generator's fuel consumption. To achieve this, a generator must be designed and operated as efficiently as possible. This, due to how an internal combustion (IC) engine works, results in a generator that is most efficient under heavy loads and least efficient under light loads. However, electrical load profiles vary, as seen in Figure 3, making efficiency inconsistent. This problem has led to the development of hybrid power systems, which solve this problem by coupling two or more energy sources with a battery pack for energy storage. A detailed review of hybrid power systems can be found in [10].

Non Ideal Battery Model

Beyond fuel, the battery pack is the next part of the system that we must consider is the battery pack since it is the center of our system. Looking at Figure 8 we can see that a battery is much more than an ideal voltage source, as there are many dynamic effects that contribute to the overall efficiency and operation of the system. Derived in [16] we can how an accurate battery model takes into account relatively slow dynamics such as self-discharging, average dynamics such as capacity, and fast dynamics such as transient responses as derived by Randles [15]. It is important to consider how this effects in our system because it will provide intuition into how the battery pack will alter overall system efficiency.

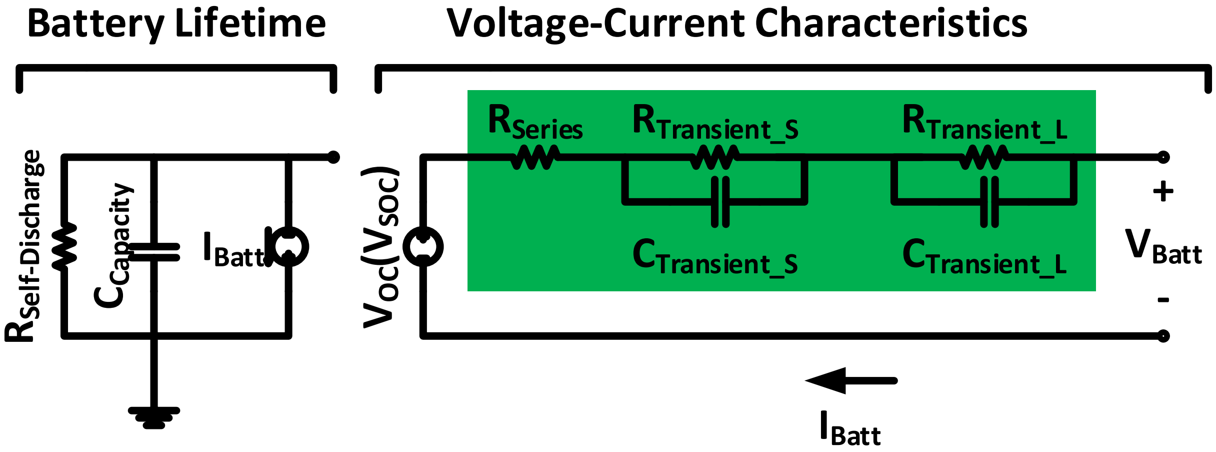


Figure 8 – Non Ideal Battery Model [16]

Designing for Batteries

Moving on, we look at Figure 9 to understand the process of how energy is converted. Starting at the left of Figure 9, we can see that an IC engine creates a rotational force that drives an alternator creating a 3Ø AC voltage. However, an alternator is not an ideal source due to its windings. This is reflected in the model as an equivalent series inductance. In the future we plan to look into this to better understand its effects on system efficiency, but for now we will consider it to be ideal.

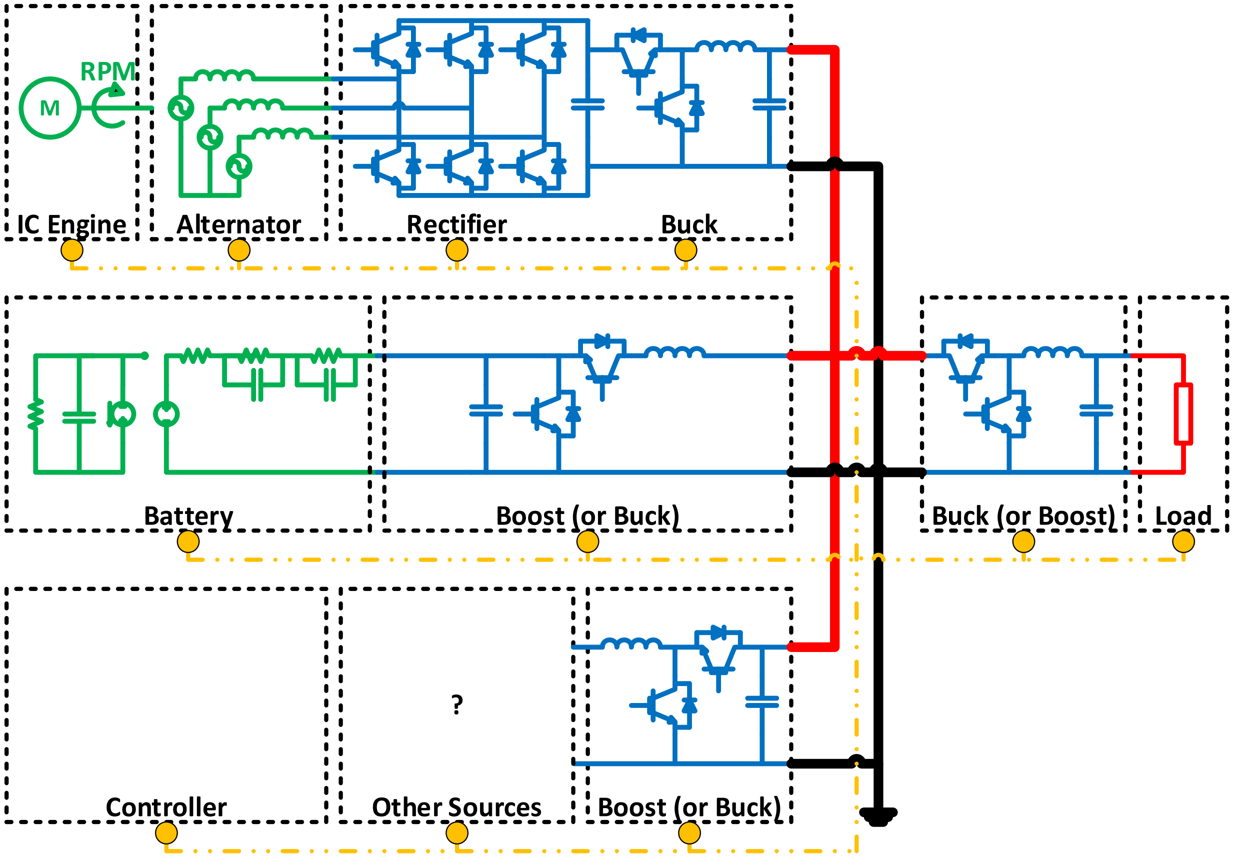


Figure 9 – Hybrid Power System Schematic

From there the power is rectified to produce a DC signal. Also this schematic shows IGBTs, as opposed to the passive and traditional method of using diodes for rectification. This reflects current trends to use transistor technology for active rectification. Afterwards, the voltage is converted to the level of the DC bus.

It is this part of the circuit, the DC Bus, where we can couple other sources of energy such as solar or scavenged power. This is also where the battery pack couples to the system using a bi-directional DC converter. This is necessary because battery current needs to flow in both directions depending on whether it needs to be charged or discharged.

Looking below the battery pack we can see where other sources of energy can enter the system. This uses a similar setup to the generator, but can be reconfigured depending on the expected energy source. This is another area that we plan to study in the future as being able to reconfigure a system to couple to both AC and DC power is highly desirable. Finally it is converted again so that it can be regulated at a level desired by the user.

Power Losses

While it may seem that we have created an ideal system we must keep in mind that it is not 100% efficient, as every piece of equipment will incur real and reactive losses including the copper wire used for connections.

Beyond the IC engine the next place that an energy loss can occur within the conversion equipment alternator. Every time the signal is modified the signal is distorted and power is consumed. This includes rectification, conversion, and even the battery pack. What this means for the system designer is that the system must be considered as a whole, because, every step affects the whole system. This is why it is so crucial to have an accurate load profile because the system cannot be designed without it. In reality the system can be thought of as being designed backward where the output determines the input. This will insure that the final system will maximize efficiency and minimize hydrocarbon fuel consumption.

Control

While each component comprising the system can operate on its own, it is the combined operation that makes this system possible. To facilitate this capability a central computer, as mentioned in [10] must be installed to handle supervisory tasks such as equipment turn on/off as well as aggregate system data for the user to make decisions from. This is why Figure 9 shows a controller connected to a communication bus that allows information to be shared within the system. A brief hierarchy of these functions is listed below in Table 1.

Table 1 – Control Hierarchy

Local Level	System Level
Load Profile Analysis	Electrical Coupling
IC Engine	Collective Efficiency
Electrical Generation	On/Off Control
Power Conversion	
Energy Storage	

Section 2.3 Load Profile Analysis

Now that we have a notion of the necessary equipment we can turn our focus to the first step in designing a MHPS, the analysis of the load profile. Obtained from [8], Figure 10 shows a load profile for a residence over a 24hrs. This will give us enough data to compare the operation and fuel savings of a generator only with a hybrid system. It should also be noted that obtaining this load profile is the most critical step for the entire system because it dictates every aspect of the MHPS. From the load profile several features need to be identified in order to design the system.

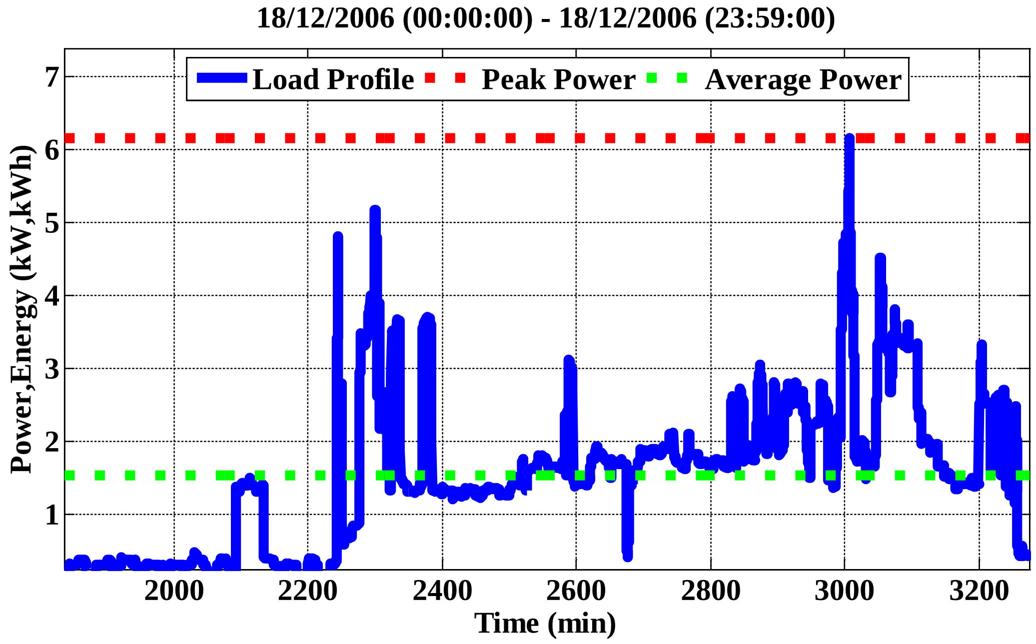

18/12/2006 (00:00:00) - 18/12/2006 (23:59:00)

Figure 10 – Residential Load Profile (1 Day)

Looking at the load profile of Figure 10 we can also extract a few features that will allow us to design a hybrid power system. The first is the peak power of about 6.2kW which occurs around 3000mins. This value is important because it determines the maximum discharge rate that the system must be designed to handle when supplying a load. If equipment was used and it could not supply the peak load then system damage or brown outs could occur. The other parameter that we can extract is the average value, which is about 1.5kW. Additionally, this can tell us how the output conversion equipment should be designed. These values are listed in below Table 2.

Table 2 – Load Profile Statistics

Average	Peak	Crest Factor
6.2kW	1.5kW	4.0

Section 2.4 Generator Efficiency Analysis

Now that we have used a load profile to derive energy and power requirements, we can shift our focus to the source of energy for our hybrid power system, diesel fuel. For our MHPS we use a diesel generator to turn an alternator as shown previously in Figure 9. However, as previously mentioned, a diesel generator does not always operate at its most efficient point. To explain this we need fuel consumption data for a generator. To aid us we will need a histogram of the load profile shown in Figure 11.

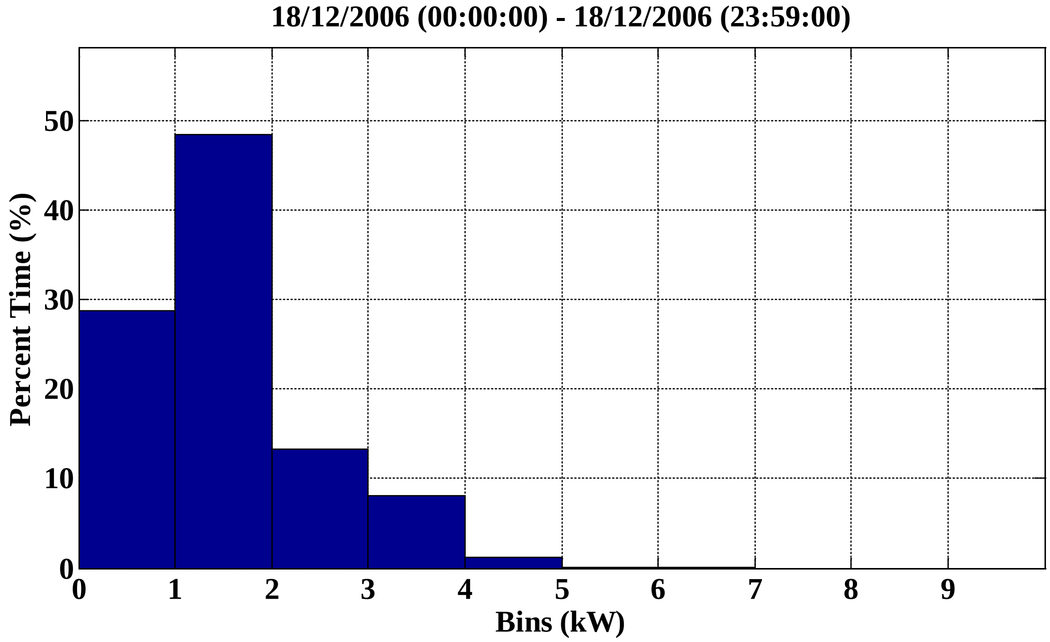


Figure 11 – Residential Load Profile Histogram (1 Day)

Starting with Figure 12, we can see how fuel consumption, in gallons per hour (gal/hr), varies for an arbitrary generator. Upon inspection it shows that under heavy loads the generator is consuming fuel at its highest rates. From this, one might argue that the best way to conserve fuel is to run the generator at light loads. However, this cannot happen, since the generator's efficiency is determined by the load profile which we have no control over. The only way to improve the efficiency of power delivery is to change the consumer's behavior, and that problem is a lot harder to solve. However, we can look at another property of a power system and that is energy, which, we can control by augmenting a diesel generator with a battery pack.

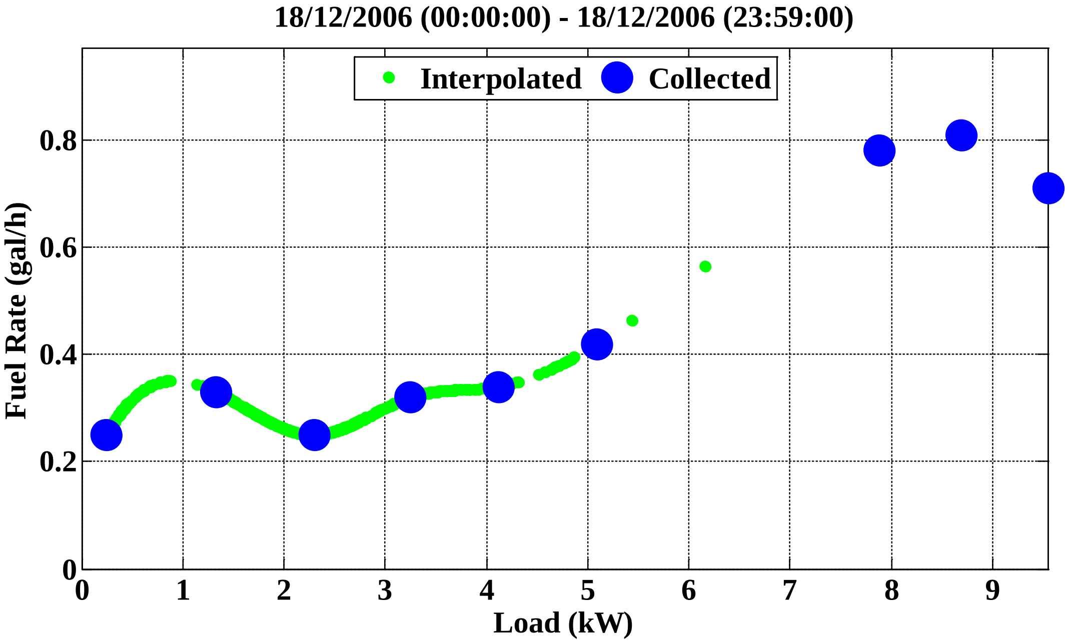


Figure 12 – Generator Fuel Consumption

To get energy we must use dimensional analysis and the equations in Table 3 to convert the units of Figure 12, from gal/hr to kWh/gal of Figure 13. After energy, we only need one piece of information to get the generator's efficiency and that is the conversion factor between diesel and kWh. Since this isn't explicitly defined we have to use the information from [17] to derive this number. Now we can use the rest of the information in Table 3 to get the energy efficiency of a diesel generator shown in Figure 14.

Now if a generator always ran at its maximum efficiency point, under full load, then there is no room for improvement of the fuel efficiency, however, this is not the case as a load profile varies. Comparing the load profile, its histogram, and the generator efficiency curve we can see that the mean efficiency is very low. This is highly undesirable as it will lead to an unnecessary amount of fuel being consumed. It is this gap in efficiency that a MHPS capitalizes on when it augments the generator with a battery pack.

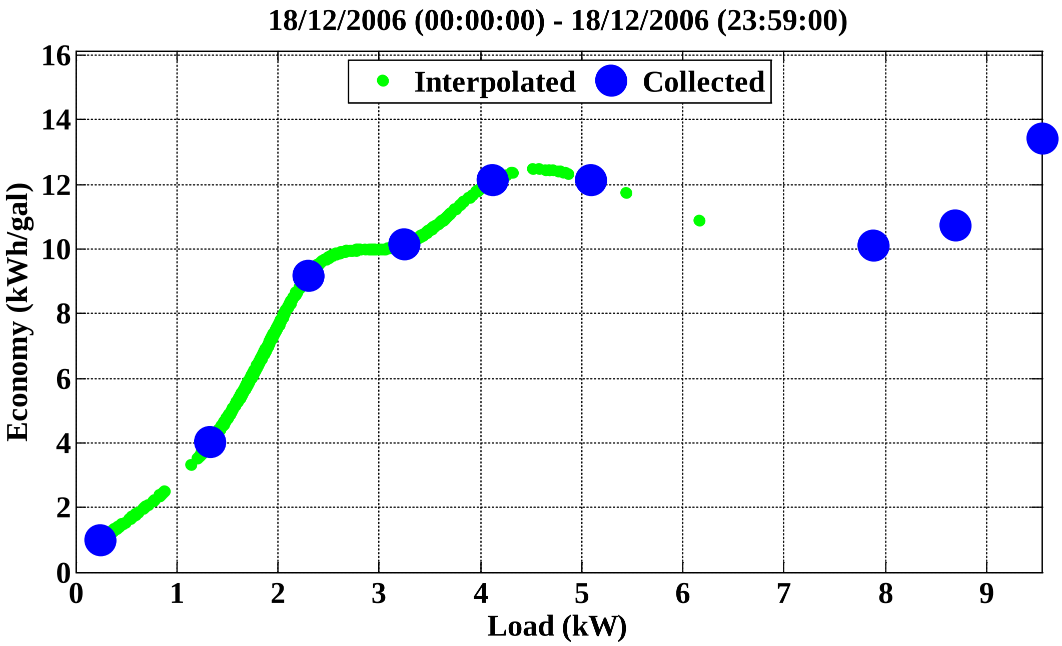


Figure 13 – Generator Fuel Economy

Table 3 – Generator Efficiency Analysis Equations

Variable	Equation	
Load (kW)	x	(1)
Fuel Consumption (gal/hr)	$f(x)$	(2)
Fuel Economy (kWh/gal)	$y(x) = \left.\frac{x}{f(x)}\right\|_{x_{min}}^{x_{max}}$	(3)
Energy Efficiency (kWh_{out}/kWh_{in})	$\eta(x) = \frac{y(x)}{40}$	(4)
Energy in 1 gal of diesel	$1gal = 40kWh$	(5)

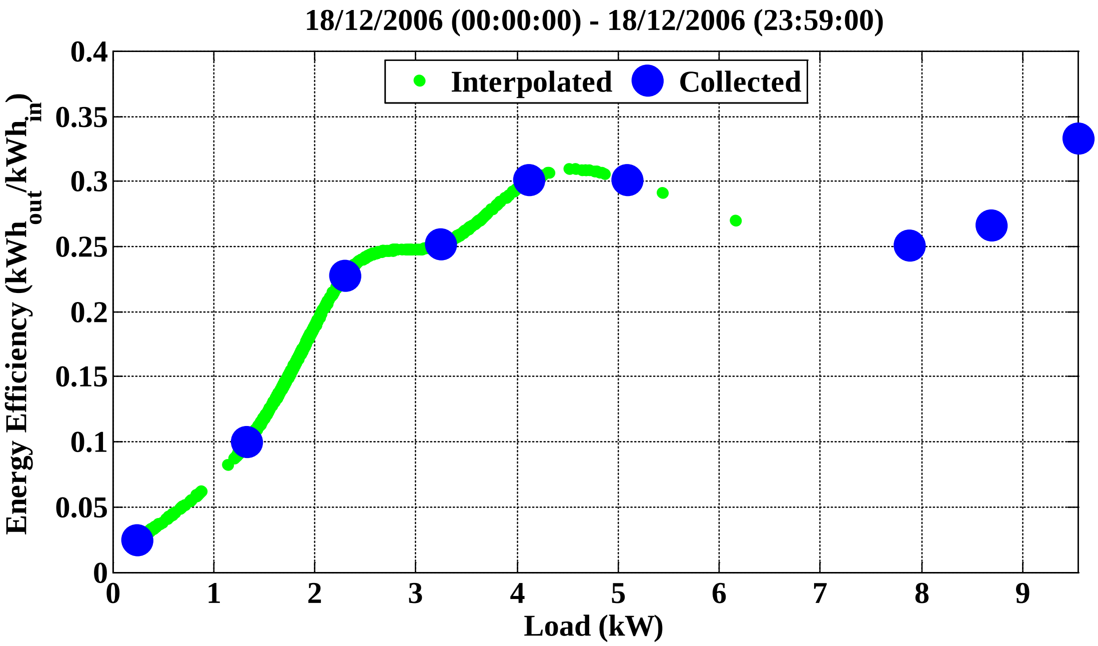


Figure 14 – Generator Energy Efficiency

Section 2.5 Energy Flow

Now that we have developed an understanding of load profiles and generators, we can move on to discussing how incorporating a battery pack changes the operation of a traditional generator. We start by looking at a traditional setup for supplying power to a load. Looking at Figure 15a, we can see that the generator is connected directly to the load. As mentioned before this is a problem because the energy efficiency will vary as well. To solve this problem we can run the generator at a fixed point, allowing the battery pack to handle the load fluctuations. However, this will change the operation of the power system. Looking at Figure 15, we can see a block diagram of both a traditional and hybrid power system.

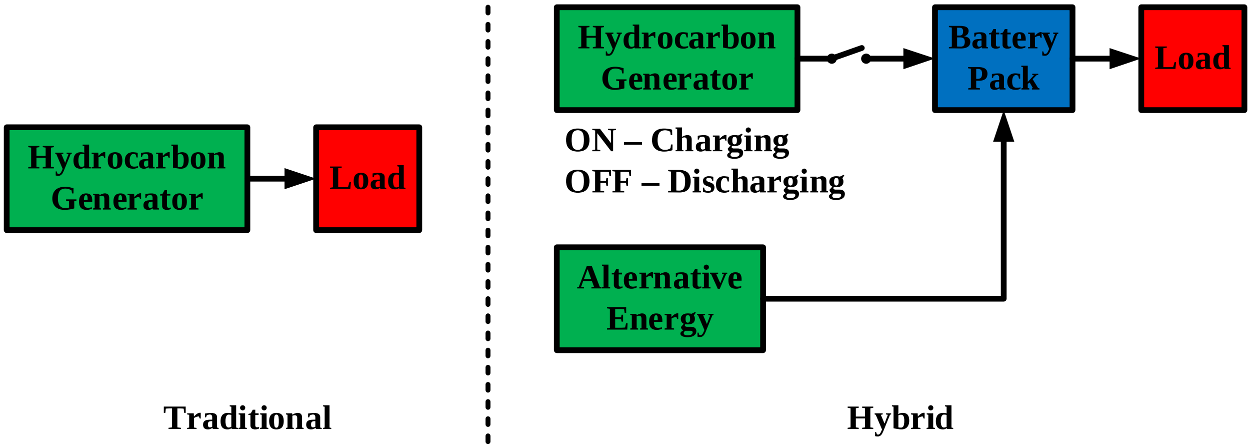


Figure 15 – Power System Block Diagram

Hybrid Operation

To fully understand the changes that happen to the operation of the hybrid power system we have to think about how a load profile is powered using the traditional method. If the load profile of Figure 10 was powered using the traditional method, the power out of the generator would vary directly with the load profile. However, hybrid operation allows us to decouple the load fluctuation from the generator allowing us to fix its operating point. To demonstrate this we will set the generator output to the average of load profile power level giving us Figure 16.

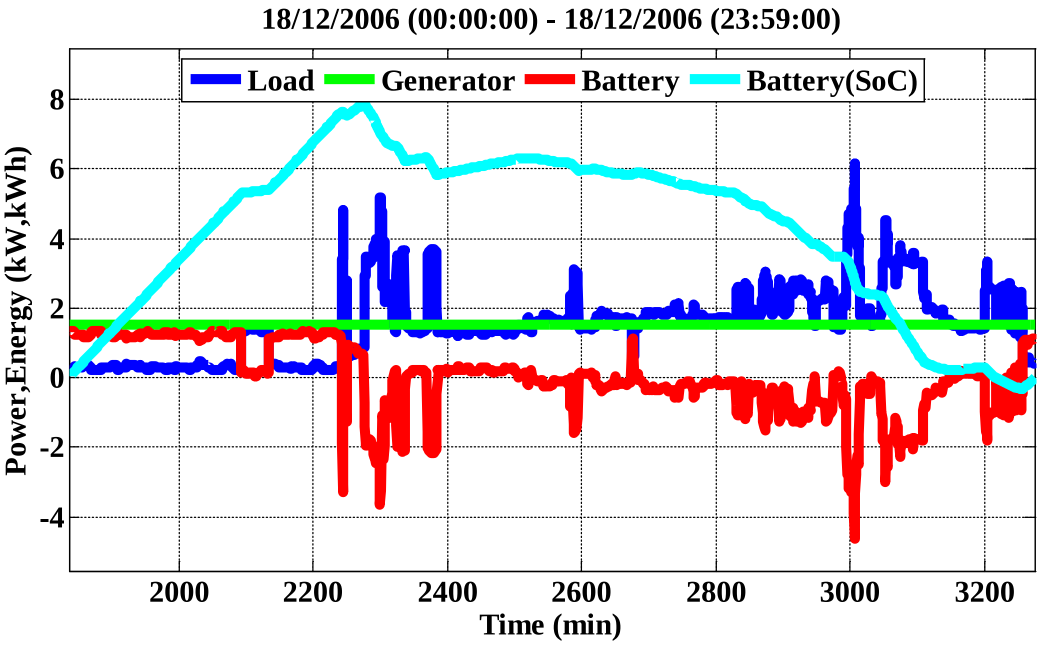


Figure 16 – Hybrid Operation Power and Energy Flow

Now that we have fixed the generators operating point we must consider the effect that this has on the battery pack. Looking at equations in Table 4, we can see how excesses and deficiencies in power production are reflected in the battery's power flow. However, because the battery's power flow is changing we must now consider the effect that this will have has on its state of charge. This means we have to integrate over time to find how the energy level of the battery pack changes, assuming ideal charging and discharge efficiency.

Table 4 – Hybrid Operation Equations

Variable	Equation	
Time (hr)	t	(6)
Load (kW)	$x(t)$	(7)
Generator (kW)	$g(t) = \bar{x}$	(8)
Battery (kW)	$b(t) = g(t) - x(t) \begin{cases} b > 0, & charging \\ b < 0, & discharging \end{cases}$	(9)
Battery (SoC) (kWh)	$h(t) = \int_{t_0}^{t_f} b(t)\, dt$	(10)

Now that we have an understanding of how the energy flow differs between a traditional and a hybrid system we can turn our attention to how hybrid operation affects energy and fuel consumption. Looking at Figure 17, Figure 18, Figure 19, and Table 5 we can see that a hybrid system has indeed allowed us to fix the generator's operation point leaving the battery pack to handle load fluctuations. This can be seen in the varying slope of the generator only curves vs the fixed slope of the hybrid curves. However, because the generator's operating point was set to the average of the load profile, energy efficiency was not improved, but actually worsened.

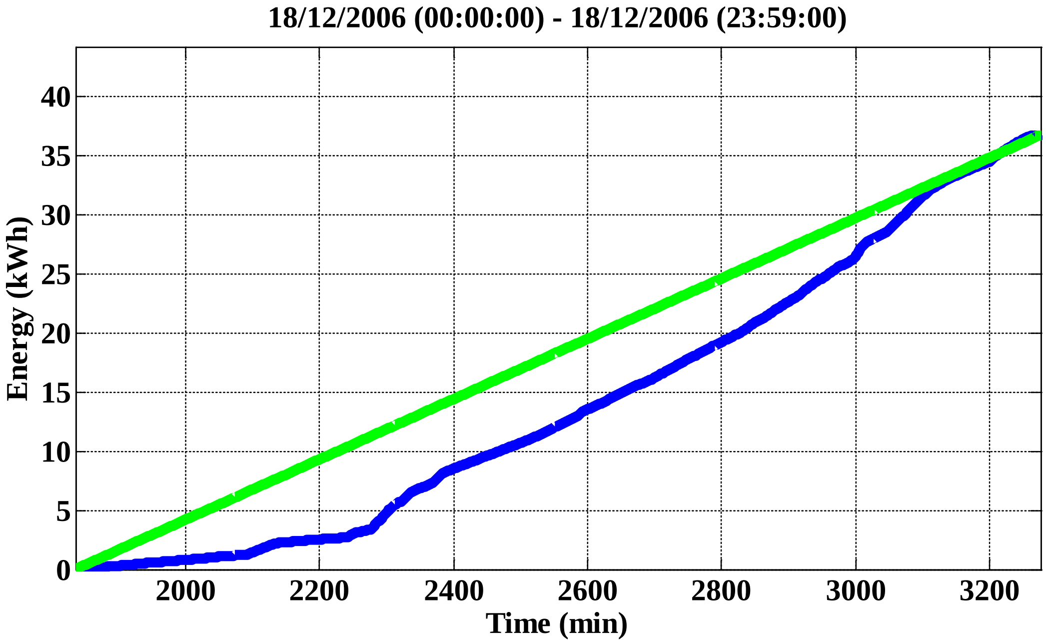


Figure 17 – Energy Consumption Comparison

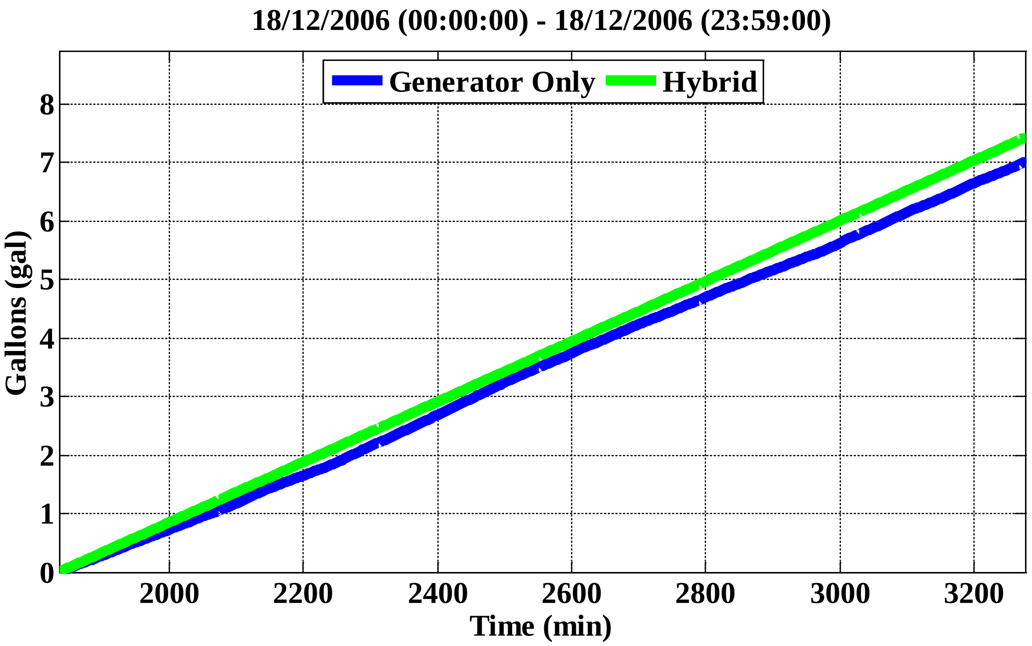


Figure 18 – Fuel Consumption Comparison

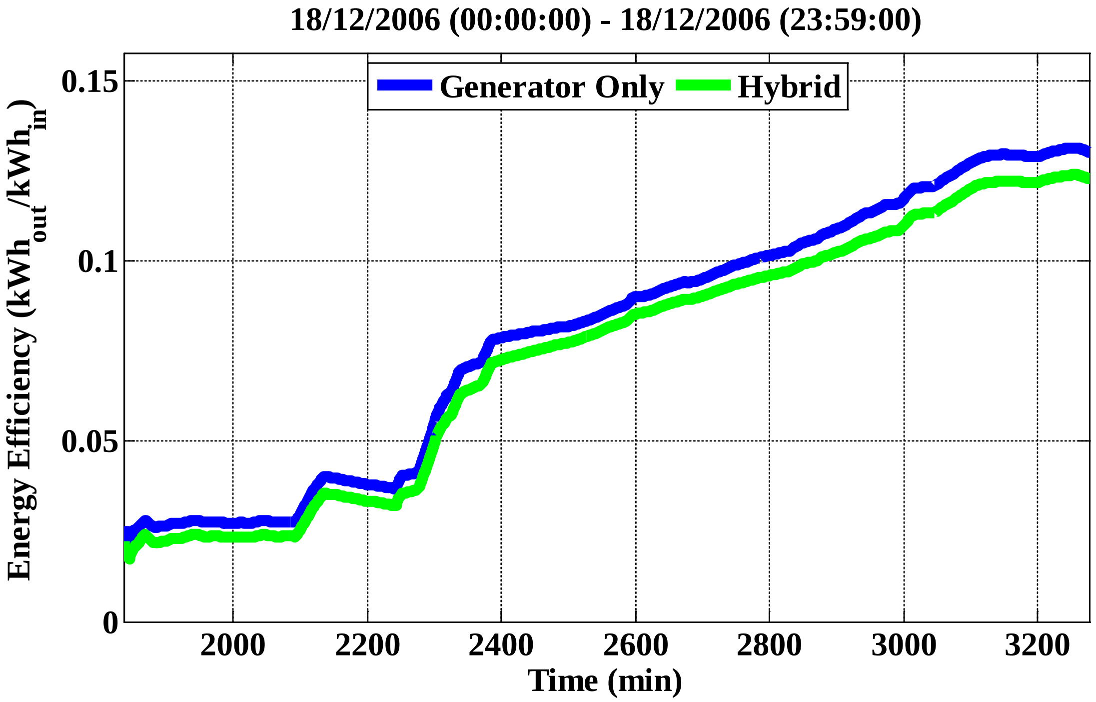


Figure 19 – Energy Efficiency Comparison

Table 5 – Energy and Fuel Consumption Equations

Variable	Equation	
Energy Consumed (kWh)	$e(t) = \int_{t_0}^{t_f} g(t)\,dt$	(11)
Fuel Consumed (gal)	$r(t) = \int_{t_0}^{t_f} y(t)\,dt$	(12)
Energy Efficiency (kWh_{out}/kWh_{in})	$\eta(t) = \frac{y(t)}{40}$	(13)

Section 2.6 Experimental Needs

Looking back at the results of Section 2.5 we can see that improved energy efficiency is not something that is guaranteed by the incorporation of a storage element. In actuality it is dependent upon the energy capacity if both the generator and battery pack, and most importantly the load profile. This is why an experiment is needed that studies the effects of varying these nonlinear parameters. From this we hope to develop an understanding of a MHPS so that we can optimize its operation for a variety of conditions.

Chapter 3 Experiment

Section 3.1 Introduction

In Chapter 1 and Chapter 2 the motivations, background, and theory surrounding a MHPS were discussed. To extend this we now turn our focus to carrying out an experiment that allows us to study the effects that a battery pack has on the system. To do this we will recall the system that we have considered far. However, we must now introduce real world constraints such as fixing the generator output at a more efficient operating point and limiting the battery pack size. This is what we would like to experiment with so we can understand what the energy flow looks like as we introduce such nonlinearities.

Section 3.2 Procedure

Table 6 – Experimental Procedure

Procedure
1. Collect load profile data (control)
2. Create traditional system (control)
3. Create hybrid system (independent variable)
4. Determine battery pack size (independent variables)
5. Determine performance metrics (dependent variables)
6. Compare results (evaluation, Chapter 4)
7. Apply findings (conclusions, Chapter 5)

Section 3.2.1 Load Profile

Now that we have defined the procedure for our experiment, we can select load profile data to analyze. To show the benefits of a MHPS clearly, we need to use a load profile that has a large gap between peak and average power. This is when the inefficiency of a diesel generator is at its greatest. It also needs to have sufficient resolution so that none of the important dynamics will be missed and averaged out. What we are looking for is the peaking associated with large and inductive loads such as motors and appliances. For this thesis the "Individual household electric power consumption Data Set" from the University of California Irvine [8] will be used as it meets those requirements. A summary describing the data is show in Table 7.

Table 7 – Load Profile Information

Parameter	Description
Data Points	2075259
Range	December 2006 – November 2010 (47 Months)
Missing Points	≈1.25%
Active Power	minute-average active power (kW)
Reactive Power	minute-average reactive power (kW)
Voltage	minute-averaged voltage (V)
Intensity	minute-average current intensity (A)
Sub Metering 1	kitchen (dishwasher, oven, microwave)
Sub Metering 2	laundry Room (washing-machine, tumble-direr, refrigerator and a light)
Sub Metering 3	water-heater, air-conditioner

Section 3.2.2 Traditional System

For our experimental control we will use a traditional system. For this case we will use the generator with the fuel consumption profile as described in Figure 12. This 10kW generator will be adequate to handle the 6.2kW peak of the load profile. It will also have to operate continuously because there is no storage element to decouple the generator from load changes. A summary of the traditional system is shown below in Table 8.

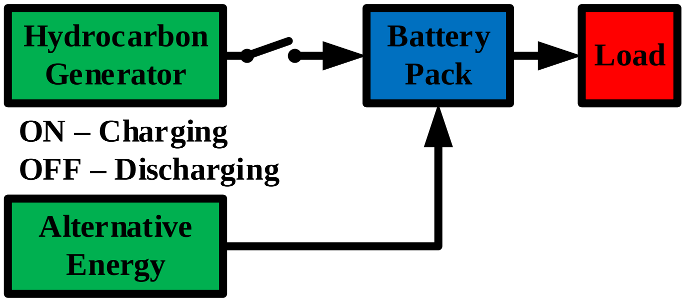
Table 8 – Traditional System

Block Diagram	Parameter	Value
	Generator Capacity	10kW
	Generator Operation	Variable
	Battery Capacity	None
	Conversion Efficiency	100%

Section 3.2.3 Hybrid System

Now that we have added a battery pack, we must consider how the system's operation will be affected. For example, we must consider battery capacity because it will limit how much energy can be stored. This is important since over charging and discharging is bad for battery health. To avoid this, the generator will have to turn on or off to keep the battery within its SoC limits. Such is the case in Figure 16 after 3200mins when the battery pack is over discharged.

Table 9 – Hybrid System

Block Diagram	Parameter	Value
	Generator Capacity	≈ 5kW
	Generator Operation	Fixed
	Battery Capacity	Variable
	Conversion Efficiency	100%

Section 3.2.4 Battery Pack Sizing

To understand the effect that battery pack sizing has on the hybrid operation, we must test the system with different battery pack sizes. From this we will be able to establish a trend from the results and draw conclusions. For this experiment we will use the following combinations in Table 10. We will also need to understand the effect that initial SoC has on the hybrid system's operation.

Table 10 – Battery Pack Parameters

Capacity (kWh)	Initial SoC (%)
0	0
1	10
5	50
10	100

Section 3.2.5 Performance Metrics

Since we have established that the battery pack is going to affect the system, we need to have some metrics to quantify the performance of the hybrid system. To account for this we will look at the following parameters listed below in Table 11. Of these the most important will be fuel consumption and energy efficiency since they are what we would like to minimize and maximize respectively.

Table 11 – Performance Metrics

Metric	Units	Metric	Units
Energy Consumption	(kWh)	Energy Cycles	(n)
Fuel Consumption	(gal)	On Time	(sec)
Efficiency	(unitless)	Off Time	(sec)

Section 3.2.6 Comparison Metrics

Finally since we have established some metrics for which to evaluate performance we need to be able to compare the hybrid system with the traditional method. For this we will use the following metrics listed in

Table 12 – Comparison Metrics

Metric	Units	Metric	Units
Fuel Saved	(gal)	Generator Run Time	(sec)
Energy Saved	(kWh)		

Chapter 4 Results

Section 4.1 Introduction

Now that we have established a procedure allowing us to evaluate an MHPS, we can now perform a complete evaluation of a data set that more accurately reflects what will be used to design a MHPS.

Section 4.2 List of Experiments

Table 13 – List of Experiments

Experiment	Trial	Generator Capacity (kW)	Battery Capacity (kW)	Battery Initial SoC (%)
1	1	4.772	10	0
	2	4.772	5	0
	3	4.772	1	0
2	4	4.772	5	10
	5	4.772	5	50
	6	4.772	5	100
3	7	9.544	5	0
	8	4.772	5	0
	9	0.954	5	0

* = Duplicate

Section 4.2.1 Experiment 1 Battery Capacity

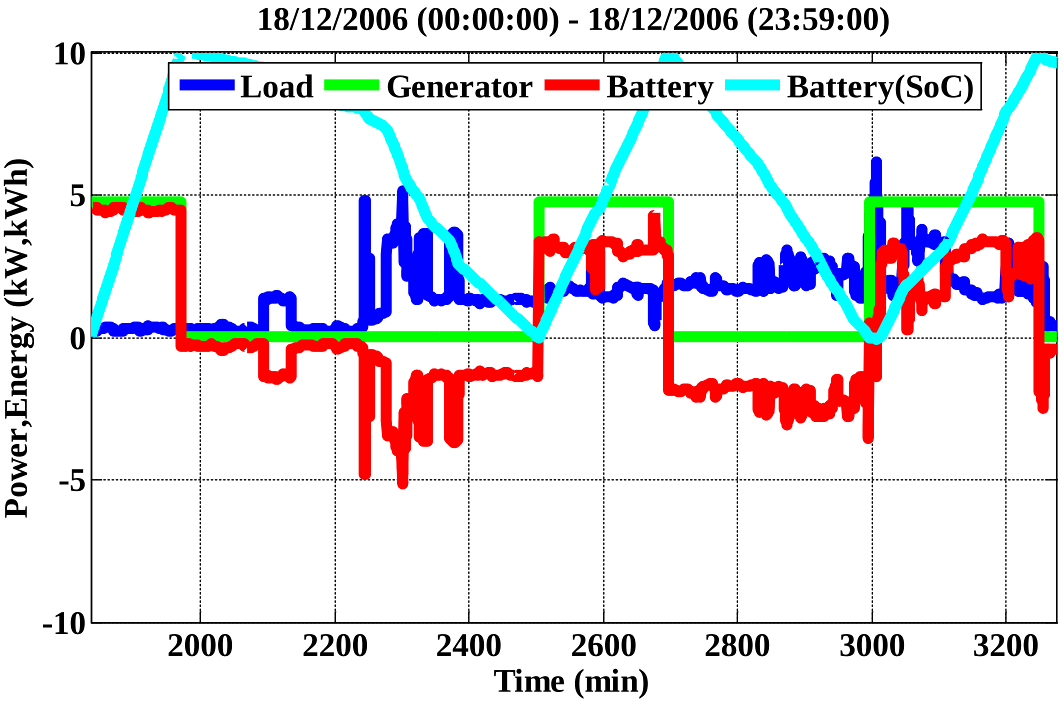


Figure 20 – Trial 1 Hybrid Operation Power and Energy Flow

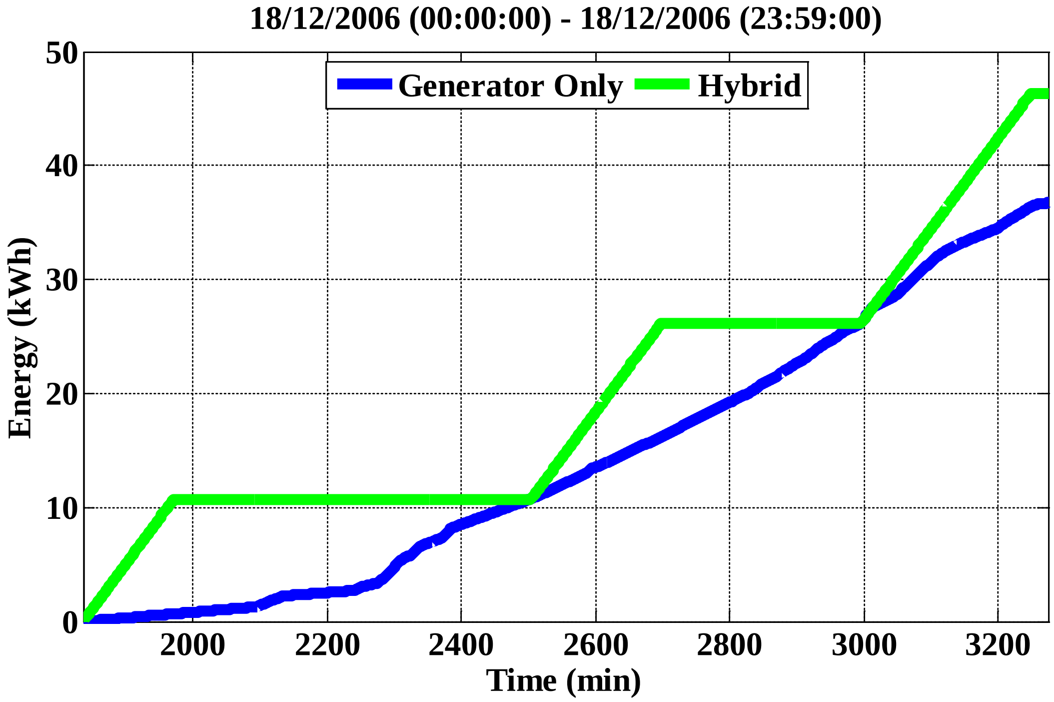


Figure 21 – Trial 1 Energy Consumption

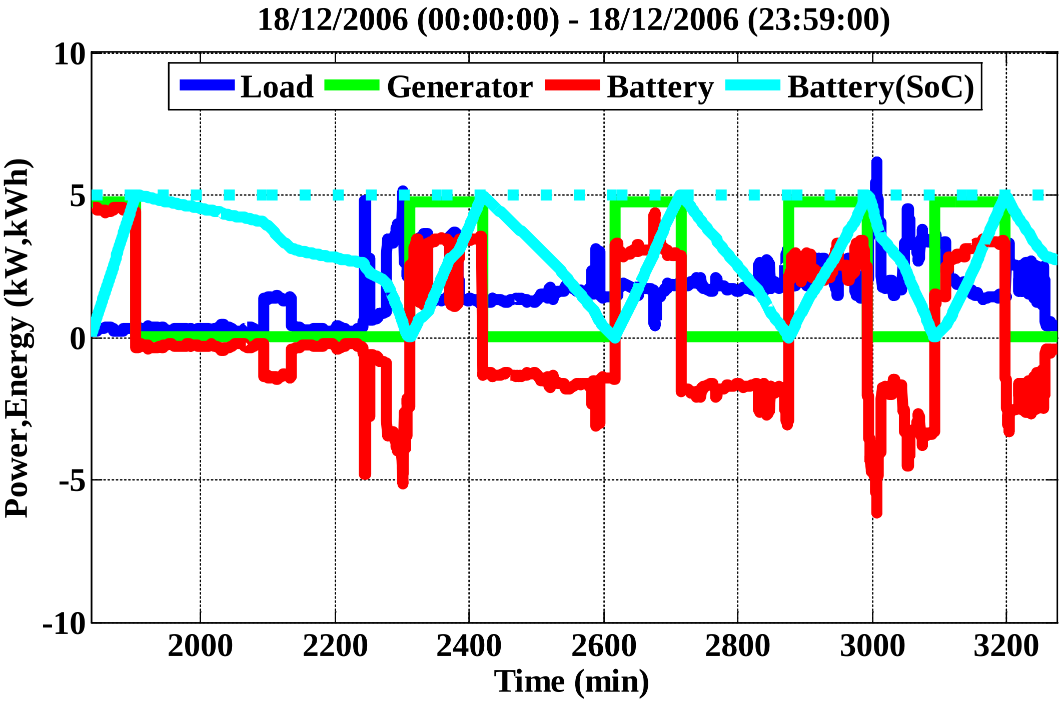


Figure 22 – Trial 2 Hybrid Operation Power and Energy Flow

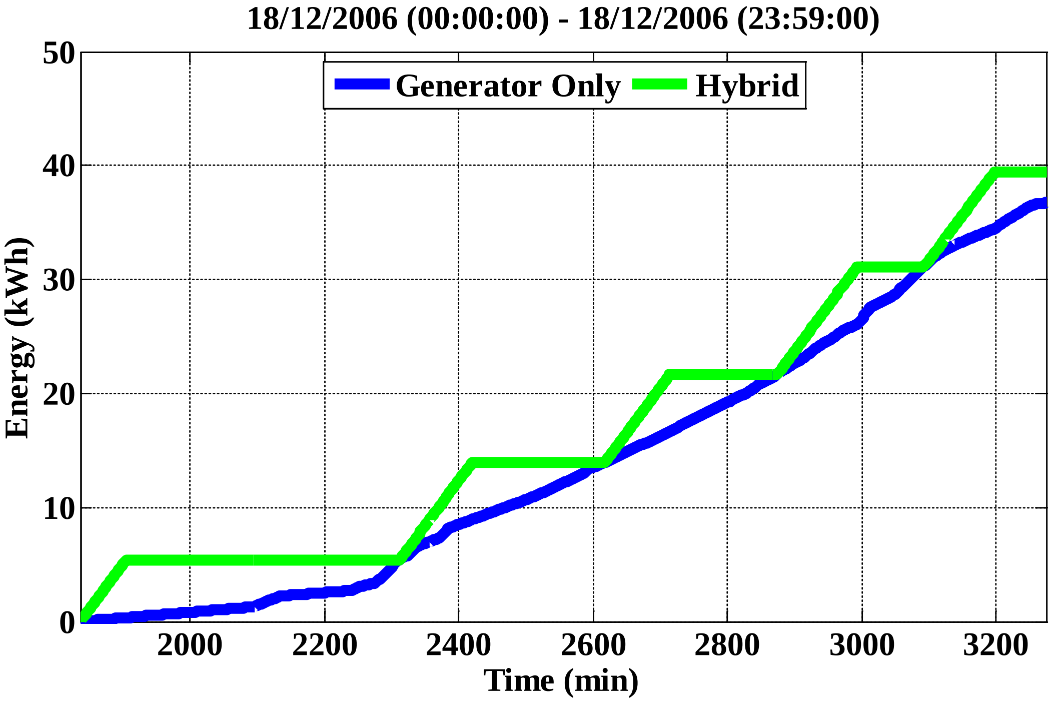


Figure 23 – Trial 2 Energy Consumption

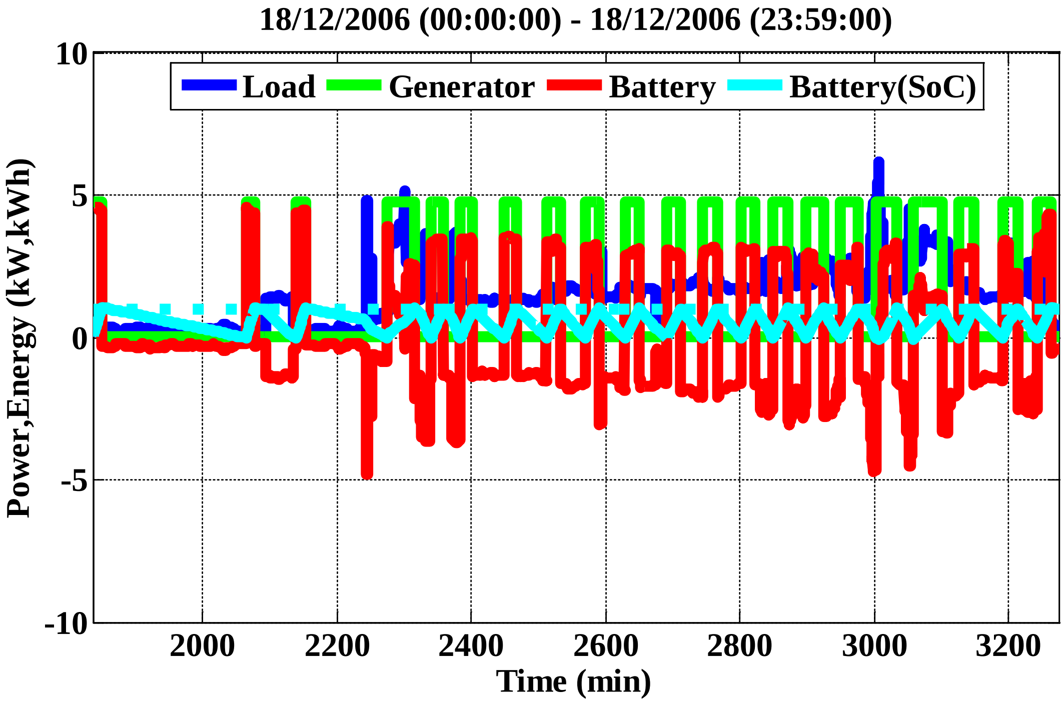


Figure 24 – Trial 3 Hybrid Operation Power and Energy Flow

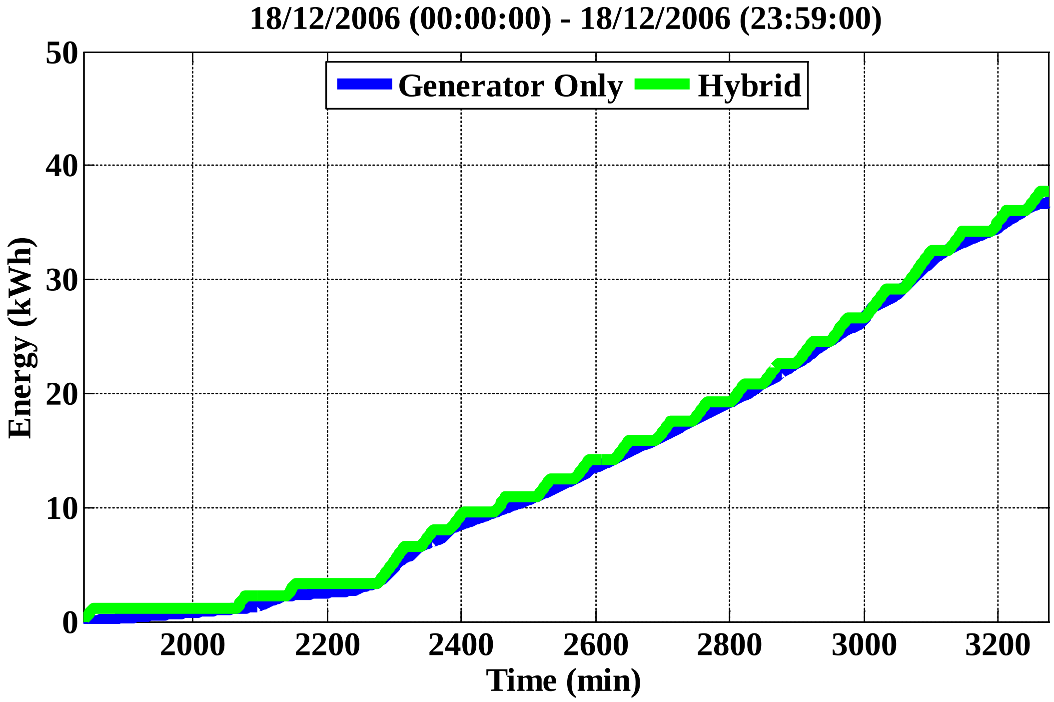


Figure 25 – Trial 3 Energy Consumption

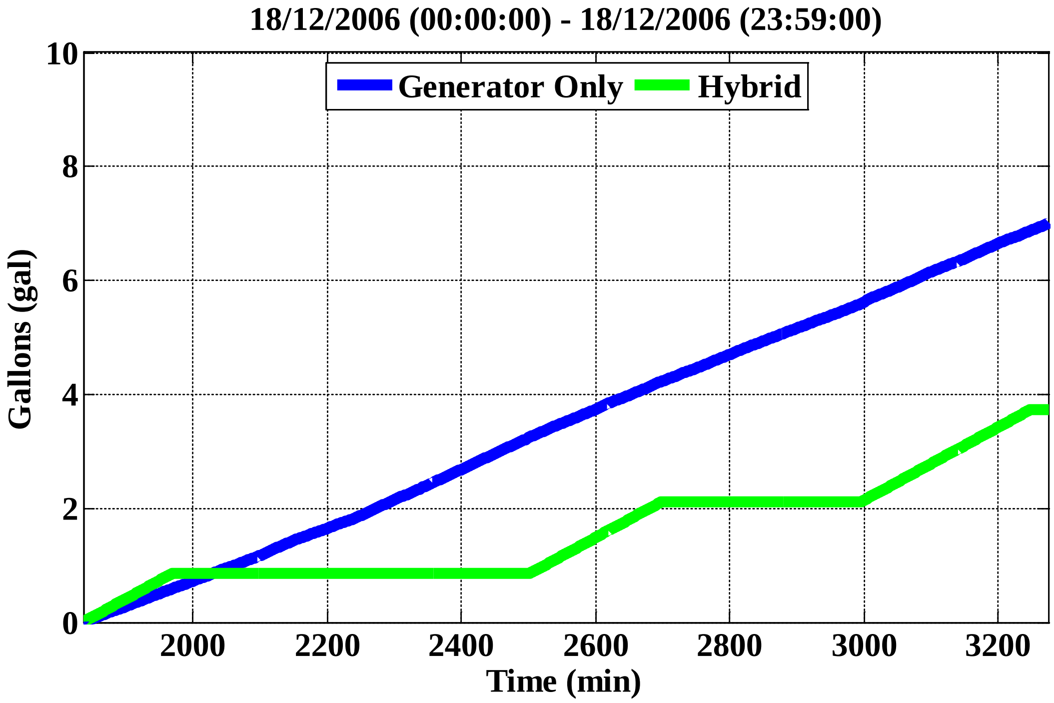


Figure 26 – Trial 1 Fuel Consumption

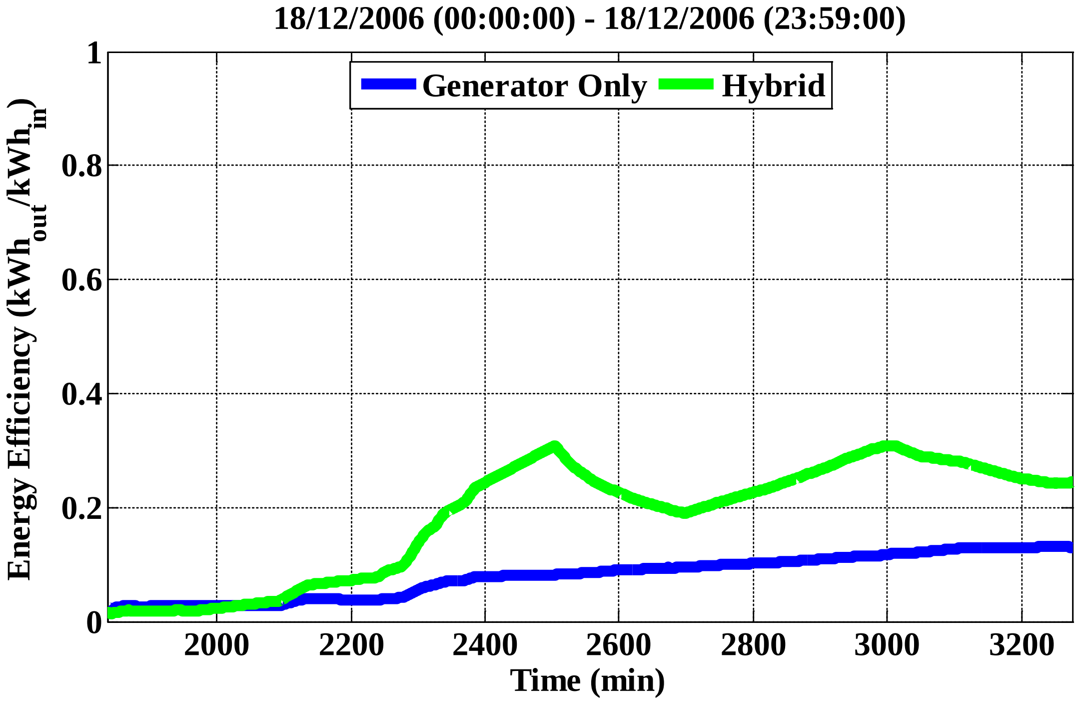


Figure 27 – Trial 1 Energy Efficiency

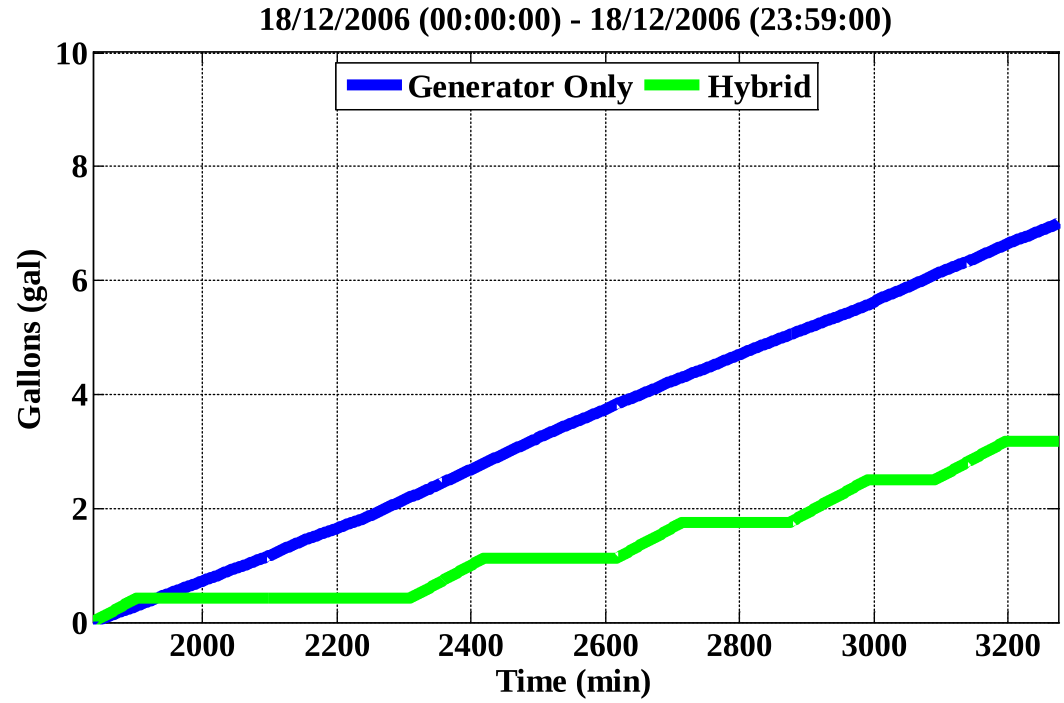


Figure 28 – Trial 2 Fuel Consumption

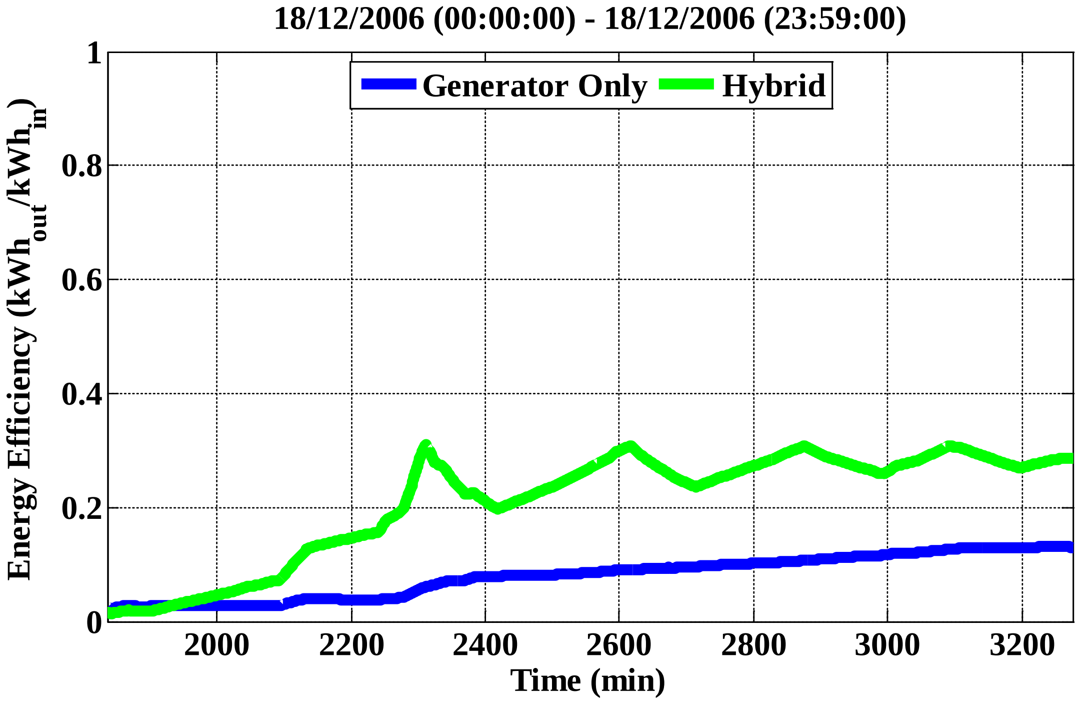


Figure 29 – Trial 2 Energy Efficiency

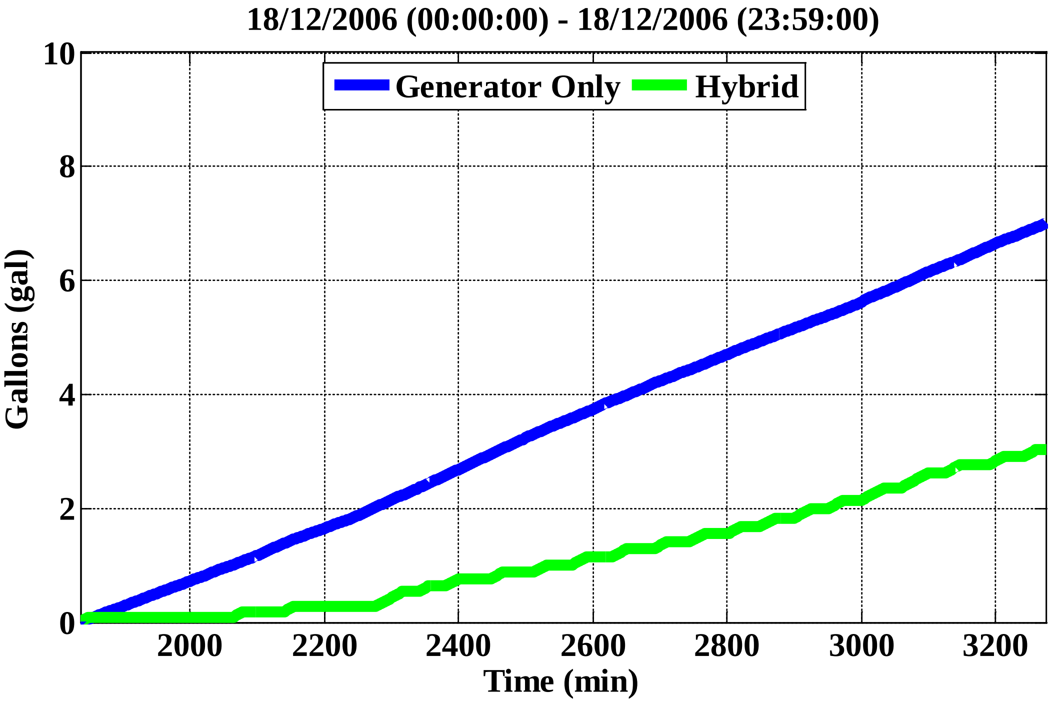


Figure 30 – Trial 3 Fuel Consumption

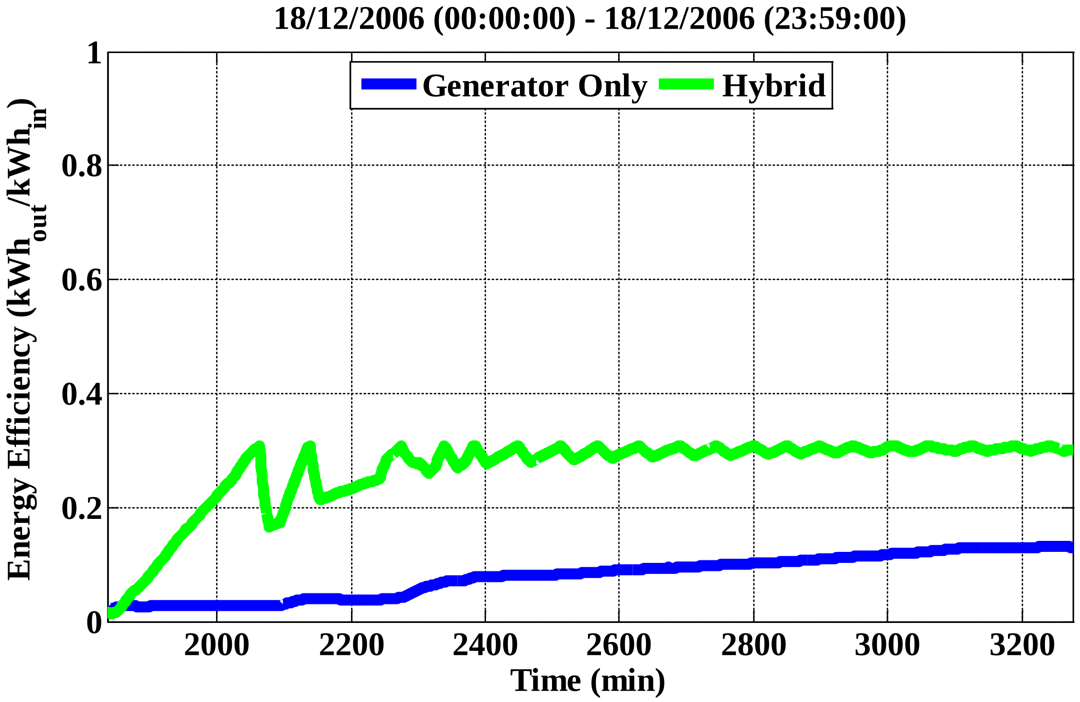


Figure 31 – Trial 3 Energy Efficiency

Section 4.2.2 Experiment 2 Initial SoC

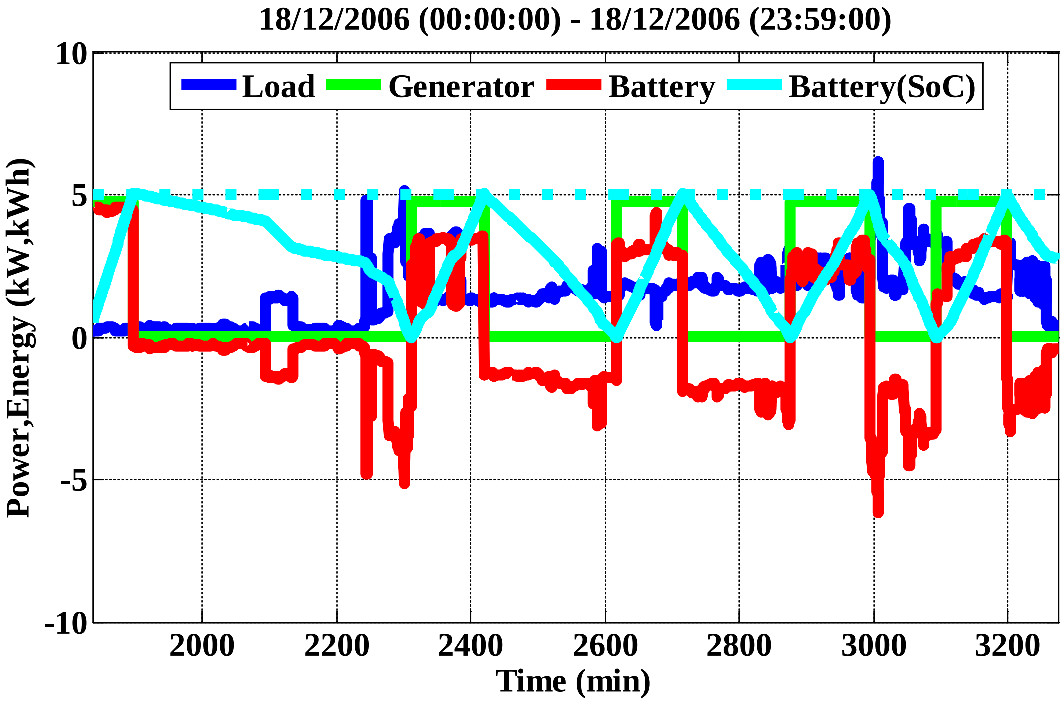


Figure 32 – Trial 4 Hybrid Operation Power and Energy Flow

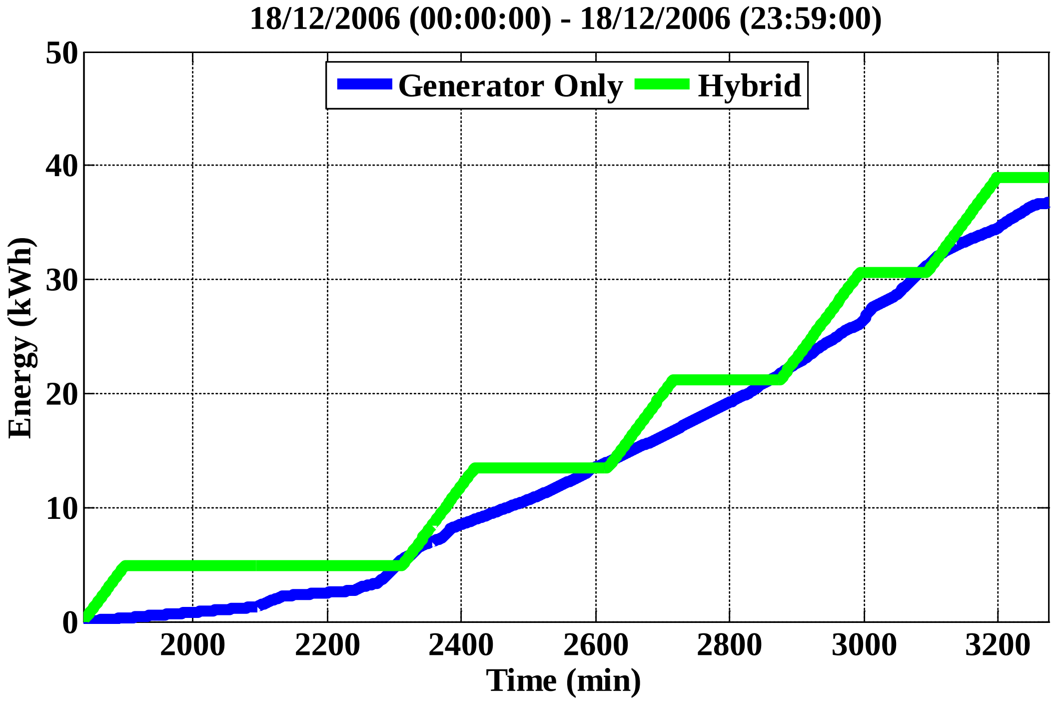


Figure 33 – Trial 4 Energy Consumption

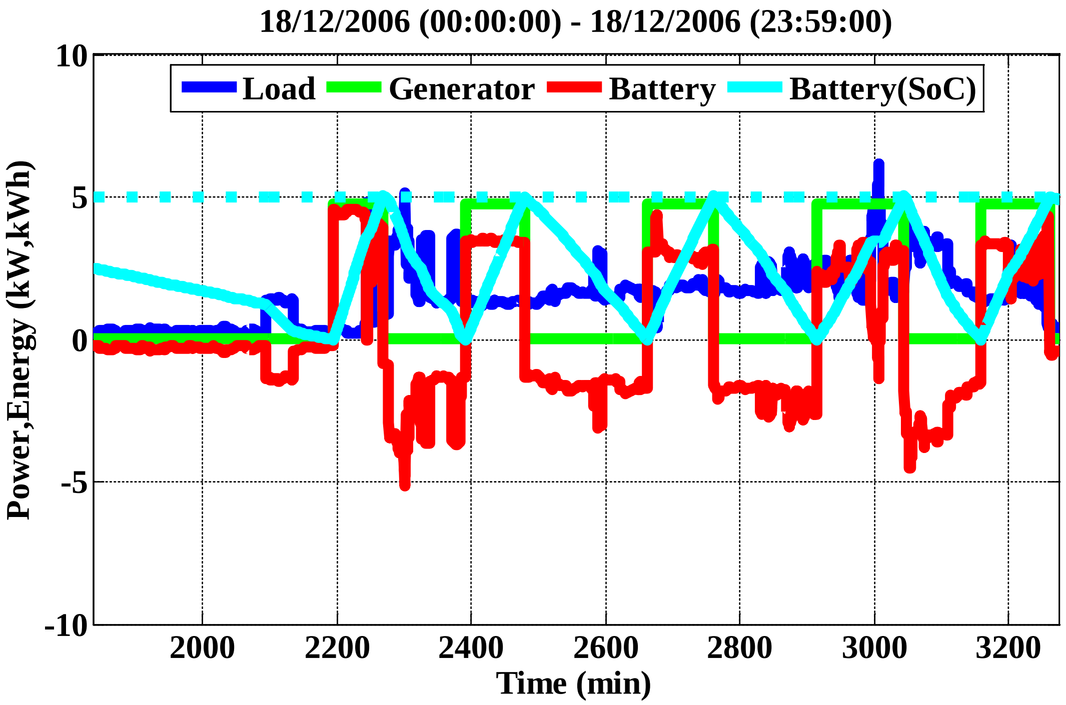


Figure 34 – Trial 5 Hybrid Operation Power and Energy Flow

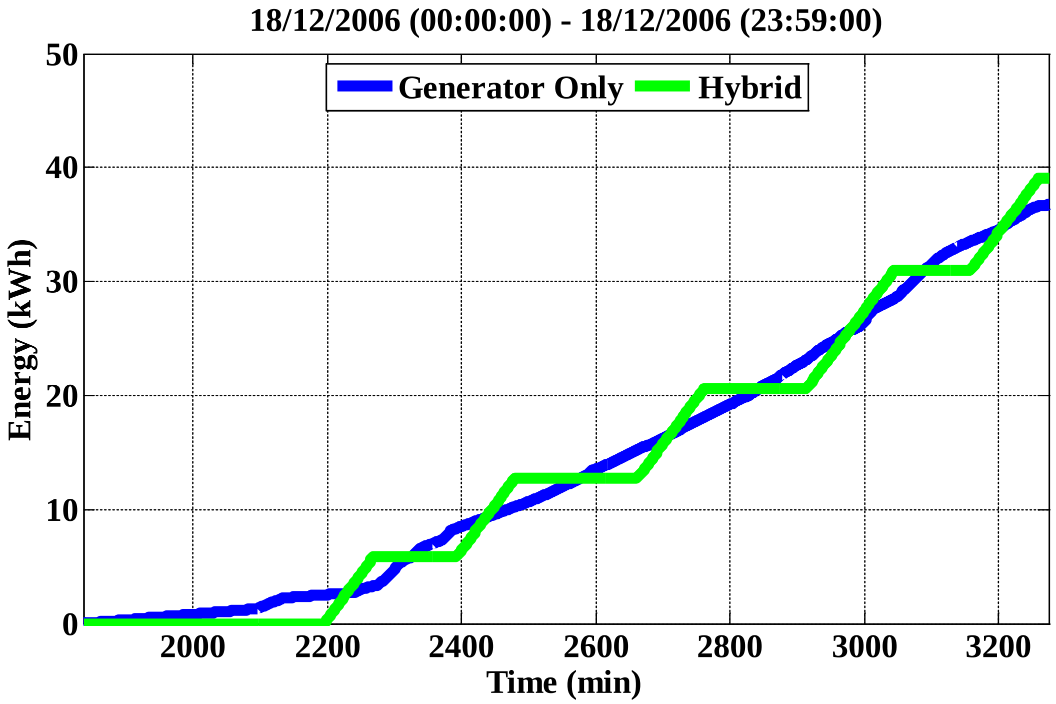


Figure 35 – Trial 5 Energy Consumption

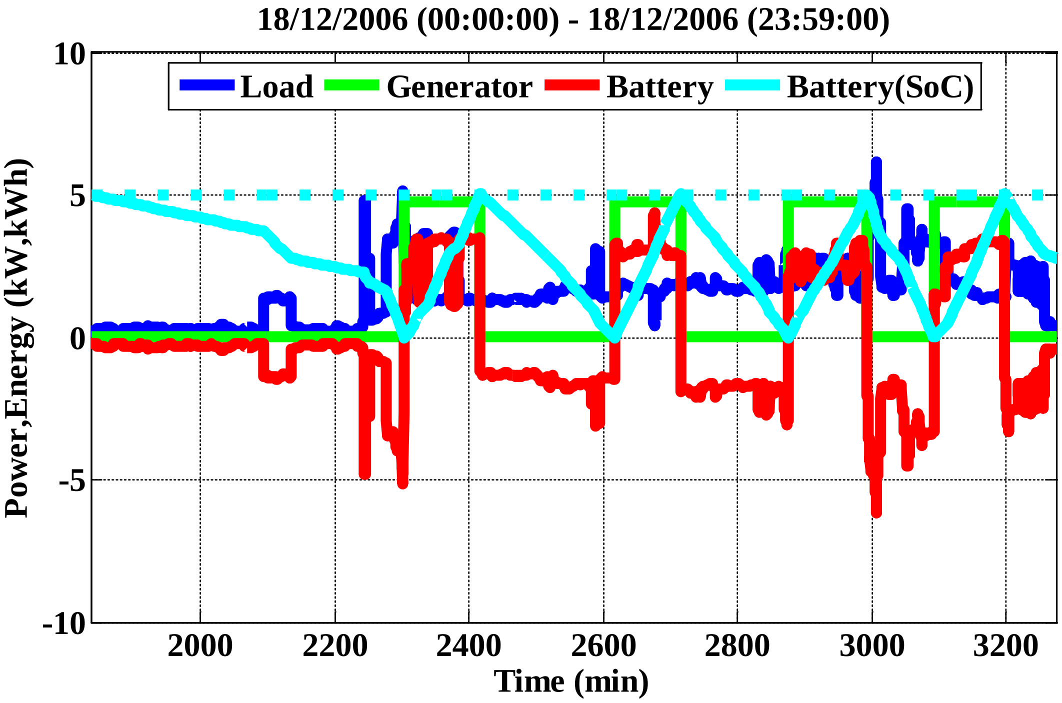


Figure 36 – Trial 6 Hybrid Operation Power and Energy Flow

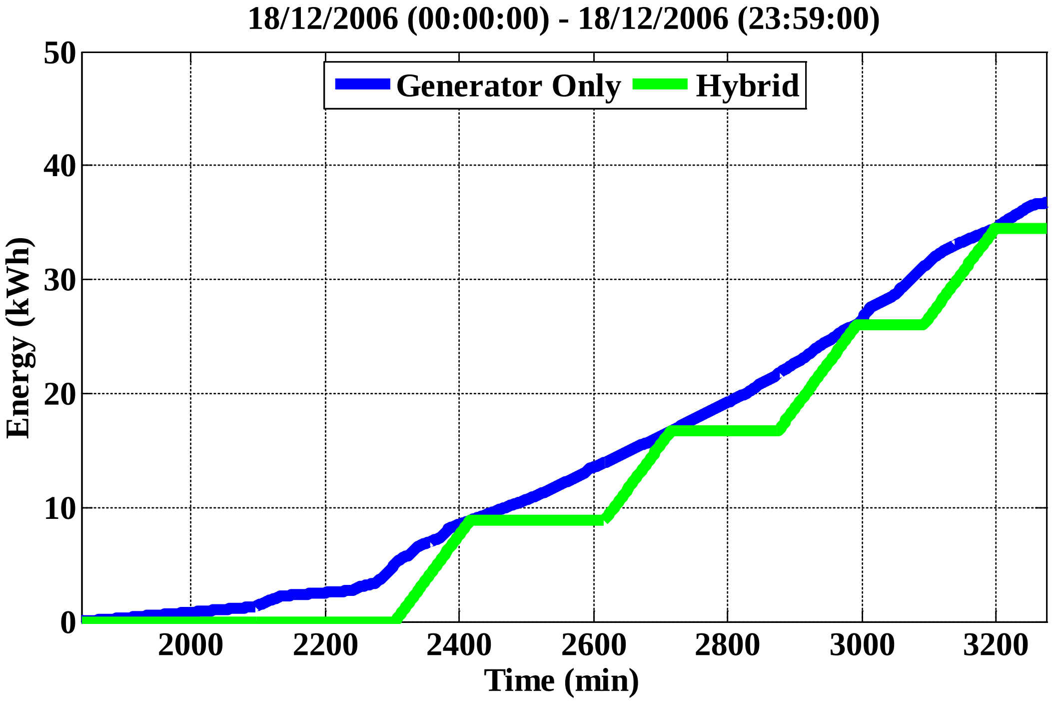


Figure 37 – Trial 6 Energy Consumption

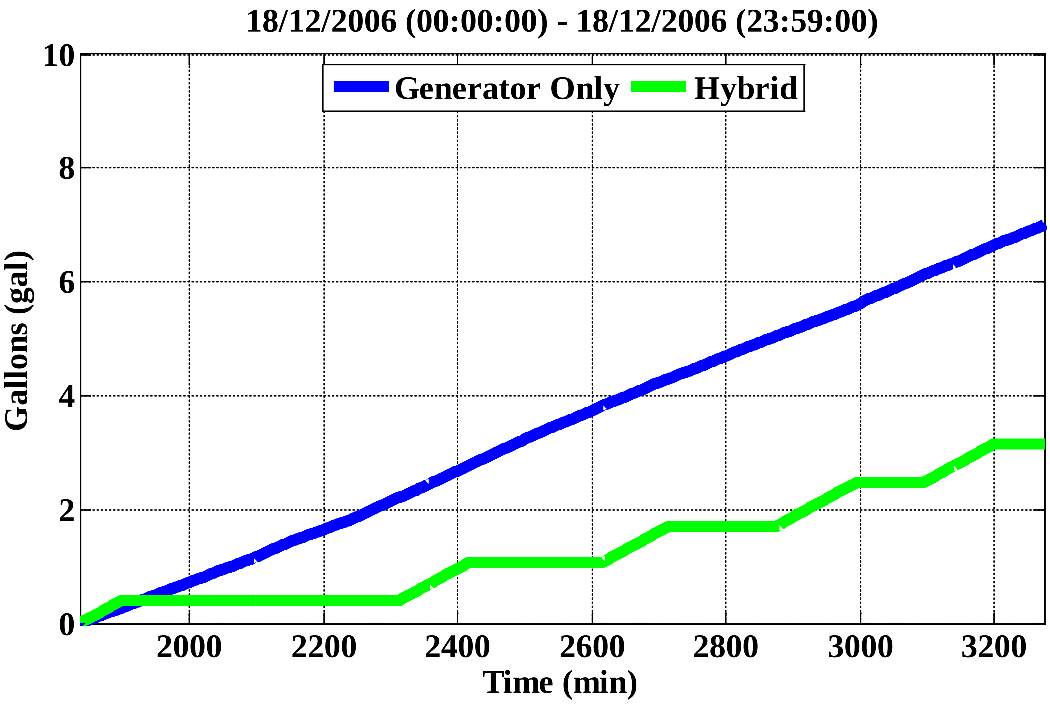


Figure 38 – Trial 4 Fuel Consumption

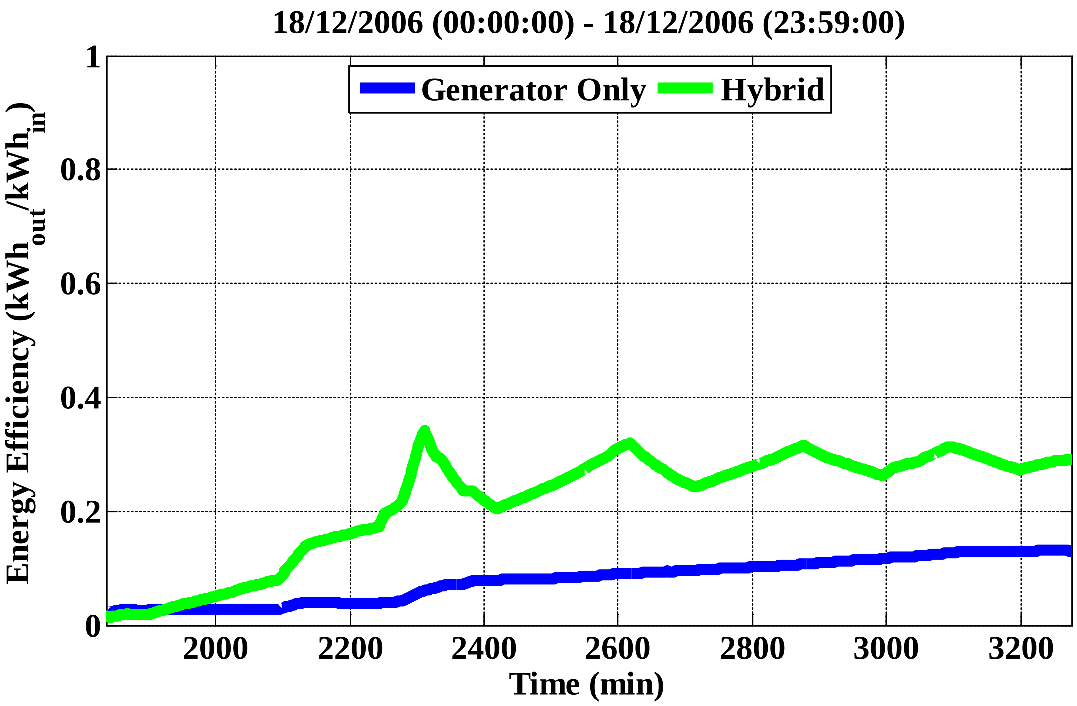


Figure 39 – Trial 4 Energy Efficiency

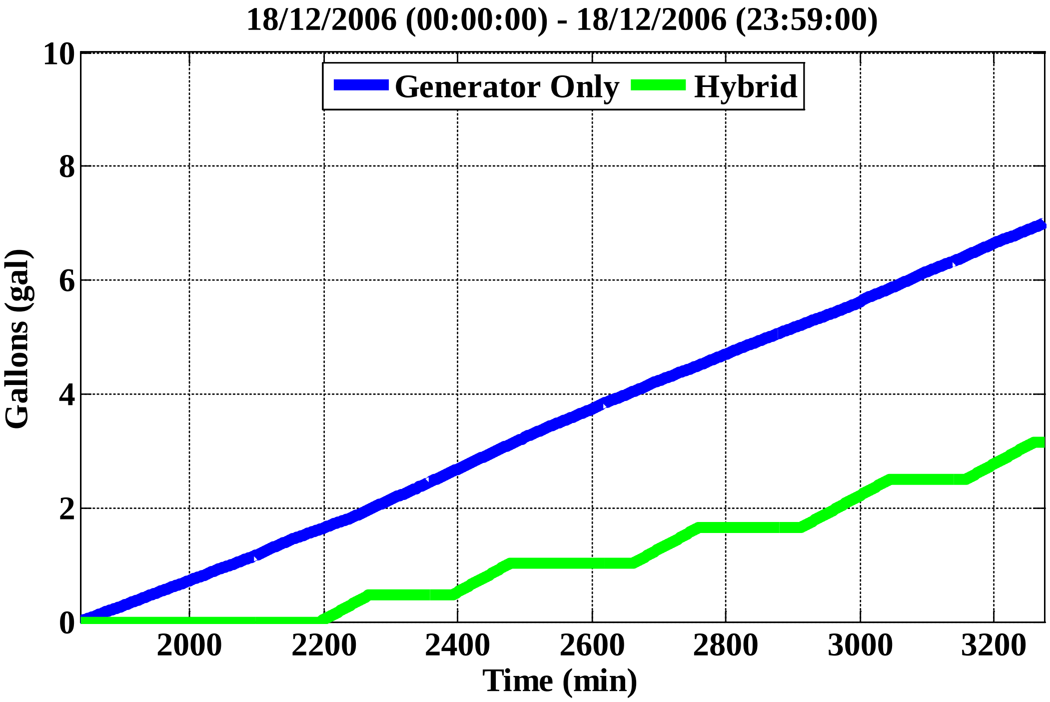


Figure 40 – Trial 5 Fuel Consumption

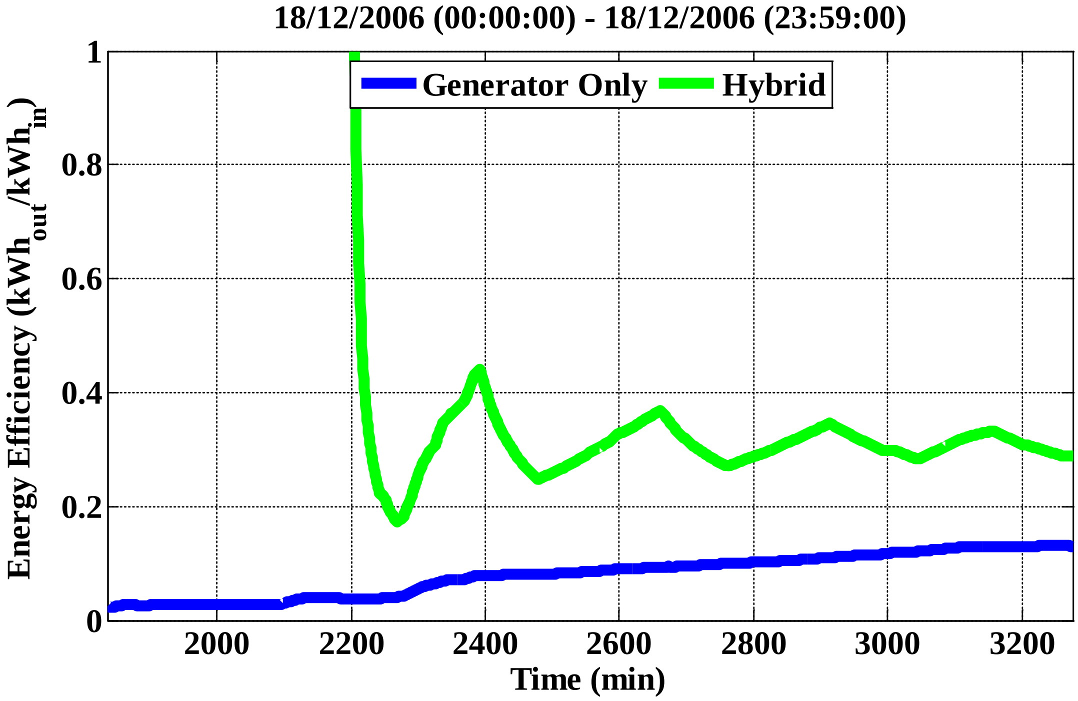


Figure 41 – Trial 5 Energy Efficiency

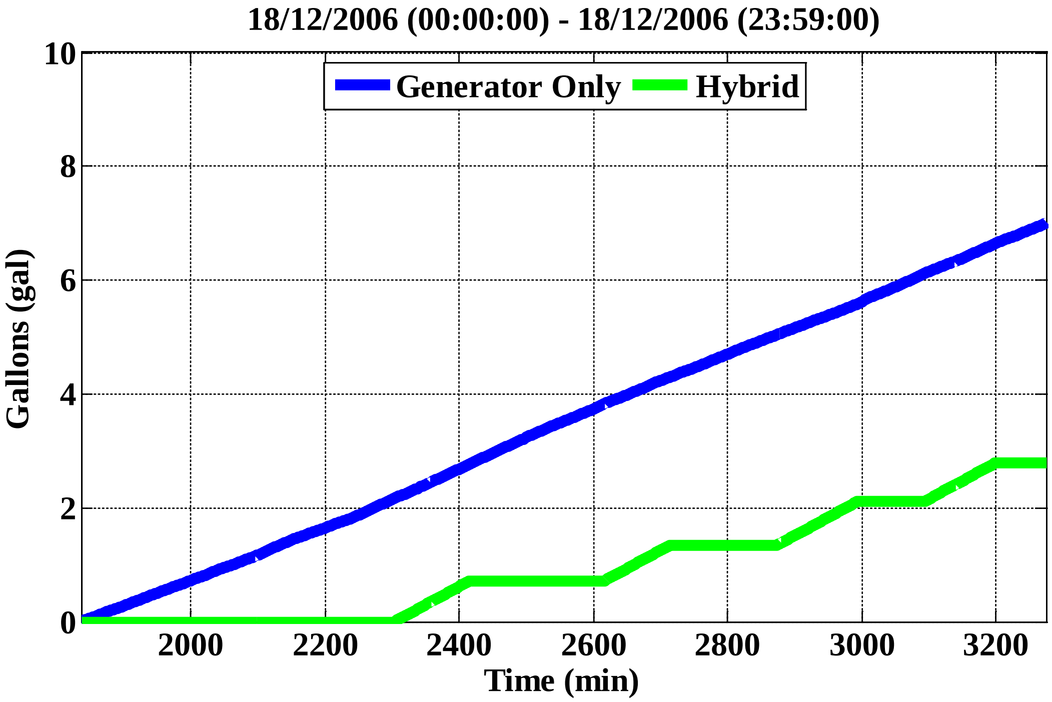


Figure 42 – Trial 6 Fuel Consumption

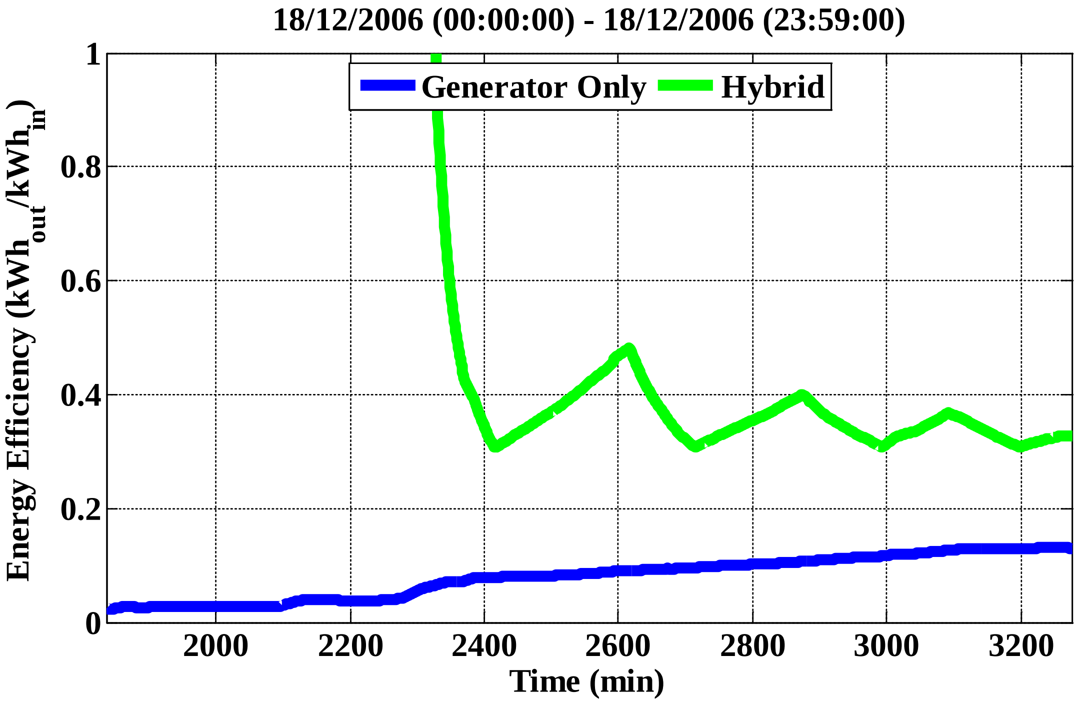


Figure 43 – Trial 6 Energy Efficiency

Section 4.2.2 Experiment 3 Generator Size

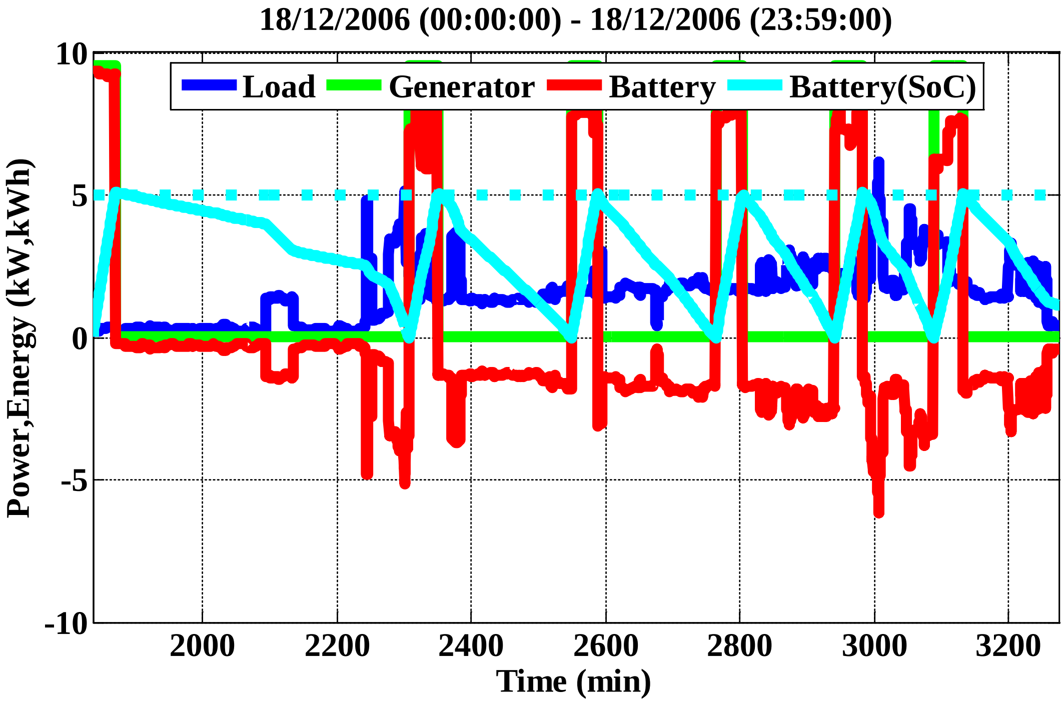


Figure 44 – Trial 7 Hybrid Operation Power and Energy Flow

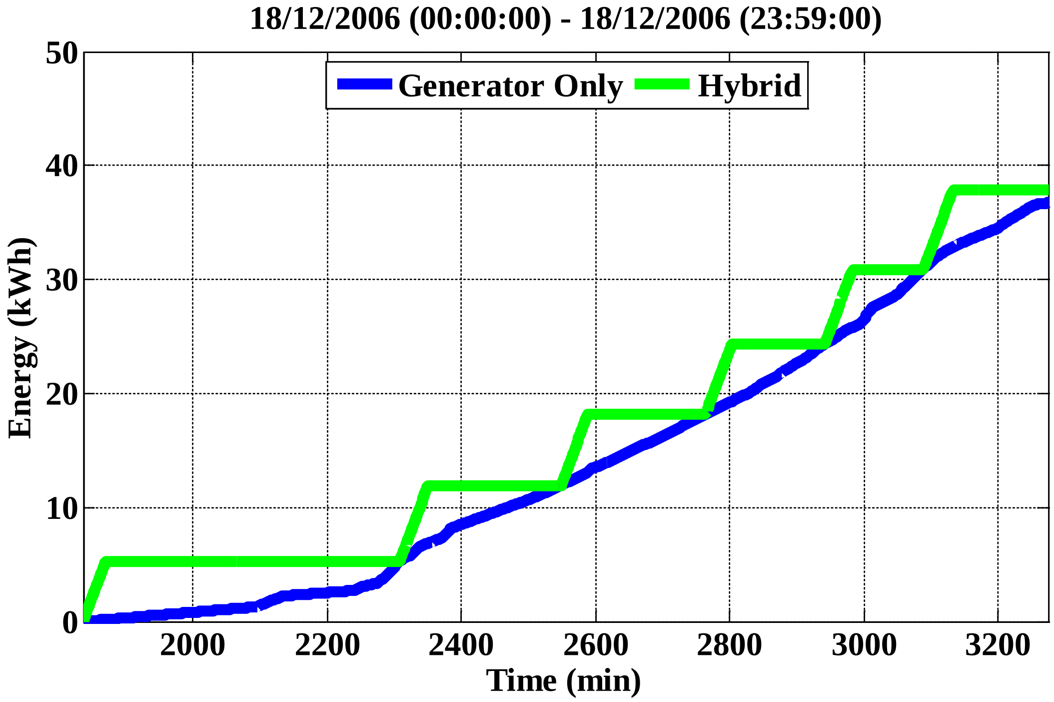


Figure 45 –Trial 7 Energy Consumption

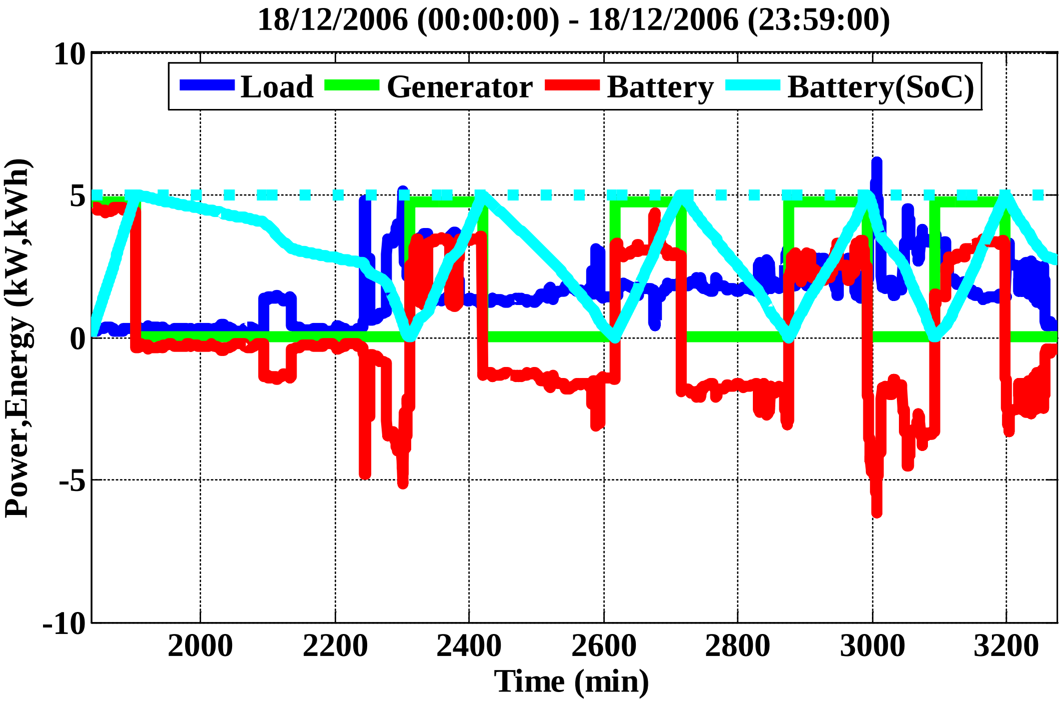


Figure 46 – Trial 8 Hybrid Operation Power and Energy Flow

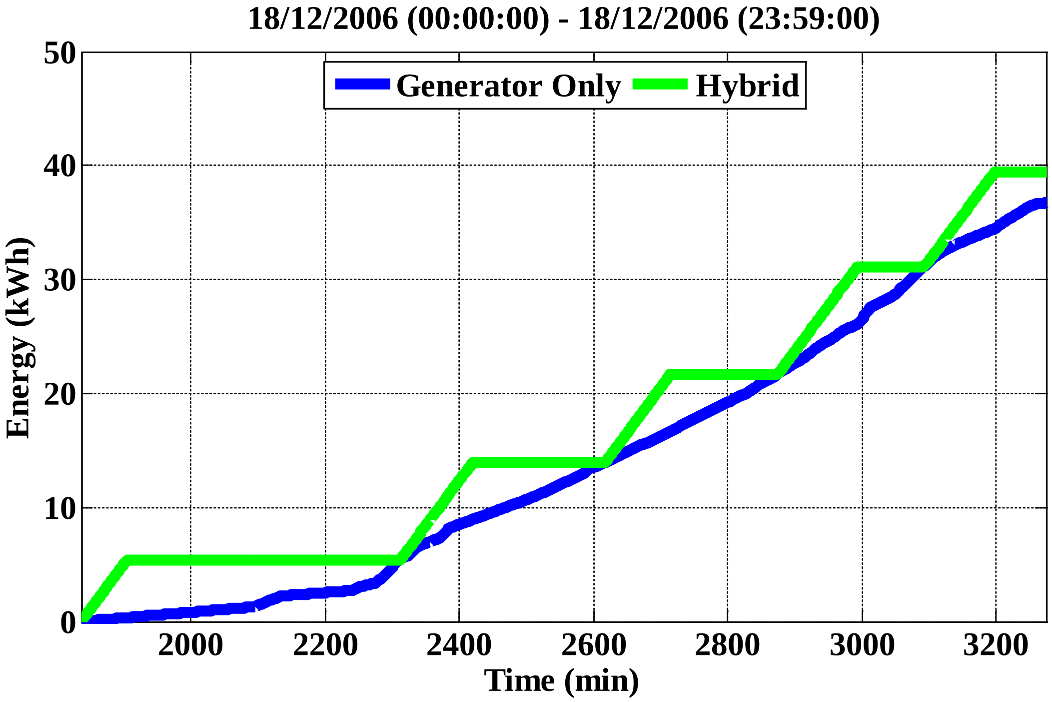


Figure 47 – Trial 8 Energy Consumption

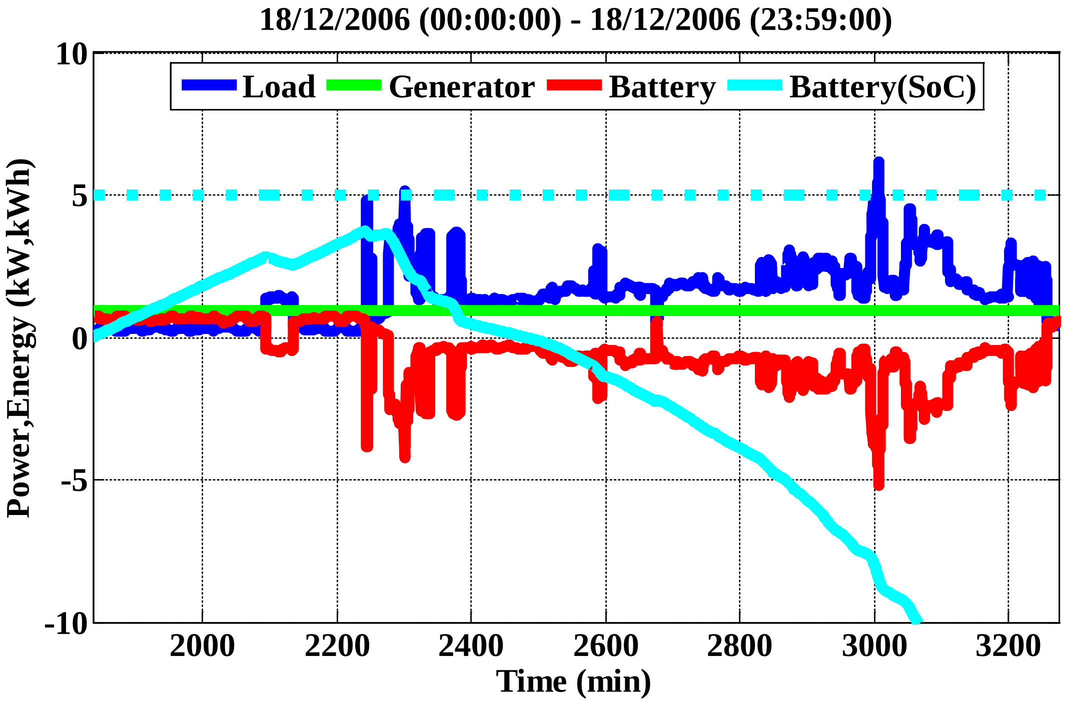


Figure 48 – Trial 9 Hybrid Operation Power and Energy Flow

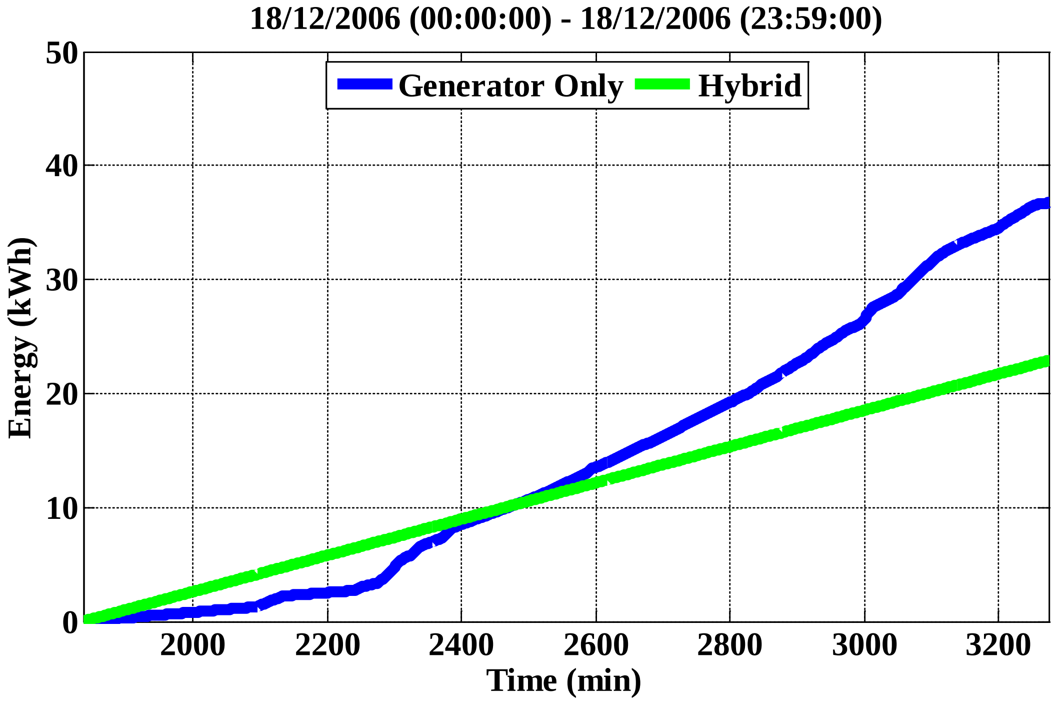


Figure 49 – Trial 9 Energy Consumption

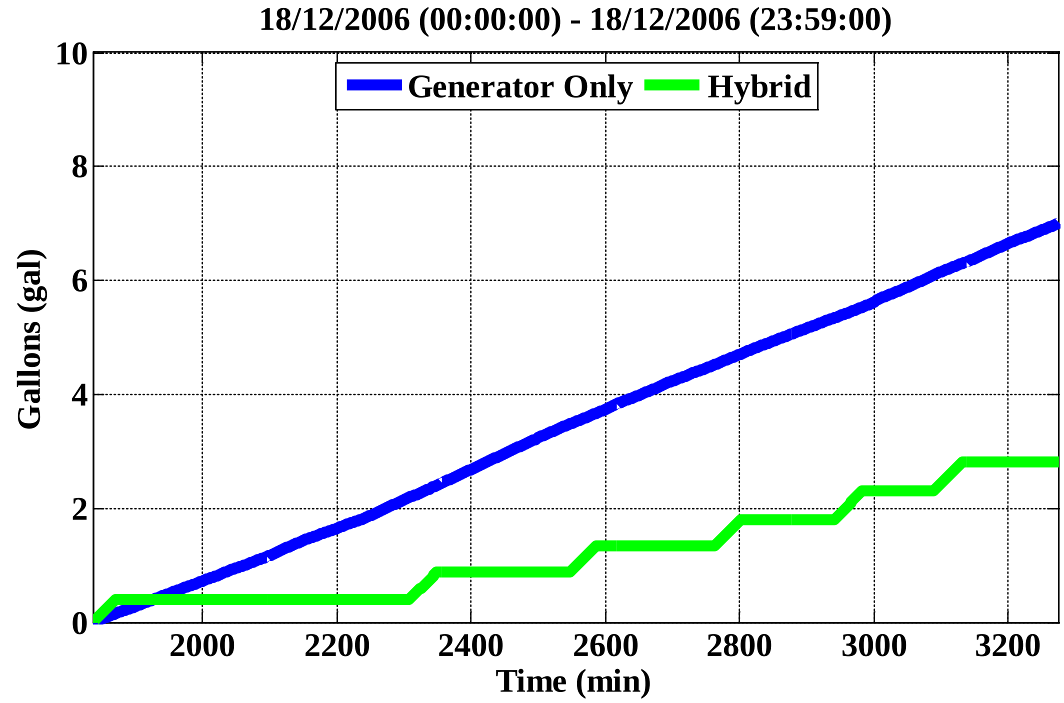


Figure 50 – Trial 7 Fuel Consumption

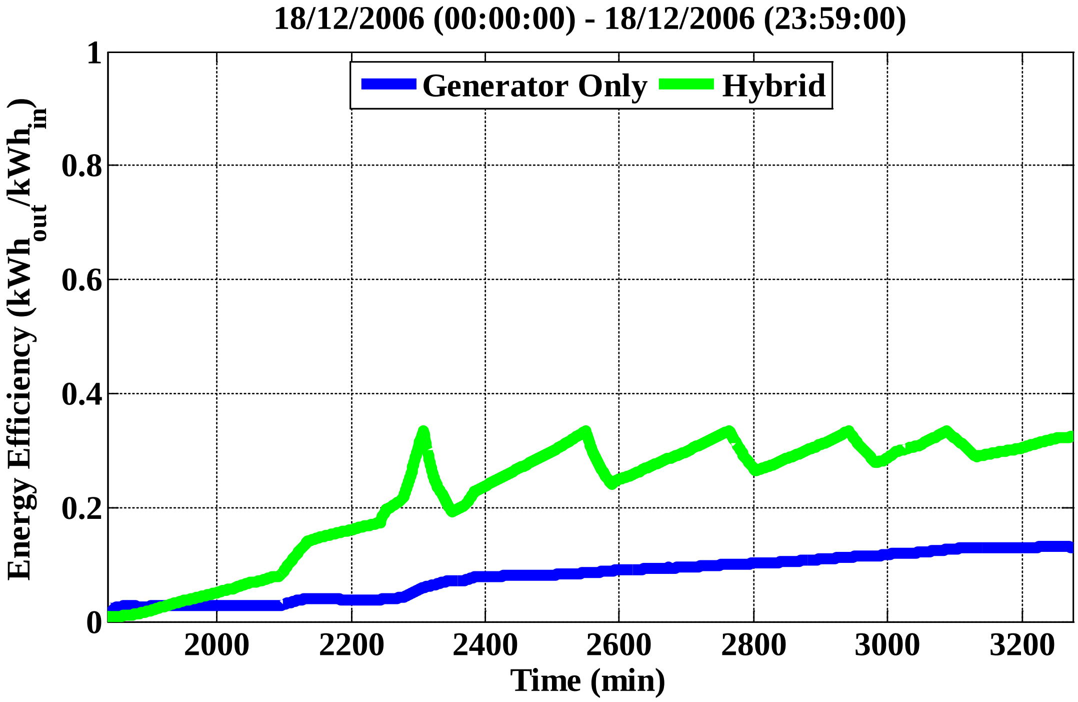


Figure 51 – Trial 7 Energy Efficiency

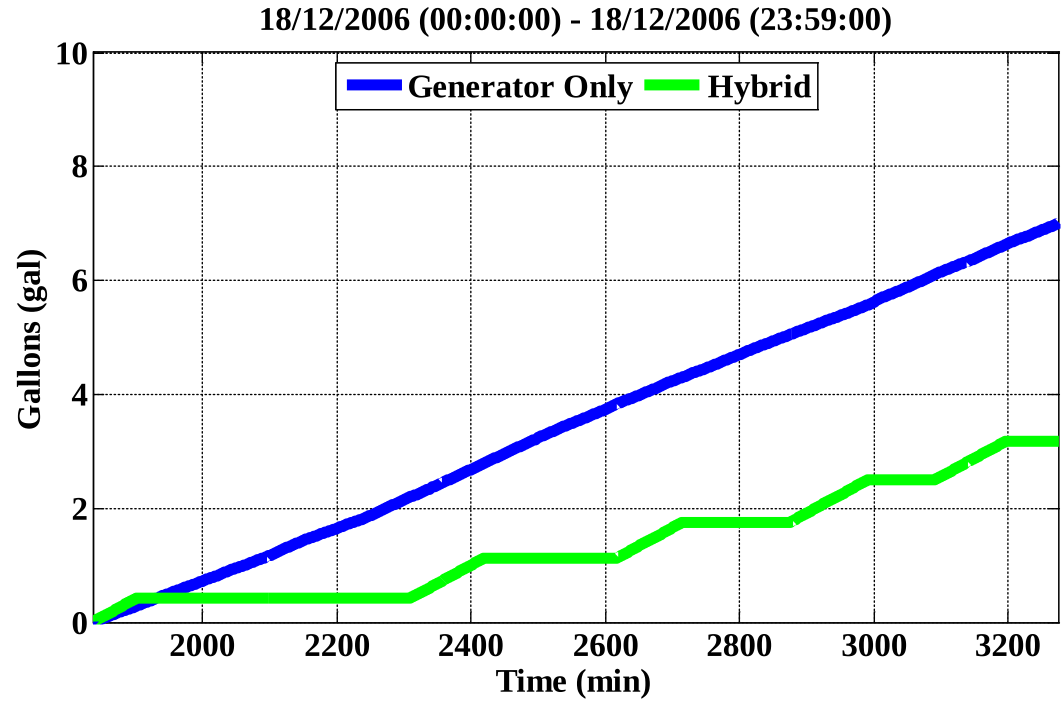


Figure 52 – Trial 8 Fuel Consumption

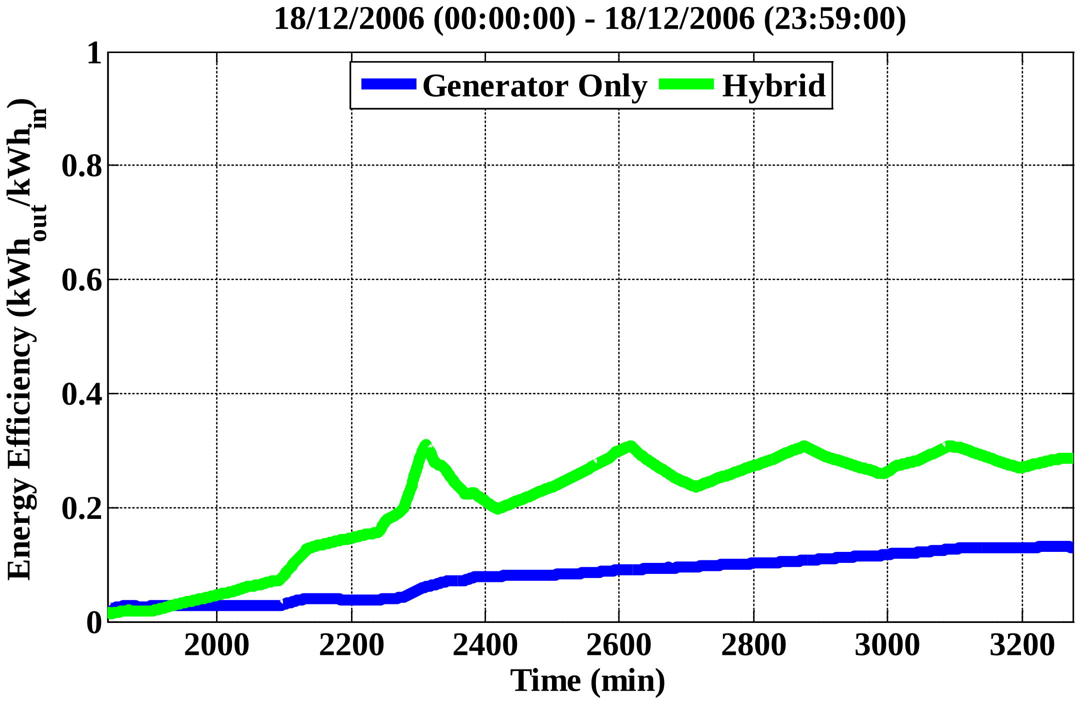


Figure 53 – Trial 8 Energy Efficiency

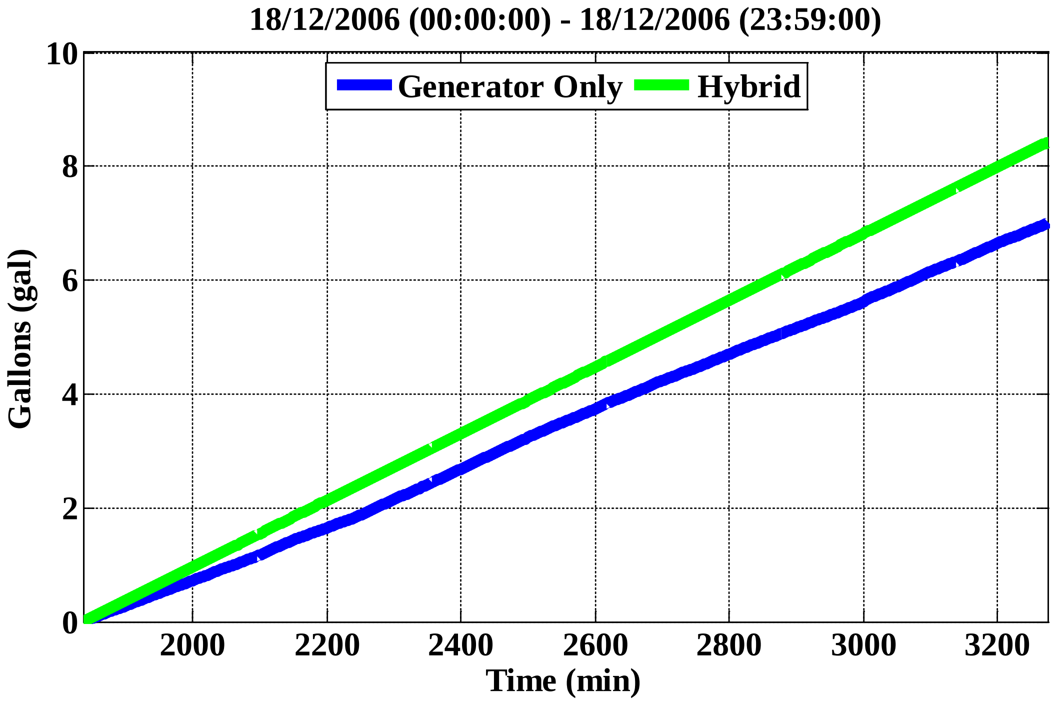


Figure 54 – Trial 9 Fuel Consumption

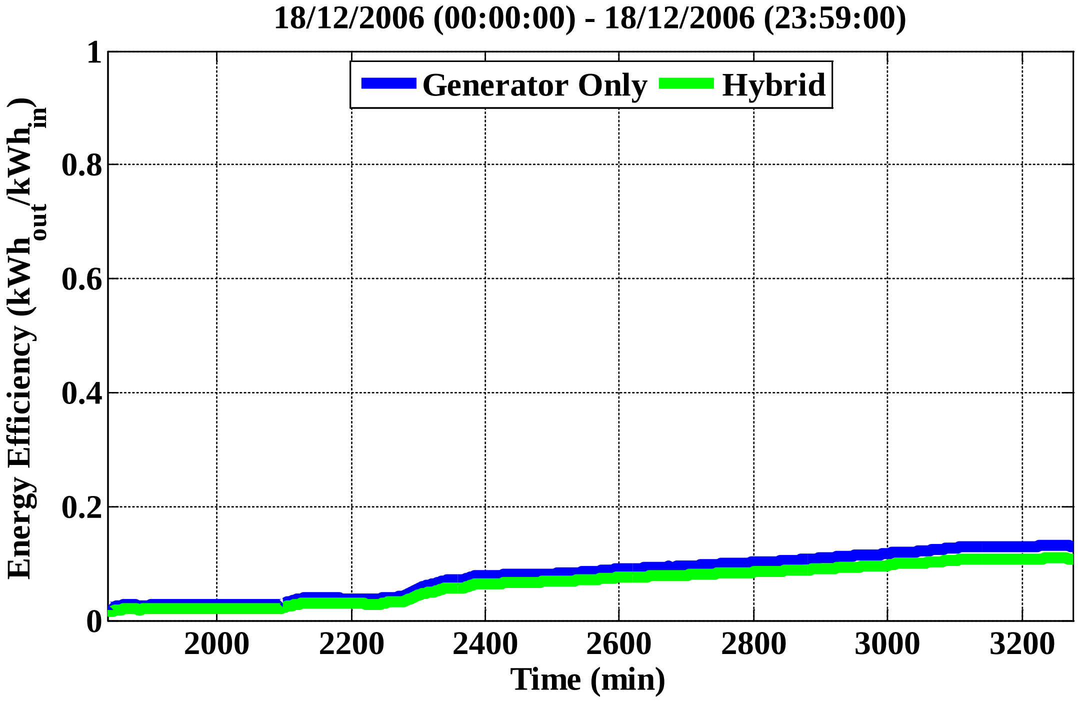


Figure 55 – Trial 9 Energy Efficiency

Chapter 5 Conclusions

- 5.1 Experimental Conclusions
    - 5.1.1 Battery Capacity
    - 5.1.2 Initial SoC
    - 5.1.3 Generator Size
- 5.2 Summary

Section 5.1 Experimental Conclusions

Now that we have collected some results as shown in Chapter 4, we can now apply some qualitative metrics to analyze the data. For this we will use Table 11 and Table 12.

Section 5.1.1 Battery Capacity

Referring to Section 4.2.1 we can see that the energy capacity of the battery pack affects the operation of the hybrid system. When looking at the energy cycles of Figure 20, Figure 22, and Figure 24, we see that as capacity is reduced the number of cycles increases meaning the frequency has increased. Additionally when looking at energy consumption of Figure 21, Figure 23, and Figure 25, we see that this high frequency operation reduces the amount of deviation the hybrid system exhibits when compared to the generator only energy consumption. What this means for military applications is that quiet time is desired a larger battery pack should be used as it will increase.

However, it should be noted that a battery pack that is too large will never be charged as shown in Figure 16 where the capacity was actually 10kWh. This will be poor for battery state of health (SoH) as a battery life time is affected by its depth of discharge. It also means the generator will never turn off which is also bad for a generator's SoH.

As for fuel consumption the battery pack capacity does have a significant amount of effect as seen in Figure 26, Figure 28, and Figure 30, as the eventually converge to the same point. However, what it does have a noticeable effect on is the rate at which the efficiency convergence to its new point. This is seen in Figure 27, Figure 29, and Figure 31, as these graphs exhibit a first order like response as capacity is increased. What this means for military applications is that energy efficiency and reduced fuel consumption is desired a smaller battery pack will allow the hybrid system to converge to an improved efficiency quicker.

Section 5.1.2 Initial SoC

Looking at Figure 32, Figure 34, and Figure 36, we can see that increasing the initial SoC does not exhibit a significant effect on the frequency of the energy cycle but what it does do is create a delay on the beginning of the first complete cycle as it is shifted farther to the right. This shifting is also seen in the energy consumption plot of Figure 33, Figure 35, and Figure 37, where the graph of hybrid system goes from staying above the generator only system to below it. What this means for military applications is that the hybrid system should be deployed with a fully charged battery pack as it allows the generator to start as late as possible reducing the energy consumed.

In regards to the fuel consumption in Figure 38, Figure 40, and Figure 42, we see that the shifting is present here as well. However, the efficiency plot is quite different in contrast to the traditional approach. Most noticeably is the presence of a vertical asymptote at the beginning of the graph. This is a result of how the efficiency is calculated. Because the generator has not contributed any new energy to the system the denominator of (13) goes to zero making the initial efficiency infinite. What this means for military applications is that when deployed a hybrid system should have a fully charged battery pack which will reduced the amount of fuel consumed and the system efficiency will start out higher than a generator only system.

Section 5.1.3 Generator Size

Finally we look at the effects that generator capacity has on the hybrid system. Looking at Figure 44, Figure 46, and Figure 48 we see that generator capacity does have a noticeable effect on the energy cycles. Starting with the generator's output fixed at its maximum point we see that the charging time for the battery pack is considerably smaller than for smaller operating points while the discharge time is not affected and remains solely dependent on the load profile. As for energy consumption in Figure 45, Figure 47, and Figure 49, we see, as expected, that the slope during the generator on time decreases as the output capacity is reduced. What this means for military applications is if generator run time needs to be reduced generator capacity should be increased.

However, there are two special cases that need to be pointed out. The first is that if the generator is sized too small then it will not be able to supply enough energy to allow the system to charge the battery pack and supply the load. This become immediately clear in Figure 48 as the Battery SoC curve goes below 0kWh and never recovers. This is also the case earlier on in Figure 16 after 3200mins as the battery pack is slightly over discharged.

Similar to the energy consumption, Figure 50, Figure 52, and Figure 54 shows that the fuel consumption follows a similar pattern in regards to the slope during charging. However, for the efficiency in Figure 51, Figure 53, and Figure 55, we can see that the graphs converge to different efficiencies. This is attributed to different generator capacities having inherently different efficiency levels which limit the performance of a hybrid system. What this means for military applications is that if better fuel efficiency is desired the generator should be run at it maximum efficiency point, which is not necessarily its maximum operating point. The final value will be dependent on the generator selected.

Section 5.2 Summary

Reflecting on what was learned from the experiment we can generalize MHPS operation performance with the following.

1. A MHPS deployed with a larger battery pack increases continuous quiet time and a smaller battery pack will allow the system to converge to an improved efficiency quicker. However, care must be taken to make sure the battery pack is not too large as it will negatively affect both battery and generator SoH.

2. A MHPS deployed with a fully charged battery pack will reduce fuel and energy consumption and allow the energy efficiency to start out at a higher point.

3. A MHPS deployed with a larger generator the continuous runtime will be reduced, which also reduces mechanical fatigue. Also if the generator operation is fixed at its most efficient point it will maximize the efficiency improvement of the MHPS. However, if the generator is too small it will not allow the battery to operate properly and it may be over discharged.

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