ABSTRACT

Title of Document: SOLAR-DIESEL HYBRID POWER SYSTEM OPTIMIZATION AND EXPERIMENTAL VALIDATION

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As of 2008 1.46 billion people, or 22 percent of the World's population, were without electricity. Many of these people live in remote areas where decentralized generation is the only method of electrification. Most mini-grids are powered by diesel generators, but new hybrid power systems are becoming a reliable method to incorporate renewable energy while also reducing total system cost. This thesis quantifies the measurable Operational Costs for an experimental hybrid power system in Sierra Leone. Two software programs, Hybrid2 and HOMER, are used during the system design and subsequent analysis. Experimental data from the installed system is used to validate the two programs and to quantify the savings created by each component within the hybrid system. This thesis bridges the gap between design optimization studies that frequently lack subsequent validation and experimental hybrid system performance studies.

Solar-Diesel Hybrid Power System Optimization and Experimental Validation

By

Headley Stewart Jacobus

Thesis submitted to the Faculty of the Graduate School of the
University of Maryland, College Park in partial fulfillment
of the requirements for the degree of
Masters of Science
2010

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Acknowledgements

Research is, by its nature, a collaborative endeavor. It is the norm for a researcher, particularly a graduate student, to rely on the resources of others and I am no exception. The funding for this project was provided by the Office of Naval Research and the Office of Under Secretary of Defense for Acquisition, Technology, and Logistics. The support given by Nova Research, Inc., Mr. Russ Jefferies in particular, was greatly appreciated. I would also like to thank my Principle Investigator and catalyst for this project: David Stenger. Without your support and encouragement, I would not have been able to follow my interest in renewable energy hybrid systems. I also would like to thank my collaborators: Baochuan Lin, David Jimmy, Rashid Ansumana, and Anthony Malanoski. I would also like to thank all my friends and family who supported me and fed me while I toiled preparing this thesis. I want to particularly thank Jenny Hu and Kenneth Kiger who went above and beyond in helping me edit this thesis.

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List of Abbreviations

BKPS	Bo-Kenema Power Supply
COE	Levelized Cost of Electricity
kWh	Kilowatt Hour
NPV	Net Present Value
NREL	US National Renewable Energy Lab
NRL	Naval Research Lab
O&M	Operation and Maintenance
PV	Photovoltaic
SoC	State of Charge

Introduction

As of 2008 1.46 billion people, or 22 percent of the World's population, were without electricity[1]. Traditionally the way communities are electrified is by connecting them to a centralized grid, but in areas where grid extension is prohibitively expensive, many are left without the prospect of connection to the grid anytime soon. Unfortunately the portion of the population that does not have access to electricity also overlaps with the 2.6 billion people live on less than $2 a day[2]. It requires innovative thinking in order for an electrification project to sustain itself within an impoverished community. Small scale hybrid power systems offer a means to quickly electrify areas that have little chance of being connected to a centralized grid in the foreseeable future. Hybrid power systems combine two or more electricity generation methods, like diesel engines and solar panels, into a single plant to reduce long term generation costs. While it is possible to find governments or organizations to fund the capital cost of an electrification project, recurring costs over the life of the system can be as large as or larger than capital costs. Without a community being able to regularly generate funds to pay for salaries, fuel, and replacement parts, an electricity plant will quickly cease operating. The principle advantage of a hybrid plant is its ability to affordably extend reliable electricity access into remote communities.

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[1] Alliance for Rural Electrification: *Energy Access in the World: Facts and Scenarios*

[2] World Bank Development Indicators, 2008

Despite the benefit that hybrid systems can bring to off-grid communities, there are relatively few commercially installed systems. The fact that hybrid systems add a layer of complexity to an already formidable problem - how to use a stand-alone technology to electrify rural communities - means that designers and installers have not built up the knowledge base to make hybrid power commercially available. To add to that body of knowledge, the US Naval Research Lab (NRL) partnered with Mercy Hospital in Bo, Sierra Leone. Despite being located in a city of 400,000 people, a significant portion of hospital resources has to be directed towards generating electricity for the hospital. The local utility company, The Bo-Kenema Power Supply (BKPS), suffers from frequent rolling blackouts, voltage swells, and excessive line loss. Given the large number of delicate research electronics in the hospital, it must have access to reliable and properly conditioned electricity. Nova Research, Inc. was hired to design a solar-diesel hybrid power system to ensure reliable power for the hospital.

The decision to incorporate renewable energy into the hybrid system for Mercy Hospital came out of the desire to reduce both maintenance costs and diesel consumption. Solar power from Sierra Leone’s skies is an abundant potential replacement for diesel fuel, but the incorporation of renewable energy into a mini-grid poses some problems. Renewable energy sources like solar and wind are not available on demand, but rather are sporadic in their supply; a squall blowing through an area can produce an excess of wind-generated electricity that must be dumped from the grid or afternoon clouds can cause a paucity of solar-generated electricity that will cause loss of grid voltage and frequency. Hybrid power systems offer a solution to this inherent problem with renewable energy sources. A hybrid system uses advanced system control logic (also known as a *dispatch strategy*) to coordinate when power should be generated by renewable energy and when it should be generated by sources like diesel generators. The real innovation of hybrid power generation is the realization that cost savings do not come from using the most powerful solar panels or the most efficient diesel engine, but by closely matching the cheapest energy production with the load. By coupling and coordinating sources together, the system provides more reliable and higher quality electricity at lower costs.

Literature Review

Research on hybrid power systems combining renewable and fossil derived electricity started 25 years ago, but few have written papers about system implementation and experimental data collection. The first papers describing renewable energy hybrid systems appeared in the mid-eighties [1], but literature on hybrid systems did not blossom until the early 1990s. Initially, this expansion in hybrid literature was driven by the need to increase grid stability and reliability as large quantities of wind power were being added to small autonomous grids [2]. Researchers then used optimization techniques to model how hybrid systems can reduce electricity generation costs over conventional fossil fuel systems.

There are many papers that optimize hybrid system cost and a few noteworthy papers are mentioned here. Schmid examined the economic feasibility of converting stationary diesel plants in rural Brazil into Diesel/Battery/Photovoltaic (PV) plants and found that conversions were economically favorable for smaller (<50 kW) diesel-based systems [3]. Park modeled the cost savings of converting a ferry's propulsion from diesel into PV/Battery/Diesel [4]. Chedid created his own software that predicted the Operational Cost of a hypothetical autonomous PV/Wind/Diesel system [5]. He concluded that the inclusion of renewable energy into a diesel power plant would significantly reduce the Operational Cost of the plant. Nehrir used a Matlab model to examine the performance of a Wind/PV system and concluded that the use of an electric hot-water heater as a dump load made the renewable-only system more economically feasible [6]. Ashok used a Quasi-Newtonian method to find the system that provided the lowest cost electricity to a rural Indian village. He finds that a PV/Wind/Diesel/Microhydro system would provide 24 hour coverage at the cost of only US$0.14/kWh [7]. Nfah examined picohydro/biogas/PV systems for use in rural Cameroon and reasoned that the inclusion of biogas would decrease the generation cost of hybrid systems [8].

All of the preceding papers, and the majority of papers that are published on hybrid systems, do not provide experimental validation of the designs they present. Out of the roughly 50 papers reviewed for this thesis there are two papers that used experimental data to support conclusions that hybrid power can produce electricity more cheaply than a diesel generators [9-10]. Another two papers described the installation of experimental or commercial hybrid power systems, but neither provided any financial data along with the description of the experimental setup [11-12]. Ruther converted a diesel-only mini-grid into a hybrid system in rural Brazil. He then used diesel consumption data to show that similar PV/diesel systems with no battery storage can reduce diesel fuel consumption in Northern Brazilian. Ruther dismissed the inclusion of battery banks into a hybrid because the losses introduced by the batteries increases diesel fuel consumption. Ruther admits one limitation to the PV/Diesel system is that a solar array's total energy contribution to a hybrid system without energy storage cannot be above roughly 10 percent because of PV's tendency to destabilize a grid. Phuangpornpitak examined the economic benefit (or lack thereof) of 10 solar/wind/diesel hybrid systems installed in Thailand between 1990 and 2004. Phuangpornpitak supplied a mix of experimental data and HOMER model data to provide information on the technical and financial operation of the systems. This was the only paper found that described the financial cost of actual systems and even stated that some systems were more costly than the baseline diesel-only system due to overdesign. Nayar et al. built, installed, and tested a PV/diesel/battery/grid Uninterruptible Power Supply (UPS) in two locations in India. He reported roughly 24 hours of data on the system performance including plots of the battery bank's voltage, inverter power output, utility voltage, and system frequency, but omitted any information on system cost. He concluded that he successfully created a system that would improve power reliability and power factor to the load. While these four papers do use and report limited experimental data on the cost of a hybrid system, they do not discuss system design and optimization.

Need in the Literature and Thesis Contribution

While there are a large number of papers that provide numerous optimization techniques and optimized designs, none of those papers subsequently validate their claims that hybrid systems provide a cheaper alternative to diesel-only generation. The few papers with experimental data on hybrid system savings are not coupled with models thus limiting the ability for readers to draw conclusion from the experimental findings.

Without validating data coupled with optimization and modeling there is little reason to believe that the conclusions stated in any paper has applicability beyond the immediate circumstances stated in each specific paper. The primary contribution of this thesis is to address this gap by combining an optimization and validation of a single design in one paper. The secondary contribution is to evaluate the cost savings engendered by converted the existing diesel-only system at Mercy Hospital into a hybrid power system.

Part 1 of this thesis is an optimization design study that is similar in form to the papers listed in the ***Literature Review*** section. HOMER, a freely available hybrid system optimization software, will be used to model several design alternatives and then select the alternative with the lowest project Net Present Value (NPV). A detailed solar/diesel hybrid system modeling program, Hybrid2, will also be used in **Part** 1 to check the HOMER's results for the best design alternative. **Part 2** of this thesis then validates HOMER and Hybrid2's models with experimental data taken from a hybrid system installed in the Mercy Hospital. The goals of this thesis are organized under the primary and secondary contributions of this thesis:

1. Optimization Design Study with Validation
    a. Evaluate the accuracy of HOMER and Hybrid2 model predictions relative to measured experimental data of the installed system.
    b. Determine if either HOMER or Hybrid2 inaccurately model specific components.
    c. Provide experimental performance parameters which can be used in subsequent modeling

2. Evaluate savings associated with conversion of the Mercy Hospital to a hybrid power system.
    a. Relate the Operational Cost savings created by the hybrid power at Mercy Hospital to the savings other communities can realize by doing the same.

Provide recommendations on which components will save a system the most in operating expenses.

Part 1: Power System Design

Design Criteria

The design criteria for the hybrid power system in Mercy Hospital are as varied as the stakeholders taking part in the project. Each stakeholder is looking for the system to perform a different function. For example, long-term cost savings are very important to the funders of the system, while users want continuous, reliable power that will not damage equipment. At the same time, researchers want to publish system performance data. The system designers came up with several design criteria that fall into a few broad categories: voltage and frequency availability, system redundancy, cost savings, energy autonomy, system monitoring, and ease of maintenance. These six design criteria are the optimization constraints that limit the search space for HOMER.

In the city of Bo, purchasing electricity is relatively inexpensive when compared to the cost of generating it with a diesel generator. In addition to the costs incurred purchasing diesel fuel in Sierra Leone (about US$1.27 a liter in 2008 dollars), normal wear and tear on a generator incurs an additional hourly cost. This means that the cost for the Hospital to generate a kWh of electricity is more than the US$0.262 it costs to purchase it from BKPS. The drawback of purchasing power from BKPS is the lack of power reliability (power can be cut at any time and without notice) and the low quality of electrical service (voltage levels and frequency are not well regulated). Despite these problems Nayar has shown that grid power can be incorporated into a hybrid system to provide reliable and affordable electricity [11]. The optimization study includes a system that is grid connected and another system that is off-grid.

The existing equipment in the hospital originated in the US, Europe, and Africa, creating a complex voltage and frequency requirement for the system. Most equipment is either powered from the 230V 50Hz utility service drop or from small 1000 VA transformers that step down the voltage to 115V. While transformers are able to change voltage, they do not change frequency. A motor's rotation speed is a function of both voltage and frequency, and supplying the wrong frequency to a motor will cause the motor to operate outside of specification. The use of several Eppendorf (Eppendorf North America, Hauppauge, NY) centrifuges configured for North American power in the Mercy Hospital research lab requires the system to supply both 230V 50Hz and 120V 60Hz. Much of the medical equipment employed in both the lab and the hospital is sensitive to electrical harmonic distortion so the power supplied by the system must also be in the form of a pure sine wave with a Total Harmonic Distortion (THD) of less than 5 percent.

The system is designed as a permanent, long-term addition to the hospital. While NRL's collaboration with Mercy Hospital is only short-term, it is desired to create a system that could be left behind and continue to benefit the hospital for years. The majority of the components (eg. the solar panels, batteries, and inverters) will last over 15 years so the system optimization is conducted assuming a project length of 15 years. This decision affects the design selection process because long term installations will tend to favor capital intensive systems with low operating costs, while short term installations will favor low capital cost systems with higher operating costs.

Western Africa has frequently been plagued by politically instability, and it is during those times when it is critical for a hospital to operate. Sierra Leone has recently emerged from a decade-long civil war that disrupted all normal operations of society including electricity production and diesel fuel distribution. It is the desire of both the system funders and users to minimize outside energy usage out of security concerns. By limiting the amount of diesel fuel the system will consume in a year to 2520 liters, or a 210-liter barrel a month, it is possible to create an optimization constraint incorporating the desire to limit diesel usage. This has the effect of encouraging the selection of a system with larger solar arrays.

Introduction to HOMER and Hyrbid2

There are a number of ways to design a hybrid power system, each with varying levels of confidence that the design produces a robust system. These methods can vary from pencil and paper calculations using rules of thumb to sophisticated computer-generated energy production and system dynamic predictions. Improper design can lead to reduced battery life and inability for the system to cover the electricity demand. With most solar systems, the batteries are the most delicate component of the system and finding replacements is a costly endeavor. Luckily a hybrid system can be more forgiving than a solar-only system to the casual designer. The inclusion of a diesel generator provides a hedge against not designing enough battery storage capacity into a solar system. The drawback is that O&M and fuel costs will increase as diesel runtime increases to protect the batteries from over-discharge. In short, optimization and system modeling programs are important for minimizing the cost of power systems utilizing renewable energy.

HOMER

HOMER stands for Hybrid Optimization Model for Electric Renewables, and is a stand-alone hybrid system optimization program released by the US National Renewable Energy Lab (NREL) in 2000. The program allows for flexible renewable energy hybrid system design using a library of components that can be inserted into the system, including a diverse set of electricity generators, energy storage, and load options.

HOMER follows seven general steps for every simulation it performs. In Step 1, HOMER reads the electric, thermal, and hydrogen load into memory. If the loads are an hourly profile inputted by the user rather than a year-long dataset, then HOMER adds variability to the profile to generate a synthetic annual dataset. This is done by multiplying each hourly value by a corresponding value of α, which is defined in Equation 1:

$$\alpha = 1 + \delta_d + \delta_h \qquad \textbf{Equation 1}$$

where δ_h is a randomly generated number between -1 and 1 picked for every timestep in the synthetic dataset and δ_d is a randomly generated number between -1 and 1 picked once every 24 timesteps. HOMER generates one value for δ_d for each day in the synthetic load dataset from a normal distribution with a mean of 0 and a standard distribution of 0.15. Similarly δ_h is generated from a normal distribution with a mean of 0 and a standard deviation of 0.2, but a unique number is generated for each 8760 hourly demand value in the synthetic load dataset. In Step 2, HOMER compares the electric, thermal, and hydrogen load input into the program with the system's ability to generate electricity, thermal power, and hydrogen using renewable resources. In Step 3, HOMER decides if the battery bank needs to be charged or discharged and what level to operate the generator to satisfy the electrical load. In Step 4, the fossil fuel use that is required to satisfy the thermal and hydrogen loads is calculated. In Step 5, the performance variables from each timestep are totaled to create a yearly system performance log. In Step 6, the system's yearly performance is then multiplied by the project length, and financial parameters are used to forecast the project's NPV. In Step 7, the program loops back to through Step 2 to re-simulate systems with resized components. Systems that do not meet the project's constraints on requirements such as operating reserve on each bus, maximum annual fuel usage, minimum renewable energy fraction, emission limits, etc. are eliminated. The remaining designs are listed according to their NPV. If a sensitivity analysis is desired then in an extra step, Step 8, the simulation is rerun in its entirety from Step 1 with modified inputs. A flowchart of HOMER simulation process can be found in Figure 1.

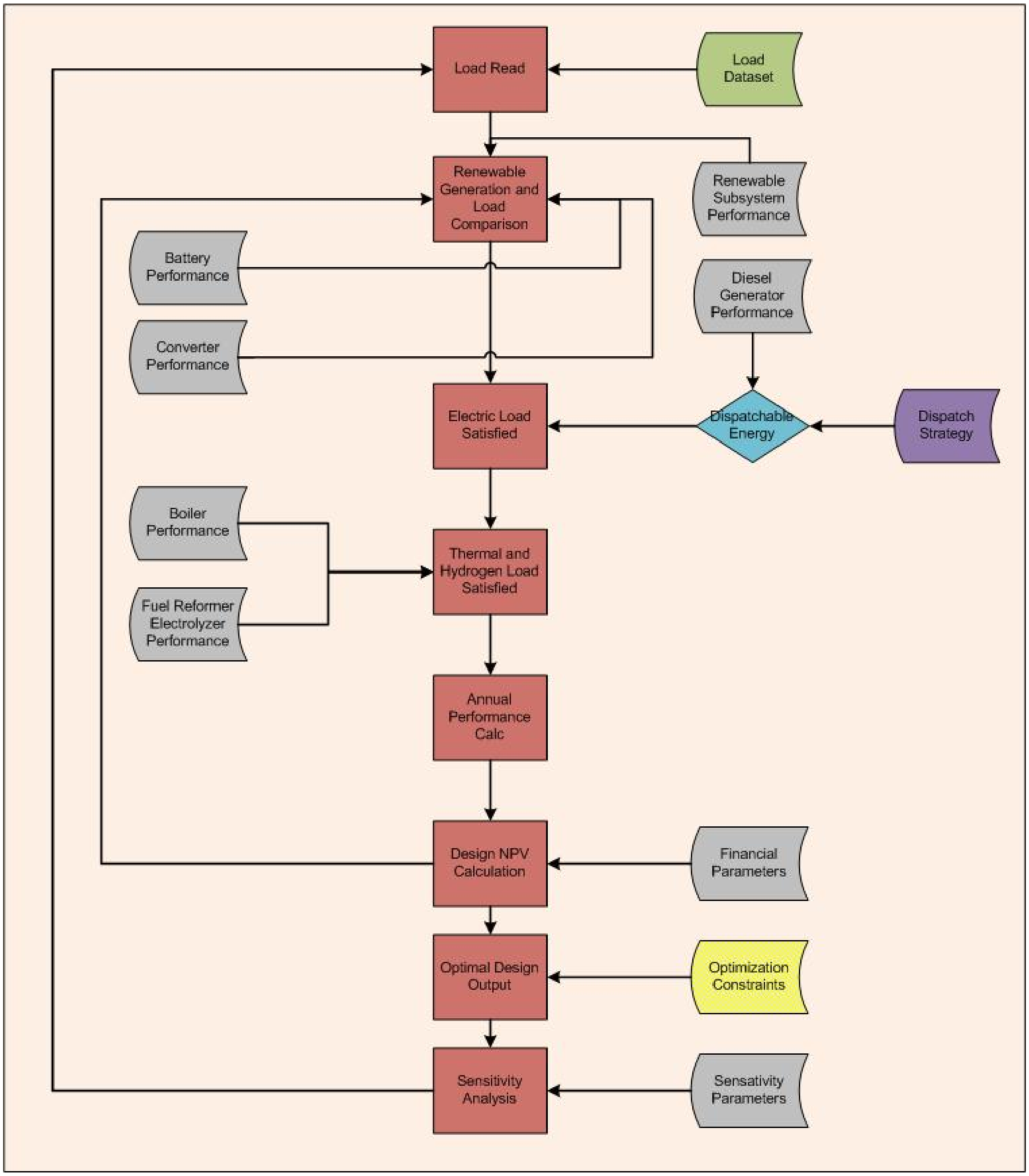

Figure 1: HOMER Simulation Flowchart

Hybrid2

Hybrid2 is a software program suite that models the performance of a single hybrid power system. The suite was developed by a partnership between NREL and

UMass-Amherst and was released in 1996. The largest component of the Hybrid2 suite is the system modeling software, but the suite also includes an economic calculation module, a data synthesizer, a data gap filler, and stand-alone modeler of an alternating current variable frequency wind turbine-water pump setup. Hybrid2 serves a slightly different purpose than HOMER. Hybrid2 is designed to provide detailed component and dispatch strategy modeling for more realistic system performance. It allows for the model to predict performance for any length of time be it a day, month, or year with the calculation timestep being minutes, hours, or days.

Hybrid2 works by calculating the energy excess or deficit on an AC and DC power bus for each timestep. Each timestep is broken into six general steps, but the simulation may loop back to each step multiple times before the timestep calculation is complete. In Step 1, Hybrid2 calculates the available renewable power produced by the hybrid system on the AC or DC bus using an available renewable energy resource dataset loaded into the program by the user. In Step 2, the net load on each bus is calculated by subtracting the available renewable power from the load. For Step 3, if there is a positive net load on either bus, power is transferred between the AC and DC bus factoring in the bi-directional inverter's performance characteristics. In Step 4, the simulation will dispatch power to a particular bus that still has a positive net load. The dispatch strategy will dictate how much power will be withdrawn from the battery bank or from the diesel generator. Next Hybrid2 calculates the system losses and notes persistent energy deficits. In Step 5, if there is excess energy on either bus then it is sourced to either secondary non-critical loads or dump loads. The results of the timestep are recorded and then the process repeats itself for the next timestep. In Step 6, Hybrid2 sums up the performance parameters from each individual timestep such as diesel consumption, demand, and production. The financial information loaded by the user is then used to extrapolate one year's performance out for the life of the project. A flowchart of the simulation process is found in Figure 2.

Hybrid2 is particularly well suited for modeling systems with sophisticated dispatch strategies. Hybrid2 has 13 parameters that can be modified in order to create a customized dispatch strategy, while HOMER only has 2. The simulations results are then fed into an economic module calculation that is able to provide greater flexibility in one's analysis than when using HOMER. One large limitation to Hybrid2 is that it is not as flexible as HOMER in terms of system design. Hybrid2 was primarily designed to model systems with wind, PV, and diesel components. Hybrid2 does not allow for the inclusion of both a generator and a grid connection in the same model. This limitation means that Hybrid2 cannot be used to simulate the 50 Hz system unless it is during a time period when it is known there is going to be either no grid electricity or no generator usage.

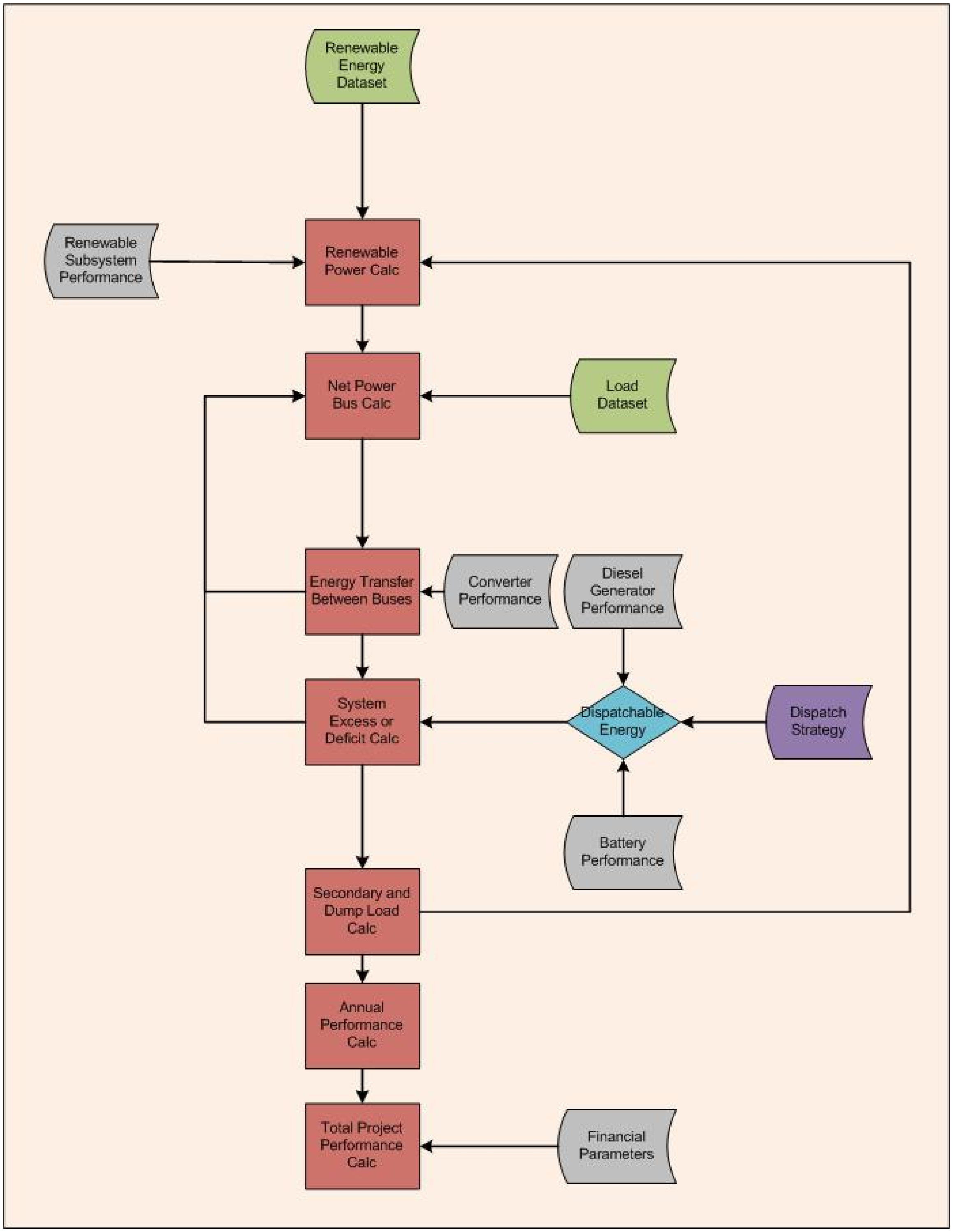

Figure 2: Hybrid2 Structure Flowchart

Assessment Trip Electricity Demand Evaluation

A three week assessment took place at the Mercy Hospital in September 2008. Roughly a week's worth electricity usage was recorded for both the hospital and the hospital's research lab. Electricity usage was recorded every hour between September 7th and September 12th, 2008 using an Elite Pro datalogger. It should be noted that both the Hospital and the Lab receive three-phase power, but the datalogger was only able to record electrical demand on two of these three phases powering the hospital. In order to produce a conservative estimate of the daily power demand for each structure, the power demand on the unrecorded phase was assumed to be equal to the greater of the two recorded phases. The total estimated energy usage for the hospital is shown in Figure 3.

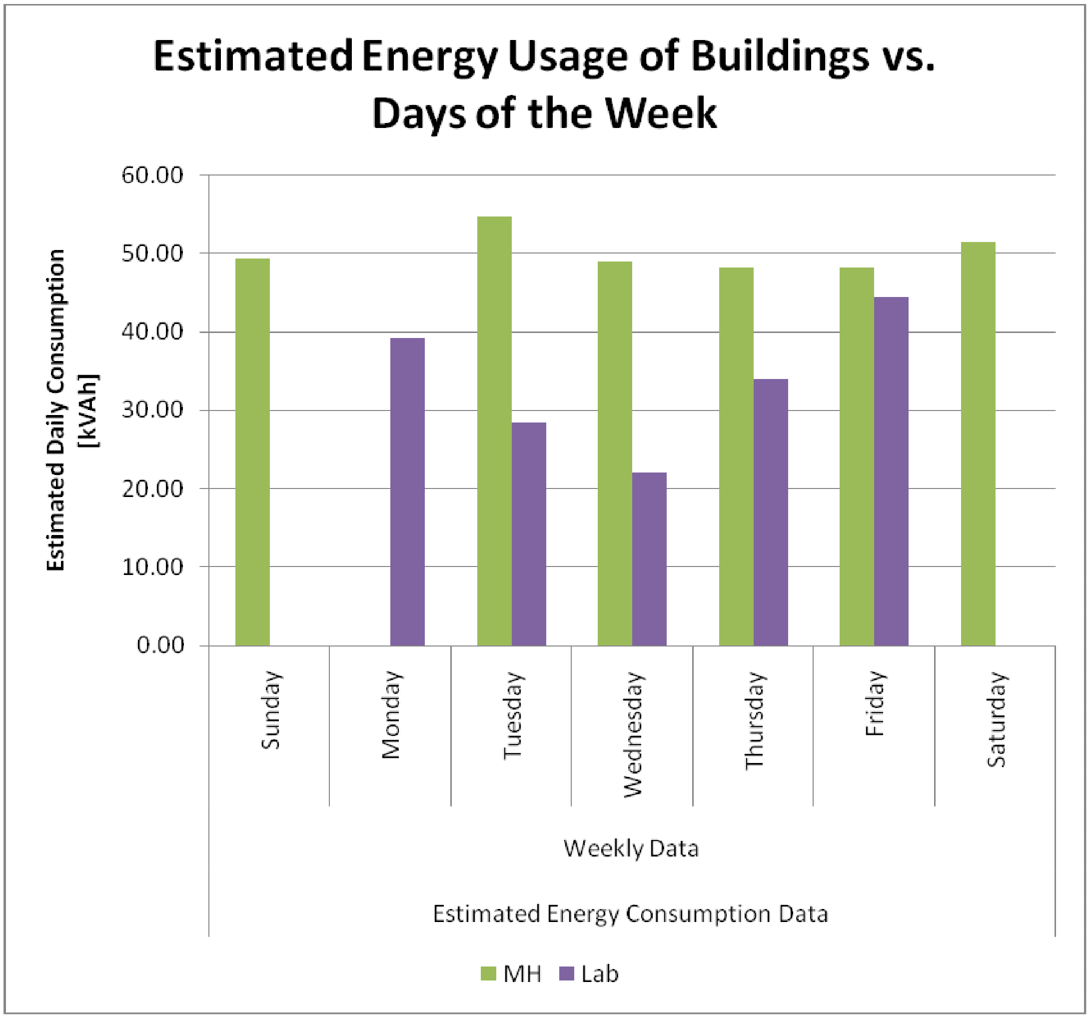

Figure 3: Elite Pro Hospital and Lab Assessed Electrical Demand

The average hospital demand in

Figure 3 is 50.1 kWh a day, and it changed only slightly during the week. The electricity demand of the hospital's research lab was measured separately from the hospital's demand. The hospital's research lab had a large day-to-day variation in electricity demand, but an average demand of 33.6 kWh per day. The datalogger suggested that the combined average electricity demand for the hospital and lab was 83.4 kWh per day. In order to verify that the datalogger captured representative data and to check the assumptions made about the magnitude of the unmeasured thirdphase, a second weekly demand profile for the hospital and the lab was constructed using an audit of all the equipment within the hospital and interviewing the local staff. The weekly profiles derived from the audit and interviews can be seen in Figure 4.

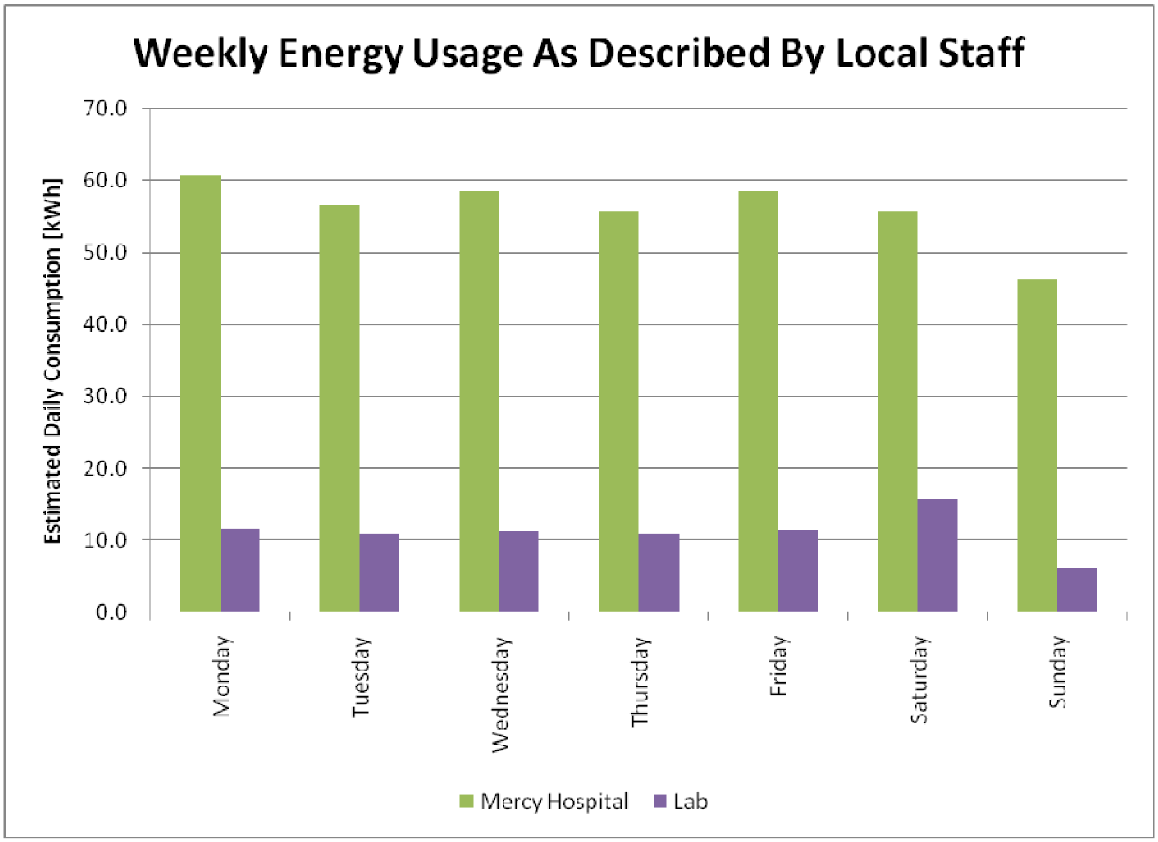

Figure 4: Hospital and Lab demand calculated from interviews

The interview-based load data suggested both that the hospital and lab have a smaller combined demand and the ratio between the hospital and lab's demands were different than that suggested by the datalogger data. The average interview-derived load was found to be 56 kWh per day for the hospital and 11.1 kWh per day for the lab. The total interview-based demand was 67.1 kWh per day. A hypothetical hourly load profile was created that averaged split the difference between the interview-based and datalogger-based weekly profiles. The hypothetical hourly profile also took into account anticipated seasonal changes to the load demand. This hourly profile was then entered into HOMER for the optimization. The daily demand total for this profile is 73.2 kWh and is shown in Figure 5.

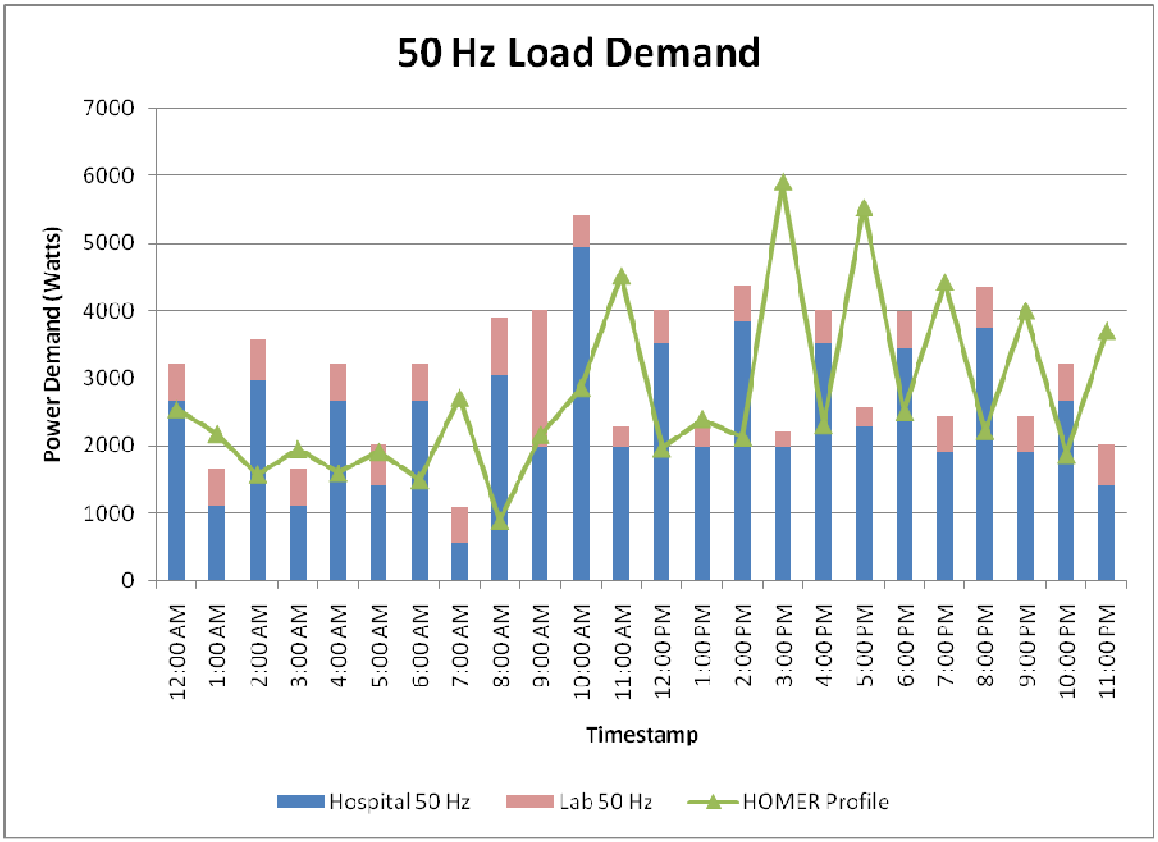

Figure 5: User inputted 50 Hz hourly profile and statistically-modified HOMER profile

While HOMER allows the user to input a single hourly profile, it applies statistical variability over the profile to create hours of unexpected peak demand and days of larger sustained demand while still ensuring that the average demand is still the same as the input profile. The user controls the amplitude of the stochastic variation of the load. As described in the *HOMER* section above, there are two user adjustable variables, δ_d and δ_h. For this study these parameters are left to the default standard deviation of 0.15 and 0.2, respectively. Figure 5 shows the statistically modified HOMER profile that the program generates.

Accompanying the installation of the new power system into the hospital was an upgrade of the Mercy Hospital research lab's equipment and capability to diagnose respiratory diseases. Much of the equipment needed for this upgrade is only available for purchase in North America, meaning that there is a significant demand for 120V 60 Hz power. This load was quantified through interviews with the scientists in charge of running samples and information from the nameplates of each appliance. Unfortunately it was not possible to confirm the total energy draw of a typical sample run using a datalogger because the experimental setup had already been broken down for transit to Sierra Leone by the time the assessment had taken place. The expected hourly profile of the 60 Hz electricity demand is graphed in Figure 6. The modified HOMER profile can also be seen in Figure 6. The added daily demand from the new research equipment was anticipated to be 21.5 kWh per day.

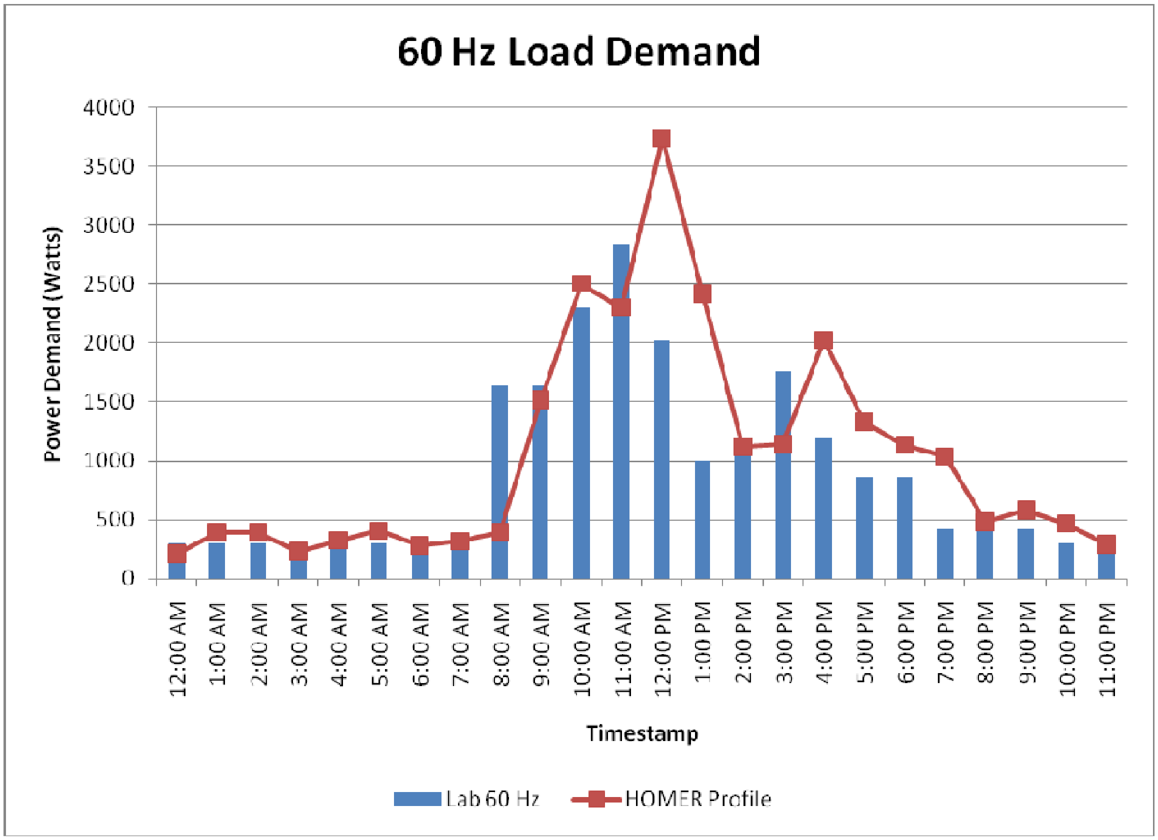

Figure 6: Anticipated 60 Hz hourly profile with HOMER profile overlaid

System Setup

As a result of the voltage and frequency requirements described in the ***Design Criteria*** section, the power generation system will consist of two nearly identical subsystems: a 230V 50Hz hybrid system that connects to the grid with a diesel generator backup, and a 120V 60Hz hybrid system that connects to a backup diesel generator. While wiring up the hospital with 120V 60Hz power in parallel to the pre-existing 230V 50Hz power supply is an added cost, it is beneficial on many levels: 1) The hospital is filled with various socket adaptors and transformers that lead to confusion within the hospital staff and creates a never-ending stream of e-waste when electronics are plugged into the wrong voltage. By providing the proper three-prong American bladed low voltage plug with 120V 60Hz power, the hospital staff will get into the habit of plugging the proper appliance into the proper plug and will reduce the number of burnt out equipment. 2) Changing the frequency of a power supply is not trivial and without the proper frequency, research equipment may operate out of specification. For medical equipment which has to operate on 60 Hz, there are only two ways to utilize 50Hz power: use a motor-generator or rectify the 50Hz power into DC power and then invert resulting DC power into 60Hz alternating current. Both methods result in a reduced efficiency. 3) By installing two independent power subsystems, the power supply to the lab is redundant and lab operation is able to continue even if one system failed. With a few adjustments, mission critical cold chain loads could be transferred from a faulty subsystem to an operating subsystem averting the costly loss of samples and reagents.

With the exception of batteries, diesel generators, and wind turbines, HOMER will not compare different models of components in a single optimization run. For example, HOMER will not compare one brand's solar panels with another in a single run; HOMER will only vary the size of the solar array. This requires the user to run multiple optimizations, each with a different brand of panel and compare the NPV of various optimization runs. In order to reduce the number of optimization runs presented in this thesis, the make and model of each component has already been pre-determined.

The heart of the hospital and lab's new power system is a pair of SMA Sunny Island (SI) bidirectional inverters (SMA Solar Technology AG, Niestetal, Germany). The SI 5048 is a 230V 50 Hz inverter and the SI 5048U is the 120V 60 Hz version. Both inverters have a nominal capacity of 5kW, but are capable of limited operation at higher power demands. The SI 5048 is connected to a transfer switch that allows either a backup generator or the utility grid to power the hospital load and recharge the battery bank at the same time. The inverters will only connect to an outside AC power source if the voltage and frequency of that source are within a user-specified window. When not connected to an outside source, the inverters will draw on the battery bank to produce AC power. The SI 5048U setup differs from that of the SI 5048 in that it is an off-grid subsystem and only receives backup power from a generator. Electricity is stored in both systems by strings of 12 4KS25PS Rolls/Surrette deep cycle flooded lead acid batteries (Surrette Battery Company Ltd., Nova Scotia, Canada) connected together in series. This creates a 48V DC bus which is required by the SI 5048 and 5048U. The optimization study helps the designer decide on the number of strings to connect together. The 4KS25PS is a 4V battery with a 20-hour capacity of 1350 Amp-hours.

A pre-existing generator will be incorporated into the 50 Hz subsystem and a new generator will be bought for the 60 Hz system. The pre-existing generator is a Lister-Petter diesel LLD 190 generator (Lister Petter Limited, Dursley, UK). The Lister-Petter generator is comprised of a LPW4 diesel engine coupled to a Leroy Somer 4-pole LSA 37 SHUNT alternator that has been rewired from 3-phase to single phase. Circuit protection is in place to limit the alternator's output to 12.2 kW. Utility power is provided by the BKPS in the form of 230/380V-50Hz service to the hospital. HOMER is used to select between two Cummins generators (Cummins Power Generation Americas, Minneapolis, USA): the DSKAA and the DSKAB. It is possible to do this in HOMER despite the fact that it has already been stated that it cannot compare between two different models because these generators utilize the same engine, but are fitted with different capacity alternators. This allows users to input the same performance parameters for both generators and have HOMER vary the size during runs. The DSKAA is rated for 9.1 kW and the DSKAB is rated for 13.6 kW.

The operation and maintenance (O&M) cost of a hybrid system is dominated by the diesel generator, but no records were kept of the expenses of servicing the diesel generator. Thus, the Lister-Petter's O&M cost is estimated based on the comparably-sized DSKAB Cummins diesel generator. Expenses included for the estimation are the cost of replacement parts for the first 5000 hours and lubricant. Parts and lubricant for the generator are calculated to be $1.00 per hour of generator operation.

Due to budgeting and logistics, it is necessary to install the two new systems in several phases. The initial phase for the 60 Hz system consists of a diesel generator, a battery bank, and an inverter; hence the description "Diesel/Bat" hybrid system. The initial phase for the 50 Hz system is similar to the 60 Hz system, but also includes a connection to the local utility, and thus is described as a "Diesel/Bat/Grid" system. The second installation phase for the 60 Hz system calls for the incorporation of a small 0.85 kW_p solar array into the hybrid system. This system is called the "Diesel/Bat/PV" hybrid system. Unfortunately, due to budget and logistic constraints, the installation of the two hybrid systems never progresses past the 50 Hz "Diesel/Bat/Grid" or the 60 Hz "Diesel/Bat" systems during the course of the project.

The original solar panels projected for use with both systems were Sharp's NU-U235 F3 panel (Sharp Electronics Corp., Mahwah, USA). Each of these panels has a peak power rating of 235 W. In the optimization model, these panels are arranged in arrays that corresponded to the largest number of panels that can be connected to SMA's

Sunny Boy 3000/4000 and 5000/ 6000/ 7000/8000 family of inverters. Figure 7 shows the 50 and 60 Hz subsystems in two different configurations: “Optimum” for the 60 Hz and “Diesel/Bat/Grid” for the 50 Hz.

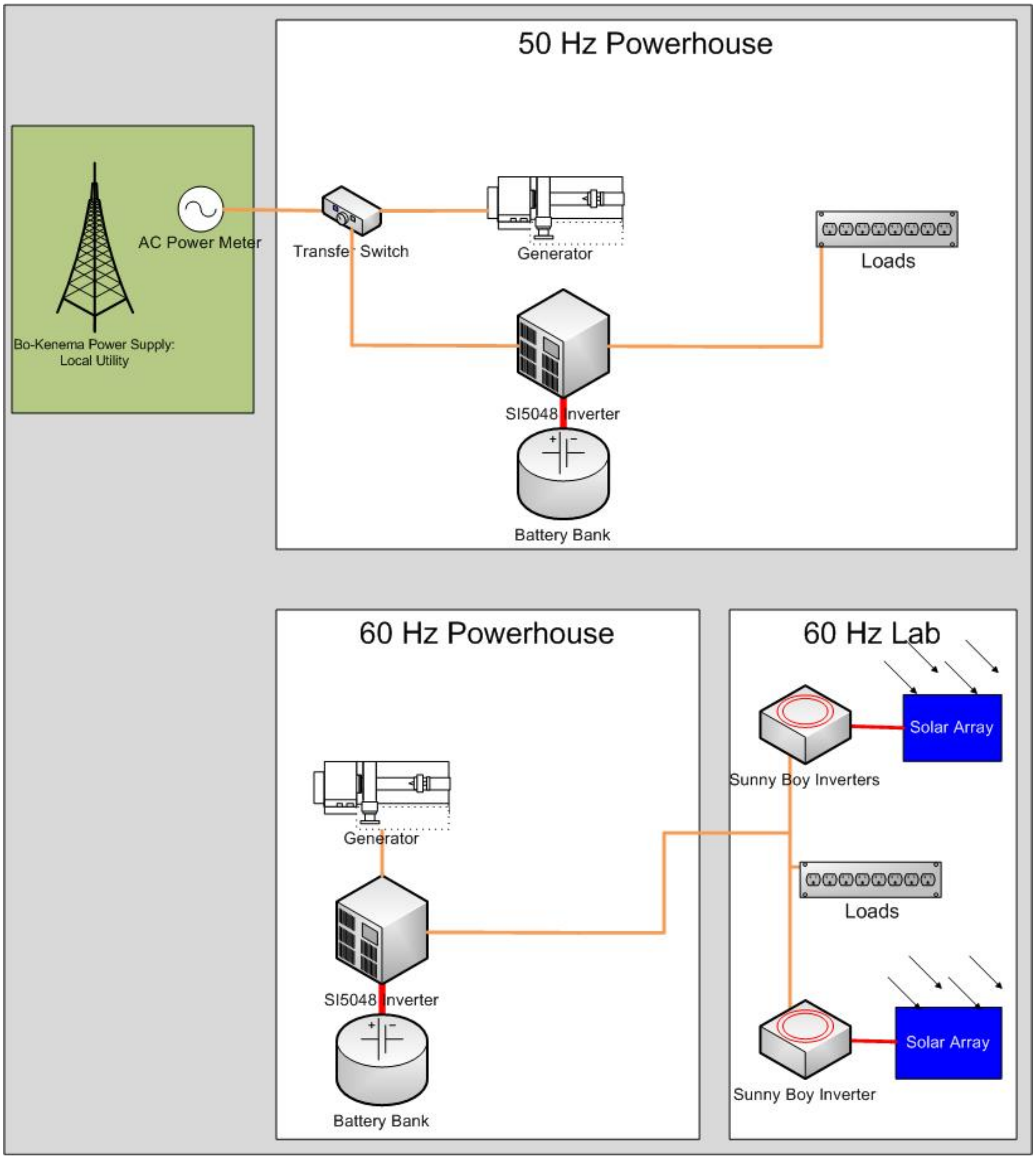

Figure 7: Examples of Subsystem Setup

Climatic Data for Bo, Sierra Leone

Mercy Hospital is located within Bo, Sierra Leone at 7° 58’ 35.86” N and 11° 44’ 14.26” W. Bo is the second largest city in Sierra Leone and is 110 miles ESE of Freetown, the capital. The weather in Sierra Leone can be characterized as hot and humid, and there are only two seasons in Sierra Leone: a wet season and a dry season. Each lasts roughly 6 months; the wet season starts in April and ends until the end of September, and the dry season is from October through March.

To predict solar energy availability at the hospital, the National Renewable Energy Lab (NREL) Climatological Solar Radiation (CSR) Solar Model is used [13]. The model uses geographic location, cloud data, atmospheric pressure, water vapor content, and aerosol content to produce a 40 km by 40 km grid of monthly averaged insolation data in the area of interest. The model originally was created and verified for predicting North American insolation but it has been expanded using global data. The average daily global insoluation of Bo is shown in Figure 8.

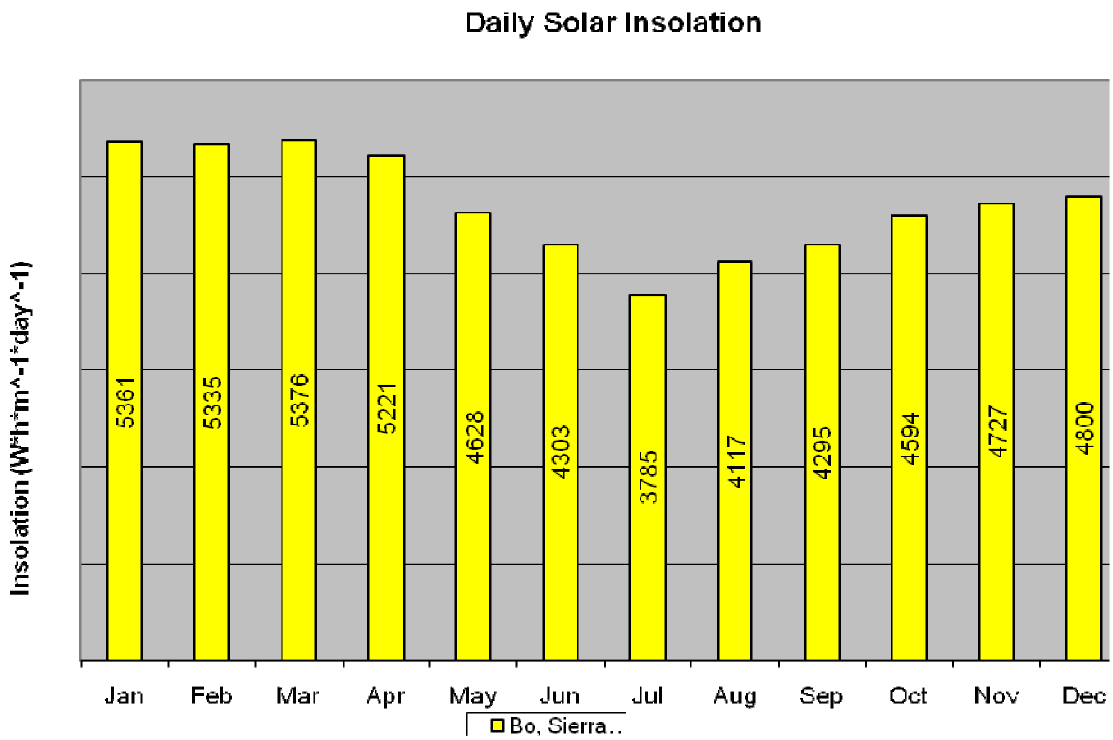

Figure 8: Flat Plate Solar Insolation based on NREL's Climatological Solar Radiation model

An estimated hourly temperature profile is generated for the optimization study from a daily temperature record of Freetown. The National Ocean and Atmospheric Administration (NOAA) has access to the Global Historical Climatology Network which archives datasets that include the max and minimum dry bulb temperature for Lungi Airport, the only weather station relatively close to Bo, Sierra Leone with publically available data. Lungi Airport is the international airport serving Freetown. The dataset spans 36 years, but is incomplete necessitating the author to generate an average daily temperature profile. A sinusoidal hourly profile is then fit to the averaged daily high and low dry bulb temperature. This hourly profile is then used in HOMER and Hybrid2 predicting models. A chart of the high and low daily temperatures can be found in Figure 9.

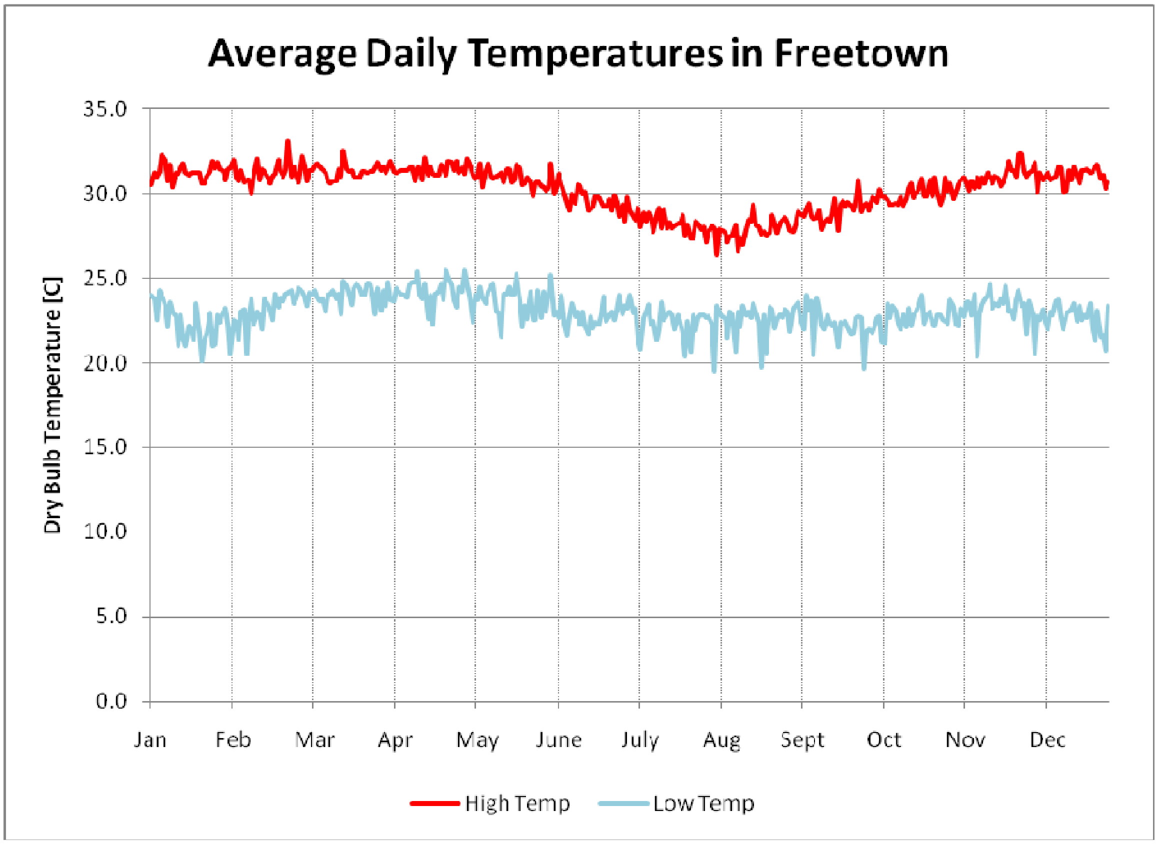

Figure 9: Averaged Daily High and Low temperatures from Lungi Airport compiled between 1973 and 2009.

Theory and Calculations

The aim of this thesis is to quantify the Operational Cost savings that are realized as a diesel system is converted into a hybrid system. Operating Cost is similar to the levelized Cost of Electricity (COE), but has the capital and replacement costs of each component removed because these costs can only be calculated *ex post facto*. The COE derived by HOMER and Hybrid2 includes the capital cost and the replacement cost of each component over the life of the project, but in order to compare experimental data with the optimized results a new parameter is created: Operational Cost. A system's Operational Cost includes: diesel fuel expenses, system O&M expenses, BKPS expenses, and electrician's salary.

To aid in this, HOMER and Hybrid2 are used to output hourly readouts of roughly 30 parameters. These parameters include: total annual load, annual production of all generators (diesel, solar, BKPS), power flow into and out of the inverters, and losses. These outputted parameters are then used to calculate the results in Table 5 through Table 7 and Table 16 though Table 18. These tables are organized into three general categories: energy tables, efficiency tables, and financial tables. The energy parameters are outputs of the modeling problems and are used for calculations in subsequent tables. The efficiency parameters are calculated using the energy data, and include the generator efficiency, roundtrip battery efficiency, both charging and discharging inverter efficiency, and the "well-to-electrons" efficiency which is a measure of how much of the diesel fuel's energy is converted into electricity used by the load. The finance tables contain a mix of parameters that are output by HOMER and Hybrid2 or calculated from the energy table, such as Operational Cost. In order to calculate the efficiency and financial parameters, several intermediate parameters are calculated. These intermediate parameters are defined below.

The first intermediate parameter to be calculated is the total energy content of the diesel fuel consumed during the dataset, $E_{diesel,month}$ (in Joules):

$$E_{diesel,month} = C_{month} * LHV_{diesel}$$ **Equation 2**

where C_{month} is the kg of fuel consumed by the generator in the dataset. LHV_{diesel} is the lower heating value of diesel fuel which for this study was taken to be 43 $MJ*kg^{-1}$.

The next parameter of importance is the monthly average generator efficiency, η_{gen}. It is calculated here:

$$\eta_{gen} = E_{g,month} / E_{diesel,month}$$ **Equation 3**

$E_{g,month}$ is the monthly energy output by the generator. The monthly average generator efficiency is calculated rather than an instantaneous efficiency due to the constraints of the instrument.

One of the methods to calculate the average battery roundtrip charging efficiency is given by:

$$\eta_{B,round} = (E_{inv,out} - E_{loss,discharge}) / (E_{inv,in} - E_{loss,charge})$$ **Equation 4**

where $E_{inv,out}$ is the inverter/charger's monthly energy output of the battery bank in Joules, and $E_{loss,discharge}$ is the sum of the lost energy while discharging throughout the dataset. $E_{inv,in}$ is the inverter/charger's monthly energy input into the batteries in Joules, $E_{loss,charge}$ is the lost energy, in Joules, while charging the battery bank summed over the dataset. $E_{loss,discharge}$ and $E_{loss,charge}$ are found by using the instantaneous efficiency curve published by the manufacturer of the inverter/charger [14].

An alternate equation of the battery roundtrip efficiency which is used when analyzing Hybrid2 results can be found in Equation 5.

$$\eta_{B,round} = 1 - \frac{E_{combo,loss} - (E_{loss,discharge} + E_{loss,charge})}{E_{inv,in}}$$ **Equation 5**

$E_{combo,loss}$ is a parameter created by Hybrid2 that is the total losses associated with charging and discharging the battery bank including inverter losses.

In order to store and then provide energy to a load, energy must pass through the inverter twice; once when charging the battery bank and again when discharging the battery bank. $\eta_{inv,charge}$ and $\eta_{inv,discharge}$ are the monthly average single trip efficiencies while the inverter is charging and discharging the batteries. They are calculated in Equations 6 and 7.

$$\eta_{inv,charge} = {(E_{inv,in} - E_{loss,charge})}\Big/{E_{inv,in}}$$ **Equation 6**

$$\eta_{inv,discharge} = {(E_{inv,out} - E_{loss,discharge})}\Big/{E_{inv,out}}$$ **Equation 7**

The electricity generated by the diesel generator is utilized either by the inverter charging the batteries or directly by the loads within the hospital. Both the absorbed inverter energy, $E_{gen,inv}$, and the total monthly generated electricity, $E_{gen,month}$, are directly measured by the SMA SI 5048. The generated electricity consumed by the load, $E_{gen.load}$, is calculated through the use of Equation 8. The unit of all three variables in Equation 8 is Joules. Note that $E_{gen,inv}$ is not the same as $E_{inv,in}$; the latter also includes electricity purchased from the local utility company while the former does not.

$$E_{gen,load} = E_{gen,month} - E_{gen,inv}$$ **Equation 8**

When the diesel generator produces electrical power, a portion is stored within the battery bank while another portion is used to supply the hospital's electricity demand. The ultimate efficiency at which the generator and battery bank supply electricity to the hospital is dependent on the battery storage efficiency, the generator's efficiency, and the fraction of energy that is used immediately versus stored for later use. Equation 9 is used to calculate this "Wells-to-Electrons" efficiency of the hybrid system.

$$\eta_{H,Total} = {(E_{gen.load} + \eta_{B,C} * \eta_{inv,charge} * \eta_{inv,discharge} * E_{inv,in})}\Big/{E_{diesel,month}} \qquad \textbf{Equation 9}$$

Many authors have assumed that the relationship between diesel fuel consumption and power output is linear, similar to that found in Equation 10 [1, 15-16]. Where $\dot{V}_{diesel}$ is the fuel volumetric flow rate in meters per second, and E_g is the power output of the alternator in Watts. The setup currently lacks the equipment to measure the constants α and β, but both Cummins and Lister-Petter published data that give fuel consumption for various loadings [17-18]. The values of α and β for the Lister-Petter are $8.2*10^{-8}$ $m^3*s^{-1}*kW_e^{-1}$ and $5.56*10^{-8}$ m^3*s^{-1}, respectively. For the Cummins, these parameters are $9.5*10^{-8}$ $m^3*s^{-1}*kW_e^{-1}$ and $2.9*10^{-8}$ m^3*s^{-1} respectively.

$$\dot{V}_{diesel} = \alpha * E_g + \beta \qquad \textbf{Equation 10}$$

The absolute cost of providing electricity to the hospital is of interest to a limited audience, while a wider audience is interested in the per kWh Operational Cost accrued to the hospital. The Operational Cost of the hybrid system or the diesel-only system over the entirety of either dataset is given in Equation 11.

$$OC = {\sum_{1}^{n}\sum_{i,j,k} DC}\Big/{\sum_{1}^{n} DL} \qquad \textbf{Equation 11}$$

OC is the Operational Cost, *n* is the number of days in the dataset, and $DC_{i,j,k}$ stand for the daily cost of the O&M costs, fuel cost, and purchased electricity cost. *DL* is the logged daily load in kWh.

Uncertainty Analysis

Before conclusions can be made about the savings attributed to the hybrid system in Mercy Hospital, it is necessary to highlight the uncertainty with HOMER, Hybrid2, and the experimental dataset. There are three main sources of uncertainty in this study: measurement error due to the resolution in the inverter's datalogger, uncertainty due to the finite number of samples used by HOMER when it creates the synthetic load dataset, and a possible measurement bias that resulted from conducting equalization charges during September 2009. All uncertainty intervals are calculated to a level of 95 percent or better.

When HOMER generates the annual synthetic load data from the experimentally derived hourly profiles, it introduces a stochastic randomness into the daily load demand. When introducing this randomness HOMER maintains the mean of the inputted hourly profile, but only over the annual dataset. When only looking at a few days or weeks, it is necessary to quantify the mean load difference between HOMER and the experimental data. HOMER's synthetic load generation is based on the creation of α, which is described in Equation 1. Within α are two parameters, δ_h and δ_d, which are randomly selected from normal distributions with mean values of 0 and the standard deviations of 0.2 and 0.15 for δ_h and δ_d, respectively. Over the course of a day, there are 24 selections of δ_h reducing the uncertainty associated with the average value of δ_h. The uncertainty range associated with δ_h is:

$$u_h = \frac{\sigma_h * 1.96}{\sqrt{N}} \qquad \textbf{Equation 12}$$

σ_h is the standard deviation for the normal distribution of δ_h, N is the number of times δ_h is selected in a day (24), and 1.96 is the standard deviation interval required for 95 percent confidence with a normal distribution. The value of u_h is +/- 0.08.

A value for δ_d is only selected once a day, so the uncertainty associated with it is larger. It is given by:

$$u_d = \sigma_d * 1.96 \qquad \textbf{Equation 13}$$

where σ_d is the standard deviation for the normal distribution of δ_d. The value for u_d is +/- 0.29.

Both δ_h and δ_d are independent variables so their uncertainty does not arithmetically add to yield the total average daily uncertainty for the value of α. Instead the total average daily uncertainty of α, u_α, is given by:

$$u_\alpha = \sqrt{u_h^2 + u_d^2} \qquad \textbf{Equation 14}$$

The value for u_α is 0.30. The value u_α is not the same as the uncertainty, in kWh, of the load demand over a specified number of days. u_H is the uncertainty introduced by HOMER over N days.

$$u_H = \frac{u_\alpha * \sigma_t(N) * \overline{L}}{\sqrt{N}} \qquad \textbf{Equation 15}$$

$\overline{L}$ is the average daily demand over N days, and $\sigma_t(N)$ is the interval associated with the double sided 95 percent confidence level of a Student t distribution with N degrees of freedom. As seen in Equation 15, the uncertainty that HOMER introduces is not an absolute quantity, but is dependent on the length and load of the dataset one wishes to analyze.

The power measurements taken by the SI5048 inverter's datalogger are limited to a resolution of 0.1 kW. The uncertainty associated with the resolution of an instrument can be described by a uniform distribution. The uncertainty is given in Equation 16:

$$u_{m,\max} = \frac{x_{\max} - x_{\min}}{2} \qquad \textbf{Equation 16}$$

x_{max} is the upper bound of the uniform distribution, 0.15kW in this case, and x_{min} is the lower bound, or 0.05 kW when calculating the uncertainty of the datalogger resolution. When the error in Equation 16 is integrated over the course of the day, the result is an uncertainty just due to the datalogger's resolution is +/- 1.2 kWh per day.

Finally, the last significant source of error to discuss is that due to the energy that was consumed during an irregular battery conditioning test. While data for both systems were being recorded in September 2009, non-regular maintenance was being conducted on both battery banks in an attempt to reverse possible capacity reduction in the cells that had resulted from atypical abuse of the battery bank. Over the course of the 17 days several equalization charges were used to stress the cell electrodes and encourage the reversal of sulfurization, which is the process whereby $PbSO_4$ crystals on the cell electrodes harden decreasing the active electrode surface area. The inclusion of the equalization charges in the performance data represents a bias error. During an equalization charge, electricity enters the battery, but the energy is used to both heat up the battery and electrolyze the sulfuric acid within the battery. Failure to remove this energy error bias from the dataset throws off diesel consumption and grid purchase calculations as well as battery bank and generator efficiency calculations. The amount of energy that is lost due to electrolyte gassing is estimated by calculating the energy that continues to enter the battery after the dataloggers state that the batteries have reached 100 SoC. The reason for the uncertainty in this estimation is the inability to precisely predict when 100 SoC occurs. However, this estimation provides the maximum wasted energy allowing the unknown bias error to be bounded and a resulting uncertainty to be calculated. By assuming that the potential values for the wasted energy fall within a uniform distribution with a minimum value of 0 kWh's wasted, the uncertainty can be calculated in Equation 16.

It is believed that, at most, 108 kWh's of electricity was dissipated by conducting equalization charges on the 50 Hz system. This amount represents 16.2 percent of the total demand recorded for three week in September, and not accounting for such a large fraction of the electricity purchased from BKPS or generated by the Lister-Petter makes the batteries appear to be a much less efficient storage medium than they actually are. The uncertainty associated with the 50 Hz system's equalization charges, $u_{e,50Hz}$, is +/-54.0 kWh's. The equalization charges for the 60 Hz system totals 111 kWh, thus the additional uncertainty with the 60 Hz Wet Season, $u_{e,60Hz}$, is +/-55.5 kWh's.

Ultimately the goal of calculating the uncertainty associated with the HOMER and experimental loads is so that it is possible to calculate the uncertainty of the Operational Cost. It is assumed that there is no uncertainty associated with the O&M and fuel costs for any dataset. This allows the formula for the uncertainty of the Operational Cost, U_{OC}, to simplify into the form:

$$U_{OC} = \frac{OC}{\sum_{1}^{n} DL} * \sum_{m,e} u \qquad \textbf{Equation 17}$$

OC and DL are defined in Equation 11, and u_m is the uncertainty associated with the inverter resolution and u_e is the uncertainty with the equalization charges.

System Optimization and Selection

The number of parameters and the number of potential values that those parameters can take determine how complicated, reliable, and time consuming an optimization study will be. There are 4 design parameters that can be modified while optimizing the 50 Hz system and 440 potential design alternatives to be examined. The 60 Hz system optimization contains 5 design parameters and 1320 potential design alternatives. The extra parameter found in the 60 Hz system is the diesel generator size. Table 1 and Table 2 show the optimization parameters for the 50 and 60 Hz systems, respectively.

Table 1: 50 Hz Optimization Parameters

Component	Design Points
PV array	11
Inverter/Charger	5
Battery Bank Size	4
Dispatch Strategy	2
Total Potential Designs	440

Table 2: 60 Hz Optimization Parameters

Component	Design Points
PV array	11
Inverter/Charger	5
Battery Bank Size	4
Dispatch Strategy	2
Diesel Generator Size	3
Total Potential Designs	1320

While it is obvious that component size affects capital cost, Operational Cost and component size are also interconnected. The smaller the solar array, the more energy will need to be generated by the diesel generator or bought from the utility grid. As the battery bank is sized smaller and smaller, less solar generated electricity can be used during the night or on cloudy days, again necessitating more electricity from the diesel generator or utility grid. The inverter/charger's size is important because the solar array outputs AC power and the inverter/charger partially dictates both how quickly the battery can be recharged and how much battery power is available to fulfill load. If the inverter is too small to completely power the load, then additional power must be sourced from either the diesel generator or the utility grid. The size of the diesel generator both limits the maximum electrical power that can be sourced from the generator and influences how efficiently diesel fuel is converted into electricity.

In addition to sizing the components of the hybrid system, HOMER also does a comparison between two simple dispatch strategies. HOMER's two dispatch strategies are: Load Following and Cycle Charging. Load Following turns on the diesel generator when power cannot be sourced from renewable energy sources or the batteries and only operates the generator at a level sufficient to power the load, but not the battery recharge. Cycle Charging operates the generator either when the renewable energy sources cannot source enough power to the load or if the battery bank needs charging. The generator is operated at a level to satisfy the load and charge the batteries as fast as possible.

Optimization Results

The 50 Hz HOMER model assumes that BKPS availability varies with the season. BKPS generates the majority of its electricity using hydro-electric plants, so when reservoirs are full during the rainiest months (July and August) grid power is available 24 hours a day. During the driest months (December through February) the lack of water reserves to run the hydro-electric turbines means there is no grid power. The other months of the year are considered transitional months and BKPS power is available 6 hours a day. In addition to the O&M costs of each component, a miscellaneous O&M cost of US$724 is added to the anticipated annual costs. US$500 of this represents the salary of the electrician that is needed to maintain the system. The remaining US$274 is to account for the BKPS monthly meter rental fee. Some hindsight is also used to account for balance of plant costs and installation costs; for the 50 Hz system these total to US$26,300. Using these additional inputs and the capital and Operational Costs of each system component, a single optimum design is selected from a total of 440 possible designs. The component sizes are listed in Table 3.

Table 3: Optimum 50 Hz System Sizing

PV Array Size	21 kW_p
Inverter/Charger Size	10 kW
Battery Bank Size	182 kWh (2 strings of 12)
Dispatch Strategy	Cycle Charging

The 50 Hz system is designed to satisfy an annual load of 26,720 kWh. The PV array generates 70 percent of the total generated energy, while the generator generates only 7 percent of the total generated energy. The balance is bought from BKPS at roughly US$0.262 a kWh. The generator operates a total of 361 hours each year and consumes 823 liters of fuel.

The initial capital required to install the optimal system is US$137,300 which includes the cost of the battery bank, solar array, inverter, generator, and shipping and installation expenses. Figure 10 shows how much each component costs as a percentage of the capital cost.

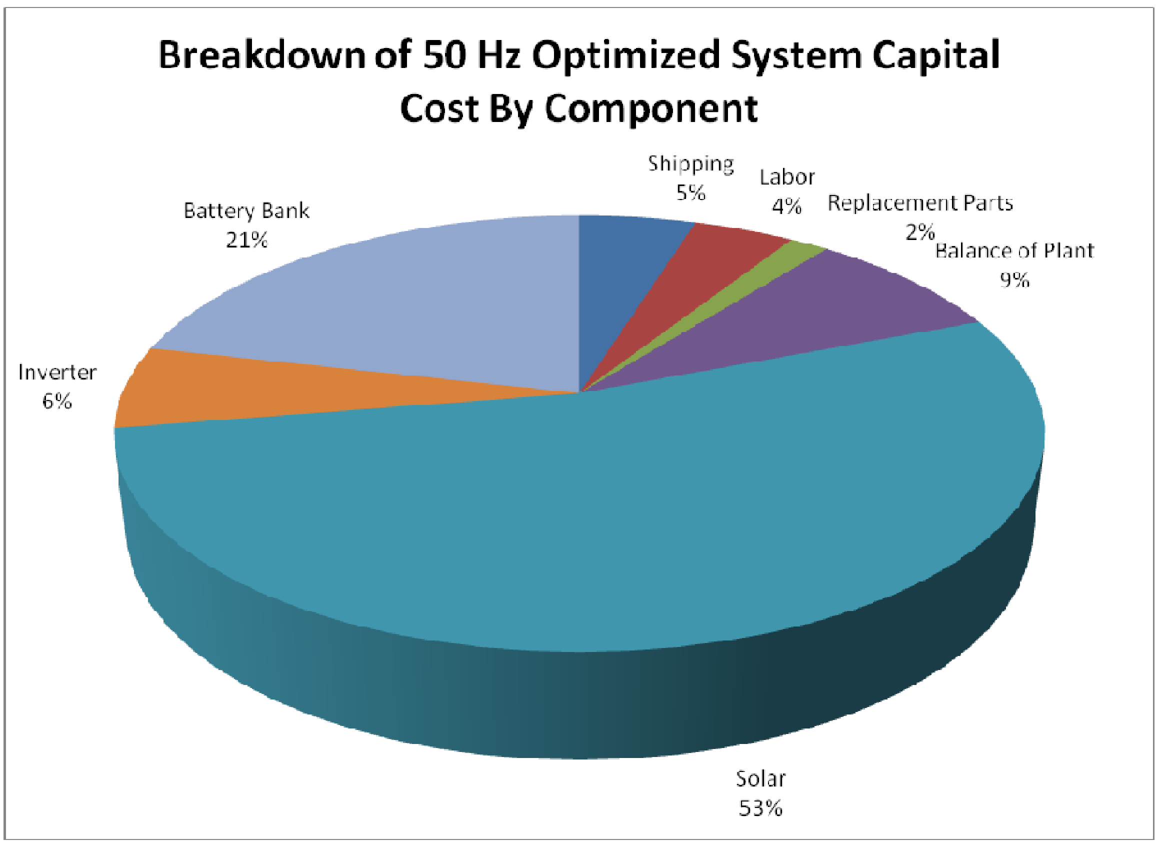

Figure 10: Component Cost of 50 Hz System as Percentage of Capital Cost

The NPV of the 50 Hz optimal design is US$246,200 spread over 15 years. Figure 11 shows the component cost as a percentage of the NPV total project cost. The cost of components change as a result of the need to replace parts, ongoing O&M costs, and fuel costs.

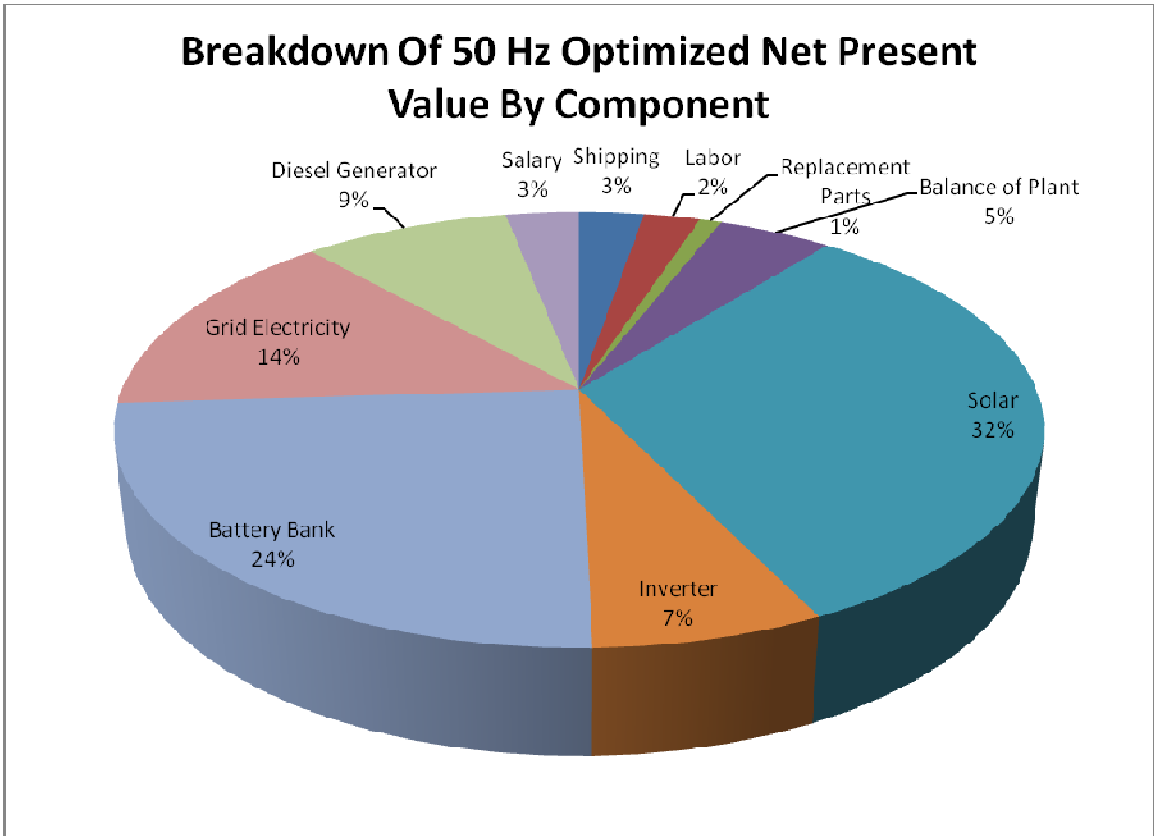

Figure 11: Component Cost of 50 Hz System as Percentage of Total Project Cost

The optimized PV-diesel hybrid system saves roughly US$225,900 over the diesel-only baseline, which has an NPV of $472,000.

The COE from the system is US$0.61 per kWh, which is the NPV of the project divided by the total electricity delivered to the load over the life of the project. The Operational Cost for the 50 Hz system is US$0.16 per kWh, and is broken down in Figure 12.

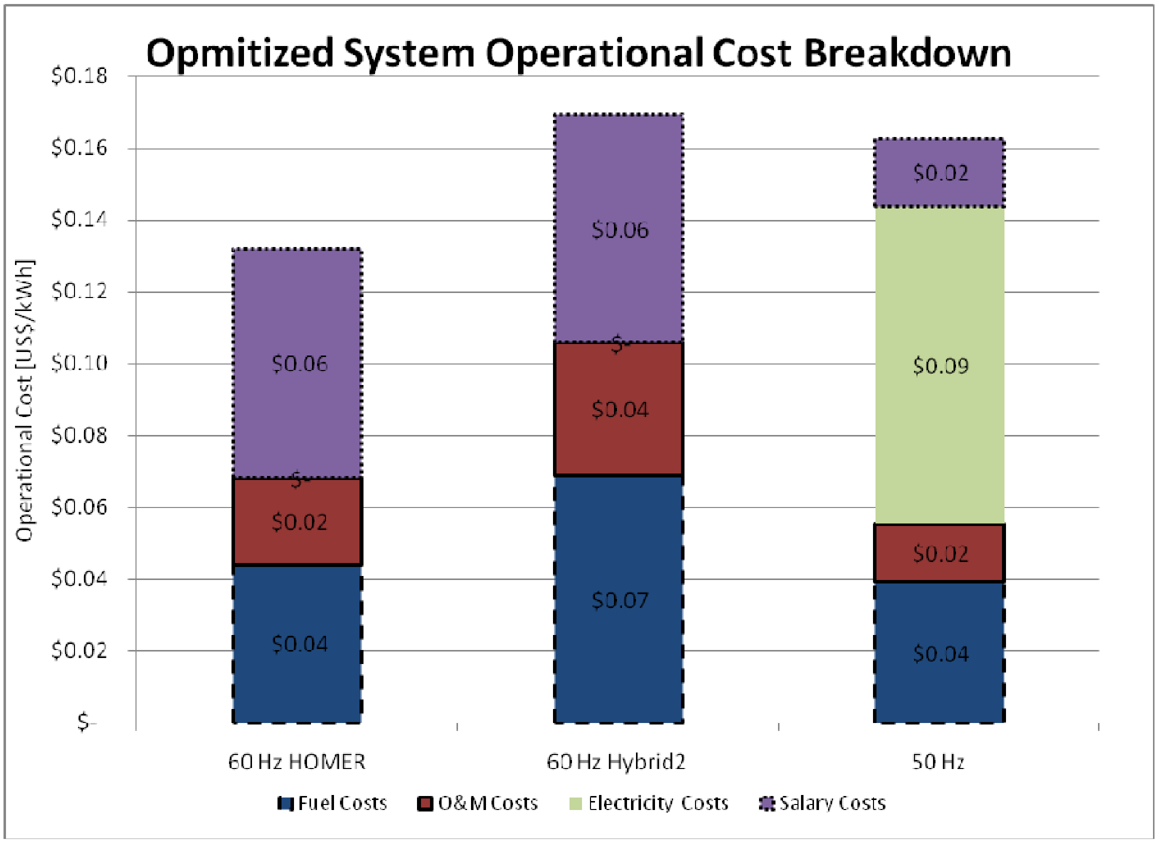

Figure 12: Per kWh cost of Operational costs for both 50 and 60 Hz systems

The 60 Hz system is a completely new system that will be installed into the hospital and is to be completely off-grid. As a new system, the generator size is now a design parameter that HOMER has to include in the optimization making a total of 5 design parameters in the 60 Hz optimization study. As seen in Table 2, HOMER will pick the design with the lowest net present value from 1320 total potential designs. The 60 Hz system has the same US$500 per year technician salary cost as the 50 Hz system because it is assumed that the electrician will split their time equally among the two systems. The BKPS monthly meter rental fee is not included because the 60 Hz system is off-grid. The balance of plant and installation costs of the 60 Hz system totals to US$27,070; a little larger than for the 50 Hz system. After the optimal system is found using HOMER, the system performance is checked with Hybrid2 to see if the two programs predict noticeably different performance and costs.

According to HOMER, the Optimal 60 Hz system is somewhat smaller than the 50 Hz system, but this is logical since the load demand is less than a third that of the 50 Hz system. The optimum 60 Hz system is detailed in Table 4.

Table 4: Optimum 60 Hz System Sizing

PV Array Size	7.8 kW_p
Inverter/Charger Size	5 kW
Battery Bank Size	91.2 kWh (1 string of 12)
Dispatch Strategy	Cycle Charging
Generator Size	9.1 kW

The 60 Hz system is sized to supply an annual electrical demand of 7,850 kWh, of which HOMER predicts 92 percent comes from the PV array. HOMER also predicts that the generator operates 154.0 hours and burns 272.3 liters of fuel each year. The distribution strategy for the Hybrid2 model allows the battery bank to be completely charged every 2 weeks according to the manufacturer's recommendations, while HOMER distribution strategy does not. The result of this is that more power is generated from diesel fuel at the expense of PV. According to Hybrid2, only 89 percent of the load is satisfied by the PV array. The generator also has to operate longer and burn more fuel each year: 250.0 hours and 405.3 liters. The capital cost of the 60 Hz system is

US$83,800, and Figure 13 shows the percentage of the capital cost each component represents.

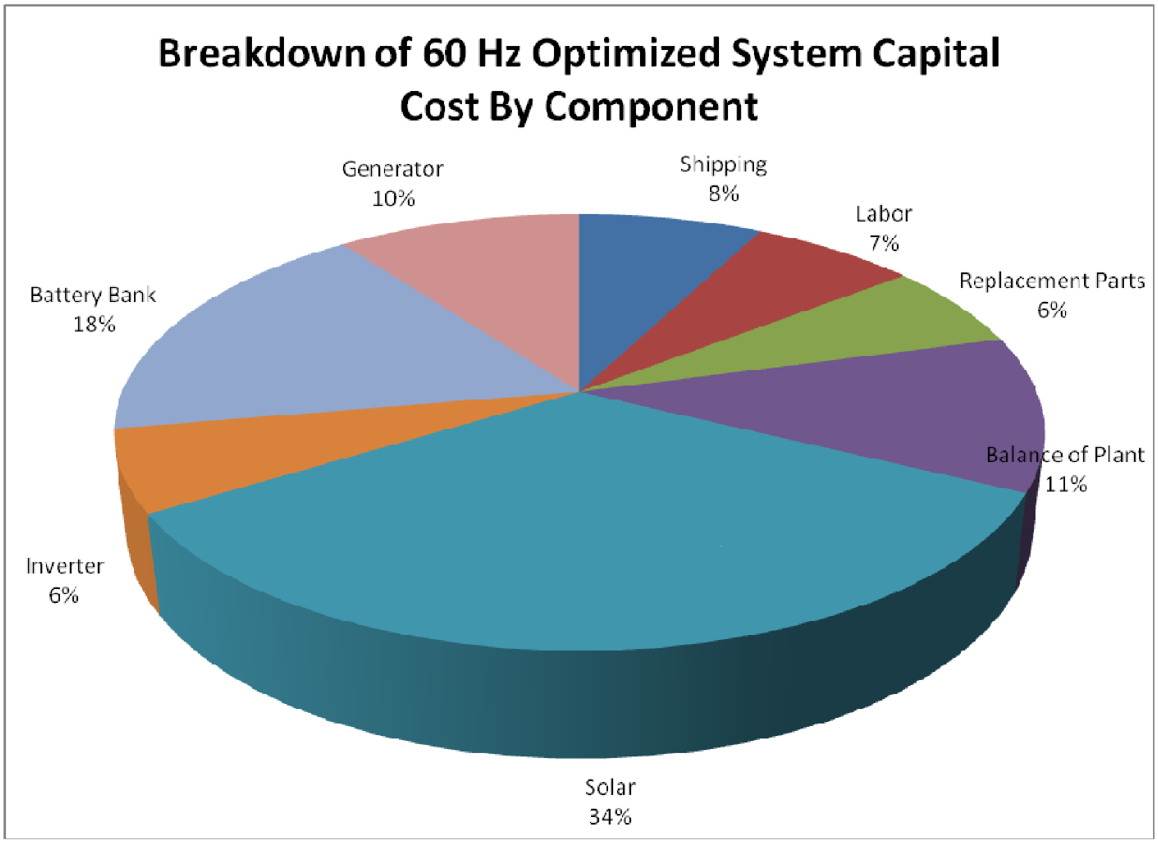

Figure 13: Component Cost of 60 Hz System as Percentage of Capital Cost

HOMER predicts the total net present value for the 60 Hz system over 15 years is US$122,500. Hybrid2 does not differ greatly from HOMER in predicting the 60 Hz system's net NPV. Figure 14 shows each component expense as a percentage of the total project's NPV. The savings over the life of the project by installing the hybrid system rather than simply relying on a diesel generator are US$230,900 according to HOMER, while Hybrid2 predicts the savings are greater: US$273,500. The levelized COE is US$1.04 per kWh. The Operational Cost of the 60 Hz system, both HOMER's and Hybrid2's predictions can be seen in Figure 12.

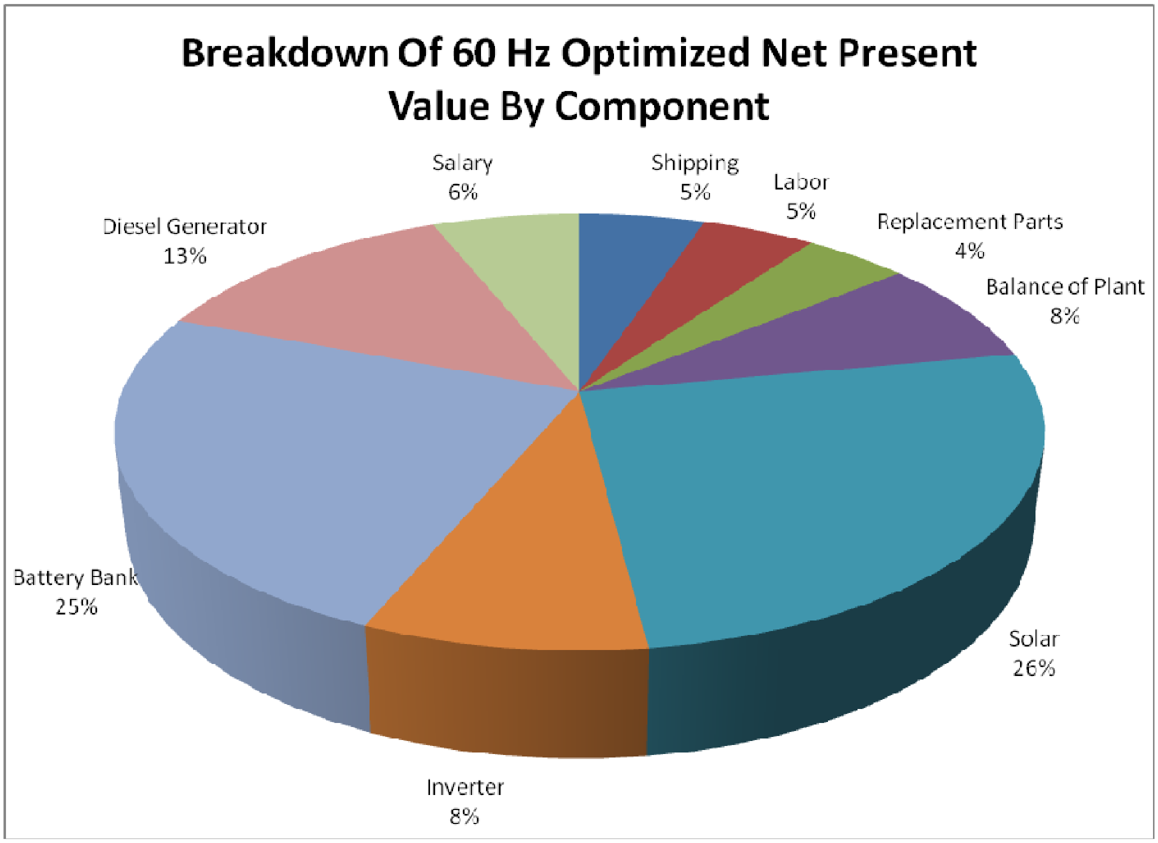

Figure 14: Component Cost of 50 Hz System as Percentage of Total Project Cost

Table 5 shows the predicted electricity demand, generation, and diesel generated electricity by all three optimized systems over the course of a year. Table 6 shows all the relevant component efficiency values for both the optimal 50 and 60 Hz systems. Table 7 shows the NPV of the optimal designs as well as various cost subdivisions, COE, and Operational Cost.

Table 5: Optimization Results Energy Table

System	Dataset	Program	AC Primary Load	Grid Electricity	PV Energy	Generator Production	Diesel Consumption	Generator Operation
			kWh/yr	kWh/yr	kWh/yr	kWh/yr	L/yr	hrs/yr
60 Hz	Optimal	HOMER	7,848	NA	9,287	766.0	272.3	154.0
	Predicted	Hybrid2	7,848	NA	9,254	1,091	405.3	250.0
50 Hz	Optimal Predicted	HOMER	26,720	8,168	25,330	2,544	822.9	361.0

Table 6: Optimization Results Efficiency Table

System	Dataset	Program	Generator Efficiency	Bat. Round Trip Efficiency	Inverter Efficiency		Well-to-Electrons Efficiency
					Charge	Discharge	
60 Hz	Optimal	HOMER	28.2%	80.0%	91.0%	91.0%	20.3%
	Predicted	Hybrid2	27.5%	92.7%	89.3%	86.6%	25.0%
50 Hz	Optimal Predicted	HOMER	31.6%	80.0%	91.0%	91.0%	24.1%

Table 7: Optimization Results Finance Table

System	Dataset	Program	NPV	Initial Cost	Replacement Cost	Fuel Cost	O&M Cost	COE	Operation Cost
			$	$	$	$/yr	$/yr	$/kWh	$/kWh
60 Hz	Optimal Predicted	HOMER	$ 122,533	$ 83,838	$ 23,165	$ 345	$ 690	$ 1.04	$ 0.13
		Hybrid2	$ 126,016	$ 83,838	$ 23,165	$ 540	$ 790	$ 1.07	$ 0.17
50 Hz	Optimal Predicted	HOMER	$ 246,191	$ 137,311	$ 43,748	$ 3,185	$ 1,157	$ 0.61	$ 0.16

Design Sensitivity Analysis

The optimum design depends on the interplay between several important input variables. In an environment where these inputs can change, it is useful to know how sensitive the optimum design is to the variation of these variables. Two separate sensitivity analyses are conducted in this thesis: the design's dependency on load and the design's dependence on several generation costs. The first sensitivity analysis looks at how component size and dispatch strategy change if the load demand for the 50 and 60 Hz systems are larger or smaller than expected. A system designer may wish to install a hybrid system in stages to gain design flexibility in light of higher or lower loads than expected. A designer in this situation would be interested in knowing how module components (solar and inverter) and non-modular components (generator and battery bank) change over a range of possible loads. The loads used in the sensitivity analysis are listed in Table 8.

Table 8: Load Sensitivity Input Table

Load Percent	60 Hz System Loads kWh/day	50 Hz System Loads kWh/day
150 %	32.3	110
125 %	26.9	91.5
100 %	21.5	73.2
75 %	16.1	54.9
50 %	10.8	36.6
25 %	5.4	18.3

Based on the resulting optimal designs given for the 60 and 50 Hz in Table 9 and Table 10, there are a few loads which mark major changes in both systems' design. Table 9 shows that at low loads (<16.1 kWh/day), the optimal 60 Hz system is solar-only rather than a hybrid. Above that load the optimal system is a hybrid system, but only the solar array size changes not the inverter size or battery bank capacity. A designer may choose to initially install a solar-only system and add a diesel generator later, but there is the drawback to this approach. If the load is larger than 16.1 kWh/day and the system lacks a diesel generator, the 60 Hz system will suffer brownouts when solar insolation is low. If a designer chooses to install a generator with a battery bank, a

“Diesel/Bat” configuration, then the load analysis shows that the optimum design will never need more than 1 string of batteries and a 5kW inverter.

As the average daily load demand increases for the 50 Hz system, optimal solar array size reaches the upper limit of what is thought feasible to install at Mercy Hospital (21.1 kW) when the daily load demand reaches 73.2 kWh/day. As a result, there is a trend in Table 10 where the optimal hybrid system’s battery bank and inverter start at 1 string and 5 kW, double in size, but then reduce back down to the original 1 string and 5 kW inverter at the highest load (110 kWh/day). At the highest load HOMER has also eliminated all systems that utilize the grid. The most common reason that HOMER eliminates a design alternative is if that design alternative is unable to generate enough electricity to satisfy the electricity demand within a timestep. Note that the optimal system for the 110 kWh/day load requires the diesel generator to consume 8,200 liters of fuel a year which is over the fuel limit stated in the ***Design Criteria*** section. In order for HOMER to output a feasible design at this load either the fuel constraint or the maximum solar array size must be relaxed. As the daily load on the 50 Hz system decreases to 18.3 kWh/day, the optimal solar array size drops to 7.76 kW and the dispatch strategy changes to Load Following. This strategy minimizes generator runtime as well as ensures that expensively generated electricity is directed to the load rather than lost as a result of the inverter and battery bank inefficiencies. The drawback of this strategy is that it relies on unpredictable renewable energy sources to recharge the battery bank. The 50 Hz load sensitivity analysis shows that a designer has to carefully weigh the benefits and drawbacks of the system’s battery bank capacity. A battery bank’s capacity cannot easily be changed once it is installed and Table 10 shows that the optimal number of battery strings changes with load.

Table 9: 60 Hz Load Sensitivity Analysis Designs

Design	Load (kWh/day)	PV Size (kW)	Battery Bank (no. of strings)	Inverter Size (kW)	Generator Size (kW)	Dispatch Strategy
A	32.3	13.2	1	5	9.1	Cycle Charging
B	26.9	10.6	1	5	9.1	Cycle Charging
C	21.5	7.76	1	5	9.1	Cycle Charging
D	16.1	6.58	1	5	9.1	Cycle Charging
E	10.8	5.17	1	5	None	Cycle Charging
F	5.4	2.82	1	5	None	Cycle Charging

Table 10: 50 Hz Load Sensitivity Analysis Designs

Design	Load (percent)	PV Size (kW)	Battery Bank (no. of strings)	Inverter Size (kW)	Grid Usage	Dispatch Strategy
G	110	21.1	1	5	No	Cycle Charging
H	91.5	21.1	2	10	Yes	Cycle Charging
I	73.2	21.1	2	10	Yes	Cycle Charging
J	54.9	15.5	2	10	Yes	Cycle Charging
K	36.6	10.6	1	5	Yes	Cycle Charging
L	18.3	7.76	1	5	Yes	Load Following

The second sensitivity analysis conducted for this optimization study examines how four cost parameters will change the optimal system design. A two-level, four-factor sensitivity analysis is used to look at the influence of diesel fuel cost, electricity cost, diesel generator replacement cost, and diesel generator O&M cost on the optimized design. These four parameters factor into the relative cost difference between fossil fuel generation and renewable energy generation. High and low values for each variable are input into HOMER, and the program re-runs the optimization study for all 16 permutations. Table 11 shows the values of the high and low values of these four variables that will be used during the sensitivity analysis.

Table 11: Sensitivity Study Multipliers

	Diesel Cost (US$/L)	Electricity Cost (US$/kWh)	Generator Replacement Cost (US$)	Generator O&M Cost (US$/hr)
High Value	$1.27	$0.52	$15,000	$1.00
Low Value	$0.63	$0.262	$7,500	$0.75

While the optimal 60 Hz system design does not change when any of the four variables are changed, the optimal 50 Hz system design changes significantly depending on the combination of variable changes that are examined. The original optimal 50 Hz setup is given in Table 12 as Design I with four alternate optimum designs. Design Alternate M is the optimum design for a number of cases mostly involved when the cost of electricity is doubled. Design Alternate N occurs in the singular instance when the diesel cost remains the same but every other variable is changed. On the flip side, Design Alternate O is the optimum in the singular instance when the diesel cost is the only variable that is changed. Design Alternate P occurs generally when the price of electricity is fixed at its original value and diesel cost is cut in half. Table 13 catalogues the results for the 50 Hz system sensitivity analysis.

Table 12: Alternate Optimum Designs

Design	PV Size (kW)	Battery Bank (no. of strings)	Inverter Size (kW)	Grid Usage
I	21.1	2	10	Yes
M	21.1	2	10	No
N	21.1	1	5	Yes
O	18.3	2	10	Yes
P	13.2	1	5	Yes

Table 13: Sensitivity Analysis Results

Design Alternatives	Diesel Cost = $1.27/L Electricity Cost = $0.52/kWh	Diesel Cost = $0.63/L Electricity Cost = $0.52/kWh	Diesel Cost = $1.27/L Electricity Cost = $0.262/kWh	Diesel Cost = $0.63/L Electricity Cost = $0.262/kWh
Generator Replacement = $15,000 Generator O&M = $1.00/hr	I	M	I	O
Generator Replacement = $7,500 Generator O&M = $1.00/hr	M	I	I	P
Generator Replacement = $15,000 Generator O&M = $0.75/hr	M	I	I	P
Generator Replacement = $7,500 Generator O&M = $0.75/hr	N	M	I	P

Part 2: Experimental and Modeled System Performance

Due to the results of the sensitivity analysis, it was thought prudent to install both the 50 and 60 Hz systems in phases allowing for maximum flexibility if electrical demand and generation costs vary significantly from those assumed in the optimization model. As a result, the experimental validation data is recorded when the 50 and 60 Hz systems do not resemble the optimal setup described in ***System Optimization and Selection***. A single 5 kW SI5048 inverter and a battery bank comprised of 1 string of 12 Rolls 4KS25PS batteries were coupled with a diesel generator in both systems. The 50 Hz system also maintains its connection to BKPS through a transfer switch producing a "Diesel/Bat/Grid" system configuration. The diesel generator for the 60 Hz system is the Cummins DKAB 13.6 kW generator making a "Diesel/Bat" system configuration. The decision to install half the inverter and battery bank capacity stated in the optimal design was made in light of the sensitivity analysis conducted in **Part 1.** By picking the smallest battery bank and inverter size listed for the range of design alternatives in the sensitivity analysis, a flexible system platform can be installed that can later be added to as knowledge about the load and system costs improves. Due to the system composition discrepancy between the optimal systems and the 50 Hz "Diesel/Bat/Grid" and the 60 Hz "Diesel/Bat" systems, new validation models are created in HOMER and Hybrid2. While Hybrid2 is not able to model the grid connection of the 50 Hz, it is used to model the "Diesel/Bat" configuration of the 60 Hz system.

Datasets

The SMA SI 5048 and SI 50348U log 106 separate performance parameters every minute, providing a rich source of data from which one can use to analyze the 50 Hz and 60 Hz systems' performance. The most useful of these regularly logged parameters are aggregated to allow for the comparison between HOMER, Hybrid2, and the actual performance of the system installed in Sierra Leone. The fact that the dual power systems installed at Mercy Hospital are not devoted experimental setups, but field systems installed in Africa, hampered our ability to create large seasonal datasets. During the first year after installation the two systems alternated between operational and non-operational with little overlapping time where both systems ran simultaneously. This complicated finding suitable datasets. As a result of the holes in the data collected by the inverters, it was necessary to approximate the annual performance of the two systems by averaging the performance of the systems in two datasets recorded in separate seasons. The wet season in Sierra Leone is characterized by readily available power from the grid, but almost daily storms that reduce solar insolation. During the dry season power is severely rationed between city districts, but clear skies provide higher solar energy availability.

Both the 50 and 60 Hz systems have a dataset for the wet and dry season, and each is 21 days long except for the 60 Hz Wet Season dataset which is only 15 days long. This is because there are no dates recorded by the 60 Hz system during the wet season that overlap with the 50 Hz data records for more than 15 days. The dates that the datasets span can be found in Table 14. For systems with the available data that extends beyond the dates listed in Table 14 an effort is taken to confirm that the parameters calculated in the truncated dataset are the same value as the parameters calculated using the entire available data.

Table 14: Dataset Timeframes

	Wet Season	Dry Season
50 Hz	Sept 12– Oct 2, 2009	Mar 10 – Mar 30, 2009
60 Hz	Sept 13 – Sept 27, 2009	Mar 10 – Mar 30, 2009

HOMER and Hybrid Validation Loads

The 50 Hz “Diesel/Bat/Grid” system and the 60 Hz “Diesel/Bat” system were installed in Sierra Leone assuming that the demand profile they would satisfy looks similar to Figure 5 and Figure 6. After examining the datasets for both the 50 Hz and 60 Hz, one realizes that the hourly demand profile for each dataset is much lower than the demand either system had been designed for. The most drastic case was the 50 Hz Dry Season dataset where Mercy Hospital implemented a new energy policy limiting when electricity was available. During the Dry Season, the 50 Hz system was only supplying power to the hospital six days a week from roughly 8:30 am until 5:30 pm and again between 7:00 pm and 10:00 pm.

In order to account for the changes in both demand profile shape and the reduction in average daily demand, new load profiles are generated for each dataset. The average daily electricity demand in each dataset is calculated and a single day’s hourly load profile with the same demand is selected to represent that season. These representative days and their respective loads are listed in Table 15. An annual load is created by assuming the hourly profile would mimic the representative wet season day between April and September and the representative dry season day between October and March. As described in the ***Assessment Trip Electricity Demand Evaluation*** portion of **Part 1**, HOMER then adds statistical noise over the inputted hourly profile to create a synthetic annual demand datalog. The HOMER-generated demand datalog is later loaded into Hybrid2 so that the two programs have the exact electricity demand. The experimental total demand, in kWh's, will be close but not identical to the demand of either program.

Table 15: Representative Load Profile Days for Datasets

	Wet Season	Dry Season
50 Hz	September 26, 2009 31.8 kWh	March 14, 2009 20.9 kWh
60 Hz	September 23, 2009 9.2 kWh	March 23,2009 3.7 kWh

Results

50 Hz Baseline System Predictions and Performance

The 50 Hz baseline system performance and cost calculations are derived from two different sources: a HOMER model with only the Lister-Petter described in the ***System Setup*** portion, and the 50 Hz "Diesel/Bat/Grid" experimental data. It is assumed that the experimental demand will be satisfied by the Lister-Petter and the generator's fuel consumption curve is used to convert the load demand into fuel consumed. The number of hours that the generator is operating contributes to the O&M cost of the generator, and it is assumed that the same technician that would be employed to monitor the optimum system is employed at the same rate for the baseline system. The Operating Costs for baseline cases derived from the experimental and HOMER data are found in Figure 15. HOMER predicts that the 50 Hz baseline system fills an annual load of 8,610 kWh. The generator runs 6,580 hours a year burning 3,860 liters of fuel. HOMER predicts that the generator operates at an average efficiency of 22.8 percent. The 50 Hz system is a conversion of a pre-existing diesel system, so there is no capital cost for the baseline system, but the 15-year NPV of the baseline system is very high: US$269,600. The expenses that comprise the project's NPV can be found in Table 18. The high NPV is a result of the yearly fuel and O&M costs that sum to US$12,000 a year. HOMER predicts the annual Operating Cost of the 50 Hz baseline system to be US$1.39 per kWh. Note that the Operating Cost does not include the capital cost or the replacement cost of the diesel generator. The replacement cost for the 50 Hz baseline system is significant; generator manufactures usually recommend that generators be completely overhauled every 6,000 hours and according to the HOMER model this would be required every year.

Only limited inferences on the annual performance of the baseline system can be drawn from the experimental data in the two datasets. For comparison purposes with the HOMER results, an annual Operational Cost is calculated by averaging the Operational Costs calculated for each dataset. The average annual experimental Operational Cost is

US$1.11 per kWh shown in Figure 15. For the energy, efficiency, and financial data calculated for the baseline in each datasets please see Table 16, Table 17, and Table 18.

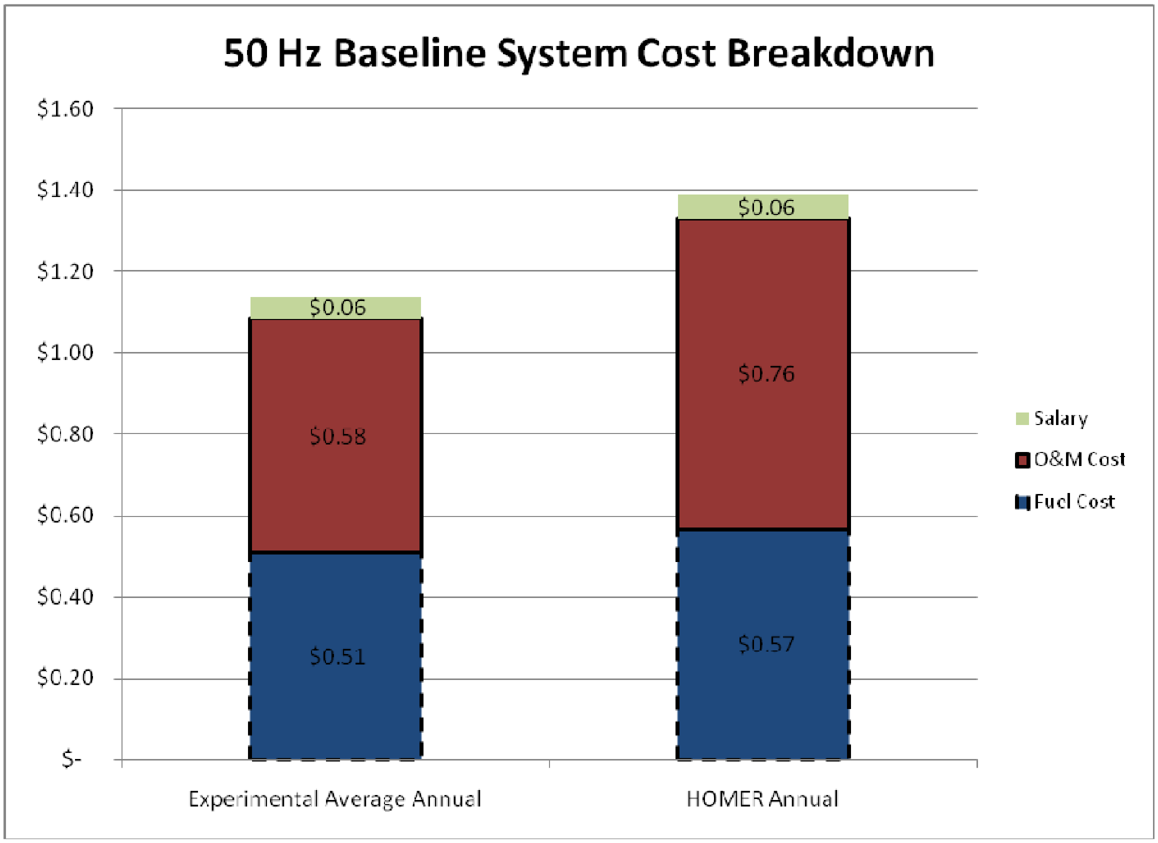

Figure 15: A Comparison of Experimental and Predicted Operational Costs for 50 Hz baseline System

50 Hz "Diesel/Bat/Grid" System Predictions and Performance

With no solar power available to recharge the batteries, the battery bank must either be recharged by purchasing power from BKPS or from electricity produced by the Lister-Petter generator. HOMER's annual electricity demand is 8,760 kWh which is satisfied by purchasing 8,179 kWh of BKPS electricity and producing 2,772 kWh with the generator. As a result of the inclusion of the battery bank and the inverter system, the generator has to produce electricity in excess of the load in order to compensate for losses in the extra components. This leads to the concept of "Well-to-Electrons" efficiency, which is an attempt to measure how much of the diesel fuel's energy is converted into power used by the hospital. HOMER predicts the "Well-to-Electrons" efficiency of the 50 Hz system during the Dry Season to be 22.4 percent. HOMER predicts the NPV of "Diesel/Bat/Grid" system to be US$133,200 which is significantly smaller than that of the baseline system. The HOMER's predicted Operating Cost of the 50 Hz "Diesel/Bat/Grid" system is US$0.53 per kWh which is lower than the 50 Hz baseline system, but still quite a bit higher than the optimal Operating Costs displayed in Figure 12. It is predicted that the "Diesel/Bat/Grid" system creates a reduction of US$7,400 per year savings in fuel and maintenance costs alone over the baseline system. These predicted parameters are summarized in Table 16, Table 17, and Table 18.

Figure 16 shows the experimentally measured electricity demand for each day in the Dry Season and how that demand is satisfied. If the generator is operating or if grid power is available during the day, they power the hospital's load but at other times of the day power must be drawn from the batteries. Figure 16 also shows the generated or purchased electricity that did not power the load, but recharges the battery bank for later use. Note that even though battery bank is recharged almost every day when the "Battery to Load" value is higher than the "Battery Recharge Energy" for that day, the result is a net removal of energy from the battery bank. The total experimental demand over the Dry Season is 434 kWh, or an average of 20.7 kWh per day. A repeating weekly trend is discernable with large electricity demands on Mondays and Tuesdays that decline until reaching a minimum on Sunday when the hospital is not open to outpatients (Figure 16).

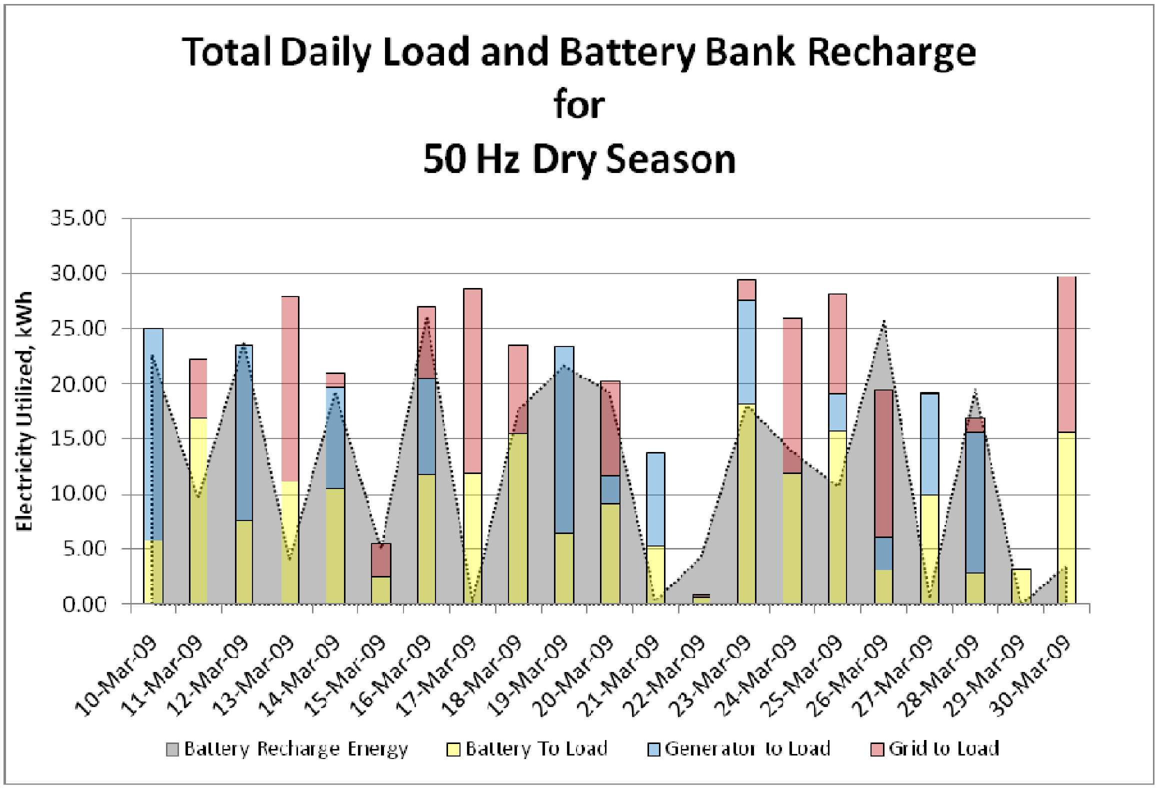

Figure 16: Experimental 50 Hz Dry Season Dataset Electricity Demand

During the Wet Season there is no policy limiting energy usage in place; electricity is available almost 24 hours a day rather than the 12 hours in the Dry Season database. This results in an average experimental electricity demand of 31.8 kWh per day or 667 kWh over the entire dataset. Figure 17 shows that the Wet Season's weekly electricity demand profile is similar to the Dry Season's, but the weekday peaks are larger and the weekend troughs are shallower culminating in a 54 percent increase in average daily electricity consumption. The figure also shows that most of the hospital's electricity during the Wet Season comes from BKPS. The Lister-Petter generator runs for only for 3 hours over the course of two days generating a total of 19 kWh.

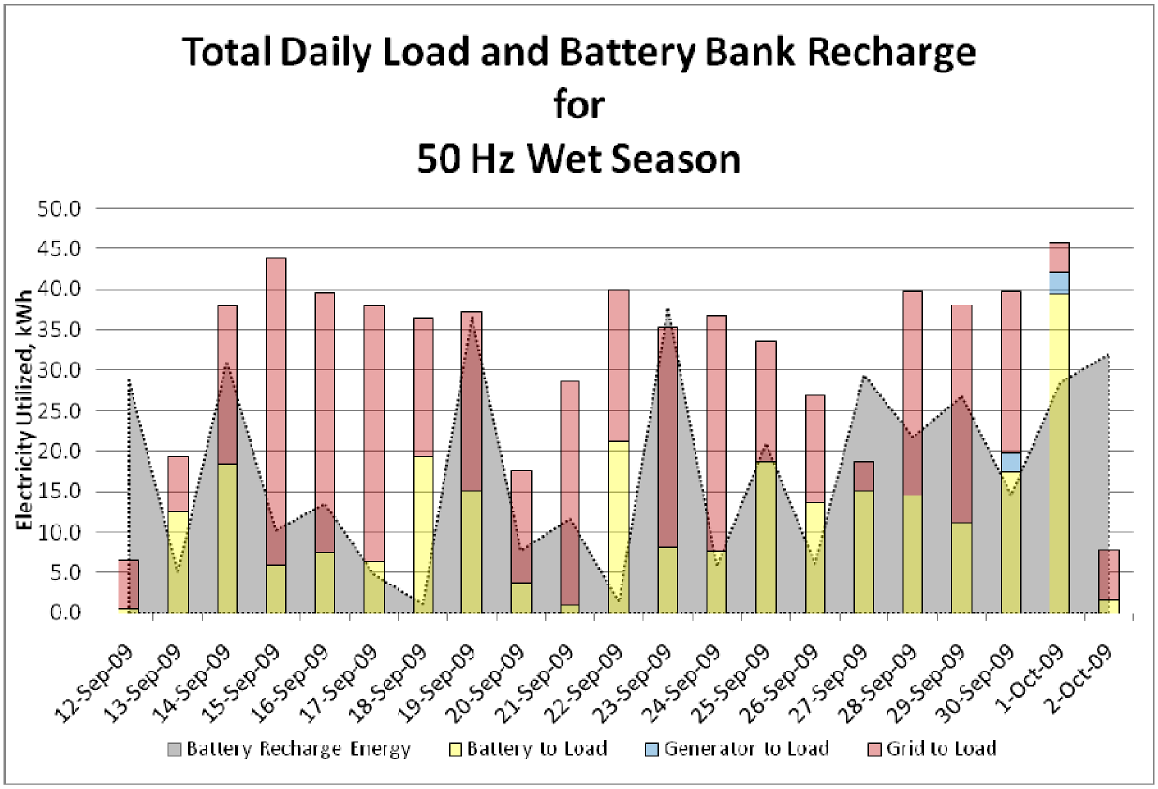

Figure 17: Experimental 50 Hz Wet Season Dataset Electricity Demand

In general, the diesel generator runs more efficiently in the "Diesel/Bat/Grid" case than in the baseline case, 31.1 percent versus 19.6 percent in the Wet Season and 30.6 percent versus 29.3 percent in the Dry Season, but the inefficiencies introduced by the battery bank negated the those efficiency gains. For both datasets, the "Well-to-Electrons" efficiency of the 50 Hz hybrid system is around 27 percent.

The Operational Cost during the logged datasets was US$0.77 in the Dry Season and US$0.40 in the Wet Season resulting in an annual average of US$0.58. When one compares the experimental average Operating Cost with HOMER's predicted annual Operational Cost shown in Figure 18, one can see HOMER underestimates the annual Operational Cost of US$0.05, or 11 percent.

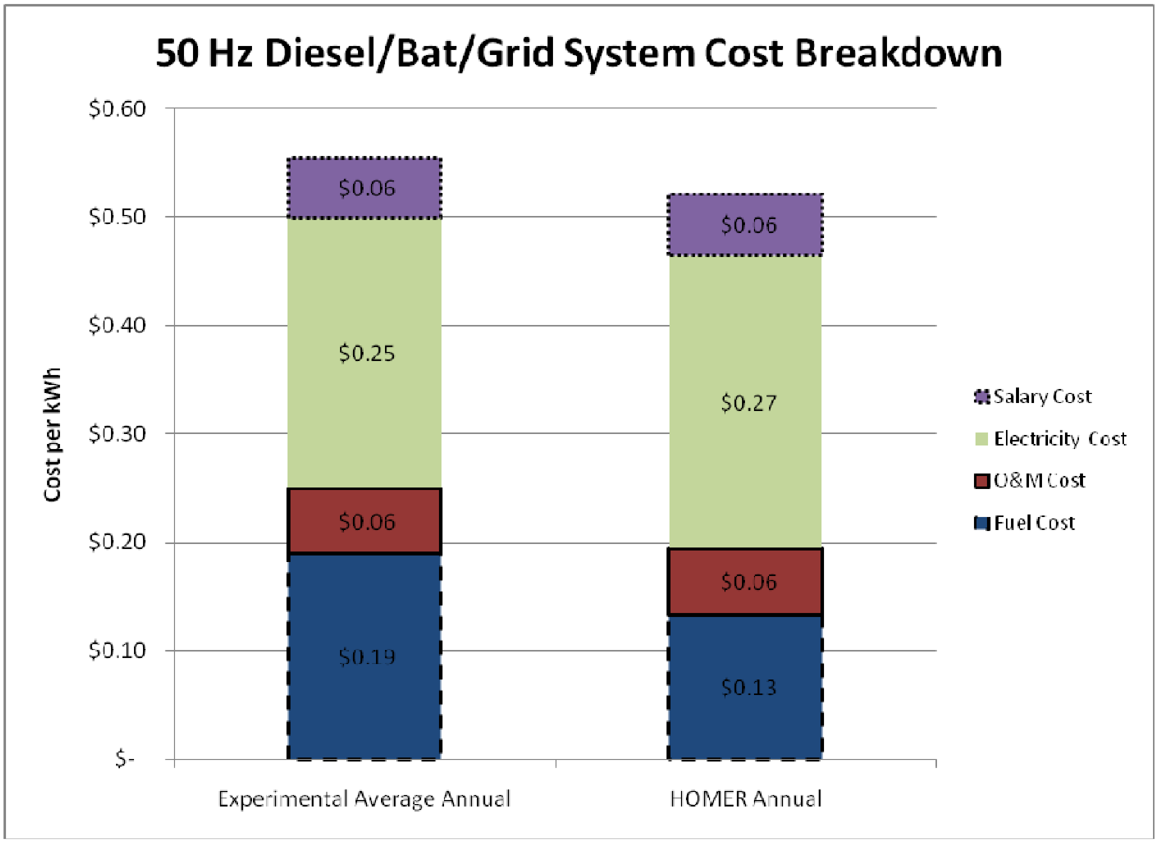

Figure 18: A Comparison of Experimental and Predicted Operational Costs for 50 Hz "Diesel/Bat/Grid" System

60 Hz Baseline System Predictions and Performance

A diesel-only baseline system is generated from the 60 Hz experimental data similar to how a baseline is generated for the 50 Hz system. The annual load is 2,285 kWh all of which is supplied by the Cummin's generator. HOMER predicts that the generator runs 8,759 hours and burns a total 1,712 liters of diesel fuel in a year. Hybrid2 predicts slightly fewer liters of fuel consumed, 1,697 a year. Table 17 shows how the baseline setup is very inefficient at generating power for the 60 Hz system: 9.5 percent for the baseline rather than 19.6 percent for the hybrid system. The capital cost of the 60

Hz baseline system is low, $39,800, but the ultimate NPV is even higher than the 50 Hz system, $312,000. Obviously, running the diesel generator continuously to fulfill the small instantaneous 60 Hz loads is a not an ideal way of providing 24 hour power. Both Hybrid2 and HOMER predict the annual Operational Cost for the 60 Hz baseline system to be to US$5.15 and US$5.22 per kWh, respectively. The average annual experimental Operational Cost is US$5.66 per kWh. These values can be reviewed in Figure 19.

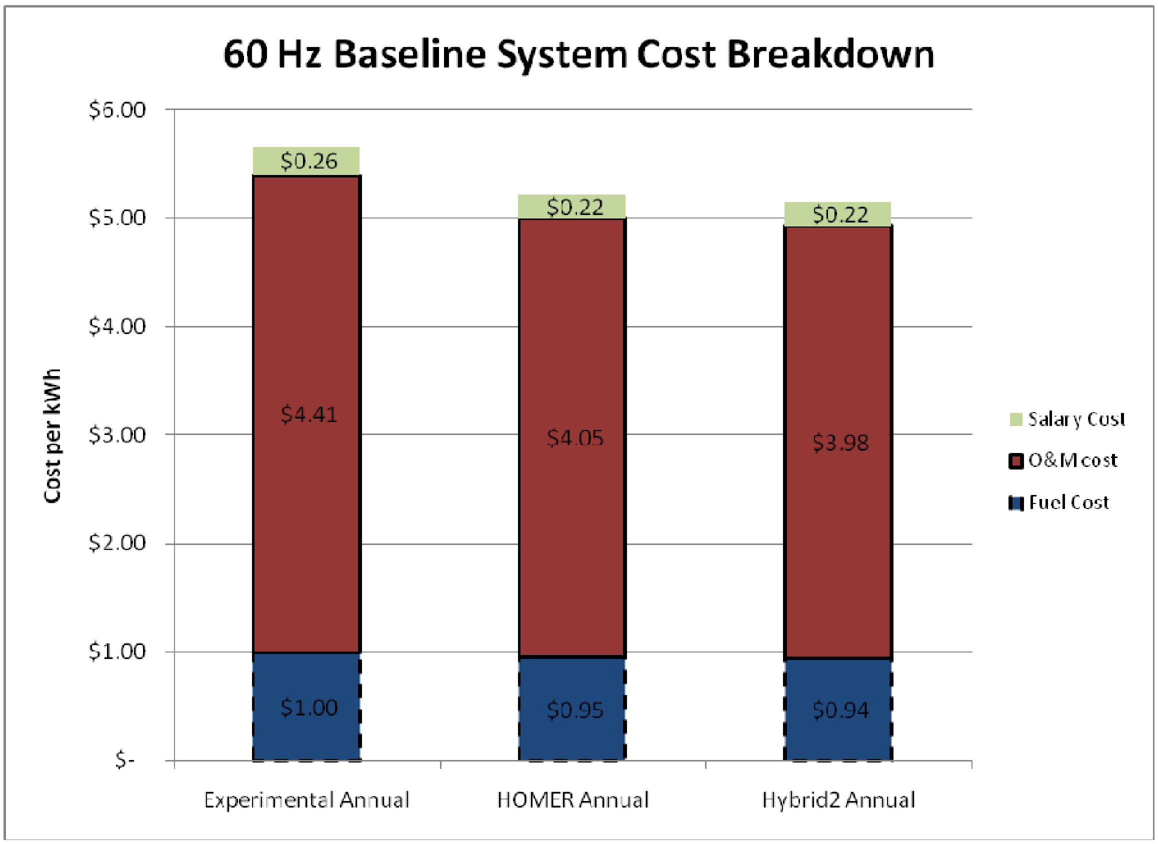

Figure 19: A Comparison of Experimental and Predicted Operational Costs for 60 Hz baseline System

60 Hz "Diesel/Bat" System Predictions and Performance

Analysis of the 60 Hz system allows a direct comparison between the outputs of both Hybrid2 and HOMER due to the fact that this system is not connected to the local grid. HOMER and Hybrid2 may be run using the same load input data, but they might not conclude the same system performance and Operational Cost. In the Wet Season, Hybrid2 predicts that the generator works both harder and longer (215 kWh generated while running a total of 43 hours) than what HOMER predicts (193 kWh in 36 hours). During the Dry Season, the results of the two programs predict similar generator outputs. The HOMER simulation requires the generator to produce 118 kWh in 30 hours, while Hybrid2 anticipates the generator to produce 117 kWh in 28 hours. These generation rates and runtimes are to cover loads of 138 kWh and 78 kWh for the Wet Season and the Dry Season respectively. These results are shown in Table 16.

Even though the 60 Hz Wet Season load is larger than the Dry Season load, it is important to realize that the 60 Hz Wet Season timeframe is shorter than the other datasets. The 50 Hz datasets and the 60 Hz Dry Season dataset are 21 days long, but the 60 Hz Wet Season is the only dataset that is 15 days long. When comparing the results shown in Table 16 care must be taken to realize that the Wet Season dataset is actually 29 percent smaller than the other sets despite the larger load. One can infer that the average load during the Wet Season is much larger than the average Dry Season load.

Table 17 shows the efficiencies of various components in the 60 Hz system. The two programs show similar efficiencies for the generator, but have different efficiency values for the inverter and battery bank as a result of Hybrid2's more detailed approach to their modeling. HOMER uses values input by the user that are assumed to be constant with the battery bank power throughput. Hybrid2 does not make the same assumption, but instead models the losses in the inverter to linearly increase with inverter throughput. When calculating battery losses, Hybrid2 attempts to calculate a theoretical resting voltage based on the battery bank's State of Charge (SoC) and then calculates losses based on the difference between the terminal voltage and the resting voltage. In HOMER's component library the Rolls/Surrette 4KS25PS batteries used for the Mercy Hospital system have a roundtrip battery charging efficiency of 80 percent. Hybrid2's loss calculations reveal that the battery bank average annual roundtrip efficiency is 88.8 percent. An inverter charging and discharging efficiency of 91 percent was input into HOMER based on preliminary experimental data that supported this value. Hybrid2 calculates the inverter's annual average charging efficiency to be 90.8 percent efficient when charging the battery bank and 86.3 percent efficient when discharging the battery bank. Ultimately, HOMER predicts a slightly higher total "Well-to-Elections" efficiency than Hybrid2, 19.3 percent versus 17.9 percent. In either case the "Well-to-Electrons" efficiency of the 60 Hz system is much lower than the 50 Hz system.

The decision to install the 13.6 kW Cummins generator rather than the smaller 9.1 kW generator was based on the desire to cover the maximum load rating of the inverter should it ever be required. The fact that the 13.6 kW generator is larger than the generator size recommended by the 60 Hz Optimization study does not necessarily mean that HOMER or Hybrid2 will predict larger Operational Costs for the 60 Hz "Diesel/Bat" system. This is because in the two programs both generators have identical fuel consumption curves, and so will burn the identical amount of fuel for a given load. The two generators differ in their capital cost, replacement cost, and capacity. Figure 22 shows the predicted Operational Cost for the 60 Hz "Diesel/Bat" system using HOMER and Hybrid2. HOMER predicts an annual Operational Cost of US$1.18, and Hybrid2 predicts an annual Operational Cost of US$1.28.

The Dry Season data corresponds to the period just after the system was installed, before many users were using the 60 Hz lab equipment. The Wet Season database was recorded 6 months after the Dry Season dataset when the system had more equipment to power. The inverters were also set up with slightly different setpoints between datasets so it was necessary to create separate models for the Wet and Dry Season in both HOMER and Hybrid2. Unlike the 50 Hz system, the 60 Hz system is always operating 24 hours a day. The generator typically runs heavily for one day and then the system runs off batteries for one or more additional days depending on the load. In addition to increasing the efficiency and decreasing the run time of the generator, adding the battery bank has another advantage that is not modeled in either HOMER or Hybrid2: running a diesel generator at less than 30 percent load can prevent the engine from reaching its designed operating temperature resulting in accelerated wear, reduced generator performance, and increased unburned hydrocarbon emission.

The total electricity demand during the Dry Season for the 60 Hz is 79 kWh, or 3.8 kWh per day. The Cummins generator ran 26.6 hours over the course of 21 days and produced 114.1 kWh of electricity to cover the lab's 60 Hz demand. These values can be compared with the predicted HOMER and Hybrid2 values in Table 16. The inverter efficiency during the Dry Season is 92.2 percent while charging the battery bank and 87.4 when discharging the battery bank. The battery bank roundtrip efficiency is calculated to be 83.0 percent. The “Well-to-Electrons” efficiency is 21.0 percent. These values can be compared with others in Table 17. Figure 20 shows the daily demand for each day in the dataset and also clearly shows the frequency with which the generator operated to maintain the battery bank’s charge. Unlike the 50 Hz system, the 60 Hz demand does not vary much with the day of the week because the majority of loads on the 60 Hz system are loads that never shutdown, such as computers and network equipment.

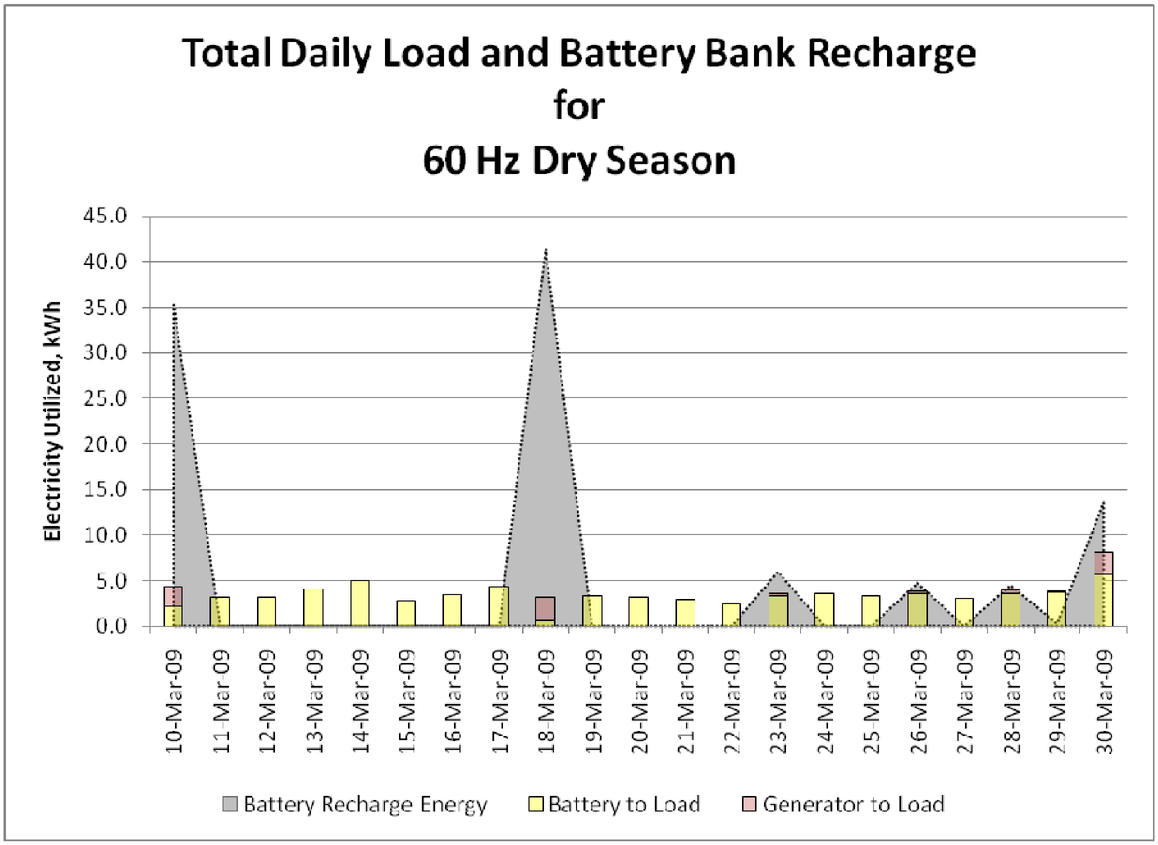

Figure 20: Experimental 60 Hz Dry Season Dataset Electricity Demand

Table 16 shows that more kWh’s are consumed in the Wet Season dataset than in the Dry Season Dataset. This is because of the addition of more equipment, such as cold chain refrigerators and freezers, to the 60 Hz circuits. The total energy generated by the system is 137.7 kWh, or 9.2 kWh per day. This is an increase in load of 142 percent in 6 months. The generator operated a total of 48 hours during the 15 days of this dataset.

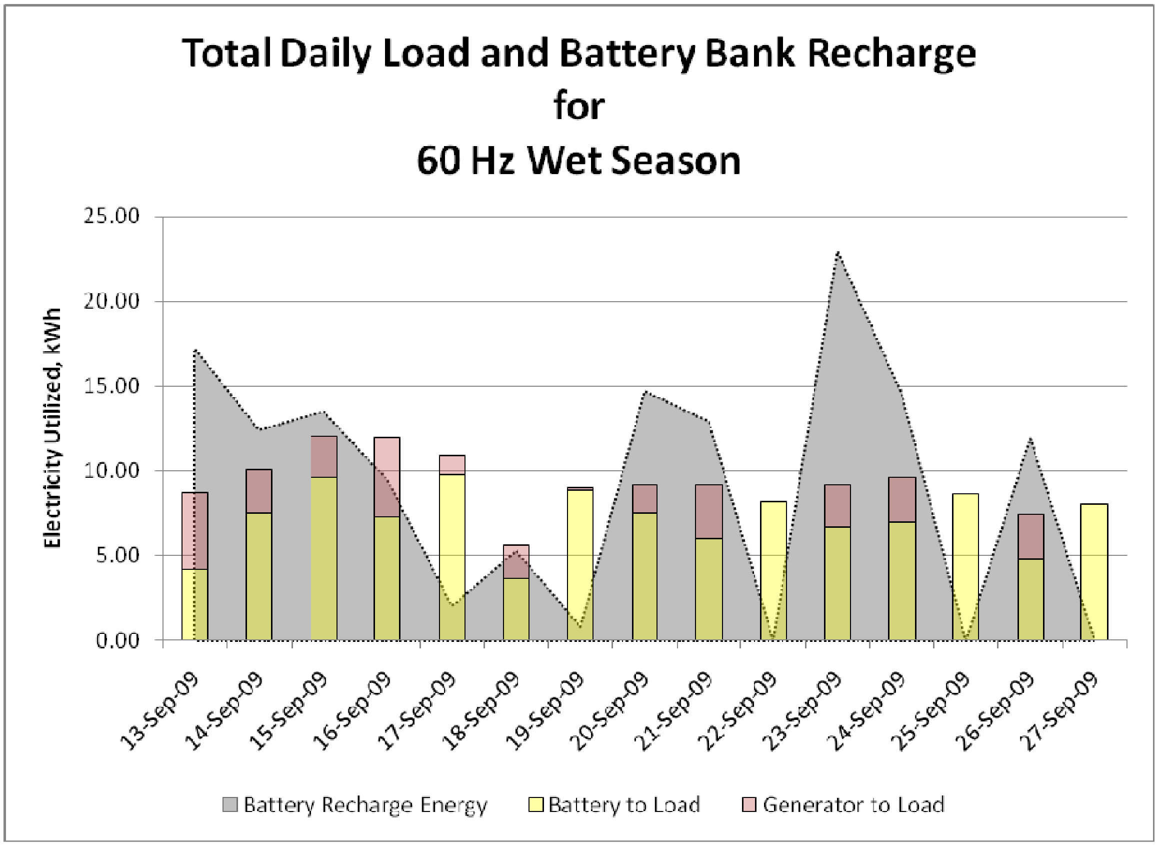

Figure 21: Experimental 60 Hz Wet Season Dataset Electricity Demand

As a result of the larger instantaneous power demands during the Wet Season dataset, the baseline system operated with a higher efficiency, 16.3 percent, than during the Dry Season. The hybrid system still operates with a higher "Well-to-Electrons" efficiency: 18 percent. The inverter is 88.3 percent efficient when charging the battery bank and 93.6 percent efficient when discharging the battery bank. These values can be reviewed in Table 17. According to the corrected data, the roundtrip efficiency of the battery bank is 94.6 percent efficient, but this number is significantly higher than the efficiency of the batteries calculated 6 months earlier and the batteries operating in the 50

Hz system. In addition, verbal conversations with the battery manufacturers suggested that the maximum efficiency battery bank is 87 percent.

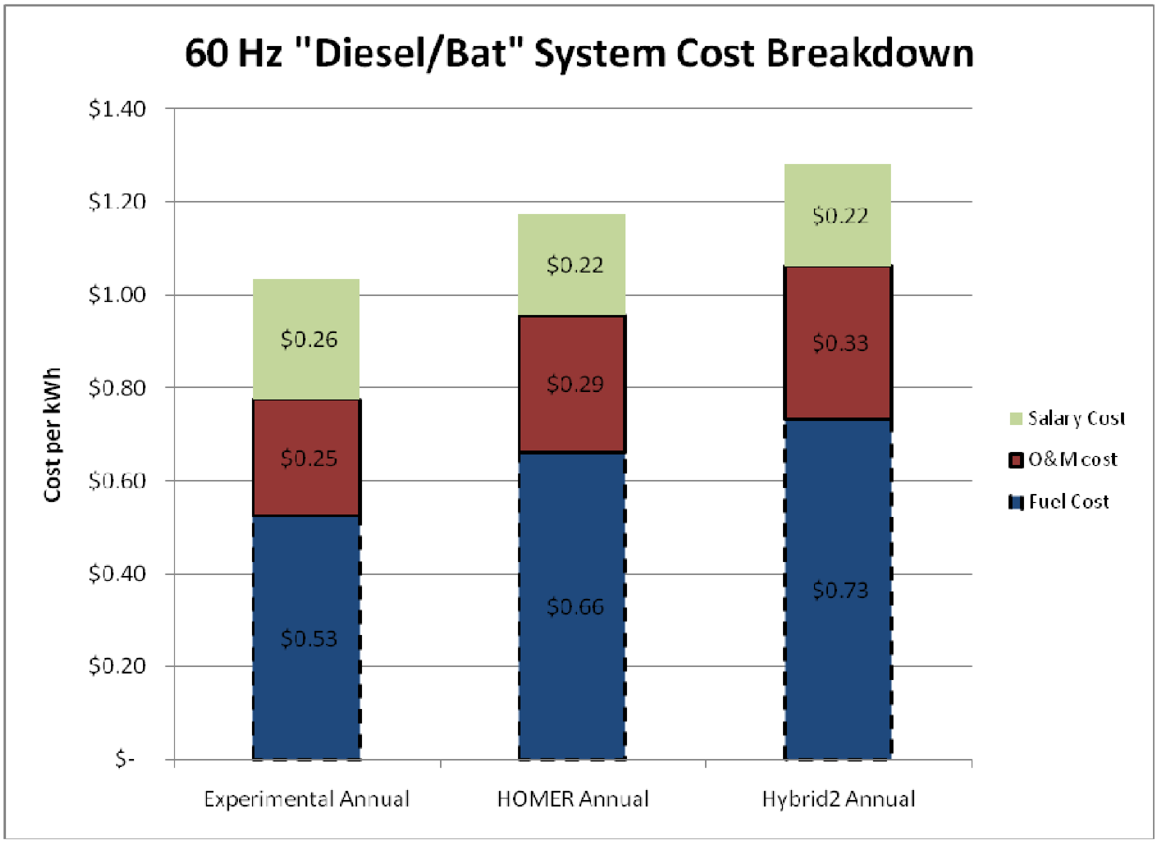

Figure 22: A Comparison of Experimental and Predicted Operational Costs for 60 Hz "Diesel/Bat" System

The Operational Cost for the 60 Hz system is larger than that of the 50 Hz system because the former produces significantly less electricity. Figure 22 shows how the hybrid system drastically decreases the per kWh cost of the 60 Hz system largely though reductions in O&M costs and to a smaller extent fuel charges. The estimated annual experimental Operational Cost is US$1.04.

Table 16: Installation Results Energy Table

System	Season	Dataset	Program	AC Primary Load	Grid Electricity	Generator Production	Diesel Consumption	Generator Operation
				kWh	kWh	kWh	L	hrs
60 Hz	Wet	Baseline	HOMER	138	-	138	85.2	360
			Hybrid2	138	-	138	85.2	360
			Experimental	138	-	138	86.1	349
		Diesel/Bat	HOMER	138	-	193	69.5	36.0
			Hybrid2	138	-	215	78.0	43.0
			Experimental	138	-	168	78.1	48.5
	Dry	Baseline	HOMER	78.3	-	80.4	80.7	504
			Hybrid2	77.0	-	77.0	78.7	496
			Experimental	79.0	-	79.0	87.0	496
		Diesel/Bat	HOMER	78.3	-	118	43.5	30.0
			Hybrid2	77.0	-	117	44.6	28.0
			Experimental	79.0	-	114	39.3	26.6
	Annual	Baseline	HOMER	2,290	-	2,310	1,710	8,760
			Hybrid2	2,280	-	2,280	1,700	8,690
			Experimental	[redacted]				
		Diesel/Bat	HOMER	2,290	-	3,280	1,190	673
			Hybrid2	2,280	-	3,580	1,315	756
			Experimental	[redacted]				
50 Hz	Wet	Baseline	HOMER	584	-	584	268	481
			Experimental	667	-	667	292	475
		Diesel/Bat/Grid	HOMER	585	751	18.9	6.78	6.00
			Experimental	667	764	18.9	6.20	3.07
	Dry	Baseline	HOMER	446	-	446	182	252
			Experimental	434	-	434	157	189
		Diesel/Bat/Grid	HOMER	463	559	-	-	-
			Experimental	434	240	264	88.3	51.2
	Annual	Baseline	HOMER	8,610	-	8,610	3,860	6,580
			Experimental	[redacted]				
		Diesel/Bat/Grid	HOMER	8,760	8,179	2,770	924	530
			Experimental	[redacted]				

Table 17: Installation Results Efficiency Table

System	Season	Dataset	Program	Generator Efficiency	Bat. Round Trip Efficiency	Inverter Efficiency		Well-to-Electrons Efficiency
						Charge	Discharge	
60 Hz	Wet	Baseline	HOMER	16.6%				16.6%
			Hybrid2	16.6%				16.6%
			Experimental	16.3%				16.3%
		Diesel/Bat	HOMER	28.3%	80.0%	91.0%	91.0%	19.5%
			Hybrid2	28.3%	88.9%	90.9%	88.1%	18.6%
			Experimental	22.0%	94.6%	88.3%	93.6%	18.0%
	Dry	Baseline	HOMER	10.2%				10.2%
			Hybrid2	10.0%				10.0%
			Experimental	9.3%				9.3%
		Diesel/Bat	HOMER	27.8%	80.0%	91.0%	91.0%	18.8%
			Hybrid2	26.8%	88.3%	90.8%	83.4%	16.5%
			Experimental	29.6%	83.0%	92.2%	87.4%	21.0%
	Annual	Baseline	HOMER	13.7%				13.7%
			Hybrid2	13.7%				13.7%
			Experimental					
		Diesel/Bat	HOMER	28.2%	80.0%	91.0%	91.0%	19.3%
			Hybrid2	27.8%	88.8%	90.8%	86.3%	17.9%
			Experimental					
50 Hz	Wet	Baseline	HOMER	22.2%				22.2%
			Experimental	23.3%				23.3%
		Diesel/Bat/Grid	HOMER	28.5%	80.0%	91.0%	91.0%	21.6%
			Experimental	31.1%	80.7%	90.8%	94.2%	26.7%
	Dry	Baseline	HOMER	25.0%				25.0%
			Experimental	28.3%				28.3%
		Diesel/Bat/Grid	HOMER		80.0%	91.0%	91.0%	
			Experimental	30.6%	85.8%	92.4%	92.9%	26.9%
	Annual	Baseline	HOMER	22.8%				22.8%
			Experimental					
		Diesel/Bat/Grid	HOMER	30.6%	80.0%	91.0%	91.0%	22.4%
			Experimental					

Table 18: Installation Results Finance Table

System	Season	Dataset	Program	NPV	Initial Cost	Replacement Cost	Fuel cost	O&M Cost	COE	Operation Cost
				$	$	$	$/yr or $/dataset	$/yr or $/dataset	$/Wh	$/kWh
60 Hz	Wet	Baseline	HOMER	[redacted]	[redacted]	[redacted]	$ 108	$ 360	[redacted]	$ 3.39
			Hybrid2	[redacted]	[redacted]	[redacted]	$ 108	$ 389	[redacted]	$ 3.60
			Experimental	[redacted]	[redacted]	[redacted]	$ 81	$ 370	[redacted]	$ 3.27
		Diesel/Bat	HOMER	[redacted]	[redacted]	[redacted]	$ 88	$ 57	[redacted]	$ 1.05
			Hybrid2	[redacted]	[redacted]	[redacted]	$ 99	$ 72	[redacted]	$ 1.24
			Experimental	[redacted]	[redacted]	[redacted]	$ 51	$ 49	[redacted]	$ 0.72
	Dry	Baseline	HOMER	[redacted]	[redacted]	[redacted]	$ 103	$ 504	[redacted]	$ 7.78
			Hybrid2	[redacted]	[redacted]	[redacted]	$ 100	$ 525	[redacted]	$ 8.12
			Experimental	[redacted]	[redacted]	[redacted]	$ 110	$ 524	[redacted]	$ 8.03
		Diesel/Bat	HOMER	[redacted]	[redacted]	[redacted]	$ 55	$ 59	[redacted]	$ 1.46
			Hybrid2	[redacted]	[redacted]	[redacted]	$ 57	$ 57	[redacted]	$ 1.48
			Experimental	[redacted]	[redacted]	[redacted]	$ 54	$ 57	[redacted]	$ 1.40
	Annual	Baseline	HOMER	$ 312,879			$ 2,175	$ 9,259	$ 9.13	$ 5.00
			Hybrid2	$ 311,559	$ 39,770	$ 101,600	$ 2,155	$ 9,191	$ 9.11	$ 4.97
			Experimental	[redacted]			[redacted]	[redacted]	[redacted]	$ 5.65
		Diesel/Bat	HOMER	$ 119,686			$ 1,512	$ 1,173	$ 3.49	$ 1.18
			Hybrid2	$ 123,299	$ 59,594	$ 19,824	$ 1,669	$ 1,256	$ 3.60	$ 1.28
			Experimental	[redacted]			[redacted]	[redacted]	[redacted]	$ 1.06
50 Hz	Wet	Baseline	HOMER	[redacted]	[redacted]	[redacted]	$ 341	$ 510	[redacted]	$ 1.46
			Experimental	[redacted]	[redacted]	[redacted]	$ 371	$ 504	[redacted]	$ 1.31
		Diesel/Bat/Grid	HOMER	[redacted]	[redacted]	[redacted]	$ 205	$ 48	[redacted]	$ 0.43
			Experimental	[redacted]	[redacted]	[redacted]	$ 224	$ 45	[redacted]	$ 0.40
	Dry	Baseline	HOMER	[redacted]	[redacted]	[redacted]	$ 231	$ 281	[redacted]	$ 1.15
			Experimental	[redacted]	[redacted]	[redacted]	$ 199	$ 218	[redacted]	$ 0.96
		Diesel/Bat/Grid	HOMER	[redacted]	[redacted]	[redacted]	$ 146	$ 42	[redacted]	$ 0.41
			Experimental	[redacted]	[redacted]	[redacted]	$ 239	$ 93	[redacted]	$ 0.77
	Annual	Baseline	HOMER	$ 269,595	$ -	$ 90,000	$ 4,898	$ 7,075	$ 2.09	$ 1.39
			Experimental	[redacted]			[redacted]	[redacted]	[redacted]	$ 1.14
		Diesel/Bat/Grid	HOMER	$ 133,192	$ 45,175	$ 18,924	$ 3,317	$ 1,290	$ 1.01	$ 0.53
			Experimental	[redacted]			[redacted]	[redacted]	[redacted]	$ 0.58

Discussion

The two main goals of this thesis are to conduct a design optimization coupled with experimental validation and use the validating data and models to predict the savings associated with converting Mercy Hospital to a solar diesel hybrid system. To support these two aims this thesis has five goals:

1. Evaluate the accuracy of HOMER and Hybrid2's ability to predict the experimental results observed in **Part 2.**
2. Determine if HOMER or Hybrid2 inaccurately model components within a hybrid system.
3. Provide experimentally derived performance parameters that other system designs can use when modeling systems.
4. Relate the Operational Cost savings converting Mercy Hospital to a hybrid system to the savings other communities can realize when switching to hybrid power.
5. Make recommendations as to which components yield the largest Operational Cost reductions.

These five goals are covered in the four discussion topics that follow. The first topic *Accuracy of HOMER and Hybrid2 and Measurement Error* quantifies the known uncertainty in the Operational Cost, the metric used for calculating the hybrid system savings over a diesel-only baseline, for both systems. Included in the section is also an attempt to explain why the certain predicted HOMER and Hybrid2 results may be outside the boundaries of the experimental data's uncertainty range. The second topic, *Comparison between the 50 Hz and 60 Hz Experimental Data with Literature*, covers the experimental papers mentioned in the *Literature* Review section to provide a reference point with which one can judge if the experimental data recorded in Sierra Leone is valid. This section supports both the first goal, to validate HOMER and Hybrid2, and the third goal to provide experimentally derived parameters for user in future modeling. The third topic *Inverter and Battery Modeling* discusses the observed discrepancy between HOMER and Hybrid2's DC bus loss calculations and those observed experimentally. The *Inverter and Battery Modeling* section also explains the potential consequence of HOMER and Hybrid2's inaccuracies in battery and inverter loss modeling beyond the trivial consequence of wasting money by wasting generated electricity. The fourth discussion topic, *Expected Operational Costs*, uses the Operational Costs observed in models and experimentally to predict the savings that other communities can realize if they switch to hybrid power. If HOMER and Hybrid2 are proven sufficiently accurate, the two software programs are used to fill in gaps in the experimental data used for calculating the successive reductions in Operational Cost as components are added to the transitioning hybrid system; thus the *Expected Operational Costs* section addresses goals 4 and 5 simultaneously. The third goal of providing experimental data for use by designers in future modeling is primarily addressed by the data in Table 16, Table 17, and Table 18. The most useful of which may be Table 17 which provides various experimentally calculated efficiencies of the inverter, battery bank, diesel generator, and system as a whole.

Accuracy of HOMER and Hybrid2 and Measurement Error

Before HOMER and Hybrid2 can support the experimental data in quantifying the reductions in Operational Cost created by the individual components of a PV/Diesel Hybrid system, their accuracy must be established. If the Operational Cost predicted by the software programs do not fall within the uncertainty bounds of the experimental data, then there is either a problem with how the models are formulated or a problem with the models that the programs use. Using the average loads from the Wet and Dry Season datasets and the equations given in the *Uncertainty Analysis* section in **Part 1**, the bounds for the HOMER and experimental Operational Cost are calculated. The symmetrical uncertainty ranges for the HOMER and experimental Operational Cost is given in Table 19.

Table 19: Uncertainty Analysis Results

		HOMER		Experimental	
		Operational Cost	Uncertainty	Operational Cost	Uncertainty
60 Hz Operational Cost	Wet Baseline	$ 3.39	$ 0.04	$ 3.27	$ 1.75
	Wet Hybrid	$ 1.05	$ 0.01	$ 0.72	$ 0.39
	Dry Baseline	$ 7.78	$ 0.05	$ 8.03	$ 2.56
	Dry Hybrid	$ 1.46	$ 0.01	$ 1.40	$ 0.45
50 Hz Operational Cost	Wet Baseline	$ 1.46	$ 0.01	$ 1.31	$ 0.16
	Wet Hybrid	$ 0.43	$ 0.00	$ 0.40	$ 0.05
	Dry Baseline	$ 1.15	$ 0.01	$ 0.96	$ 0.06
	Dry Hybrid	$ 0.41	$ 0.00	$ 0.77	$ 0.04

Figure 23 shows the uncertainty ranges graphed with the addition of the Operational Cost of Hybrid2. While Hybrid2 calculates different Operational Costs than HOMER, the uncertainty for Hybrid2 is the same because both programs use the

HOMER derived synthetic load dataset. Figure 23 shows that the experimental uncertainty on the 60 Hz system is quite high. As a result of the large uncertainty, all the HOMER values are within the expected uncertainty range. All the Hybrid2 values, save the 60 Hz Wet Season Hybrid model, are within the experimental uncertainty as well. The consistently high Hybrid2 Operational Cost is due to the addition of the bi-monthly complete battery recharge dispatch strategy described in *Optimization Results* in **Part 1**. This recharge ensures that the battery bank reaches 100 SoC at least every other week, as recommended by the manufacturer, but as a result Hybrid2 requires the generator to operate longer and consume more fuel than the HOMER model or, apparently, the experimental results.

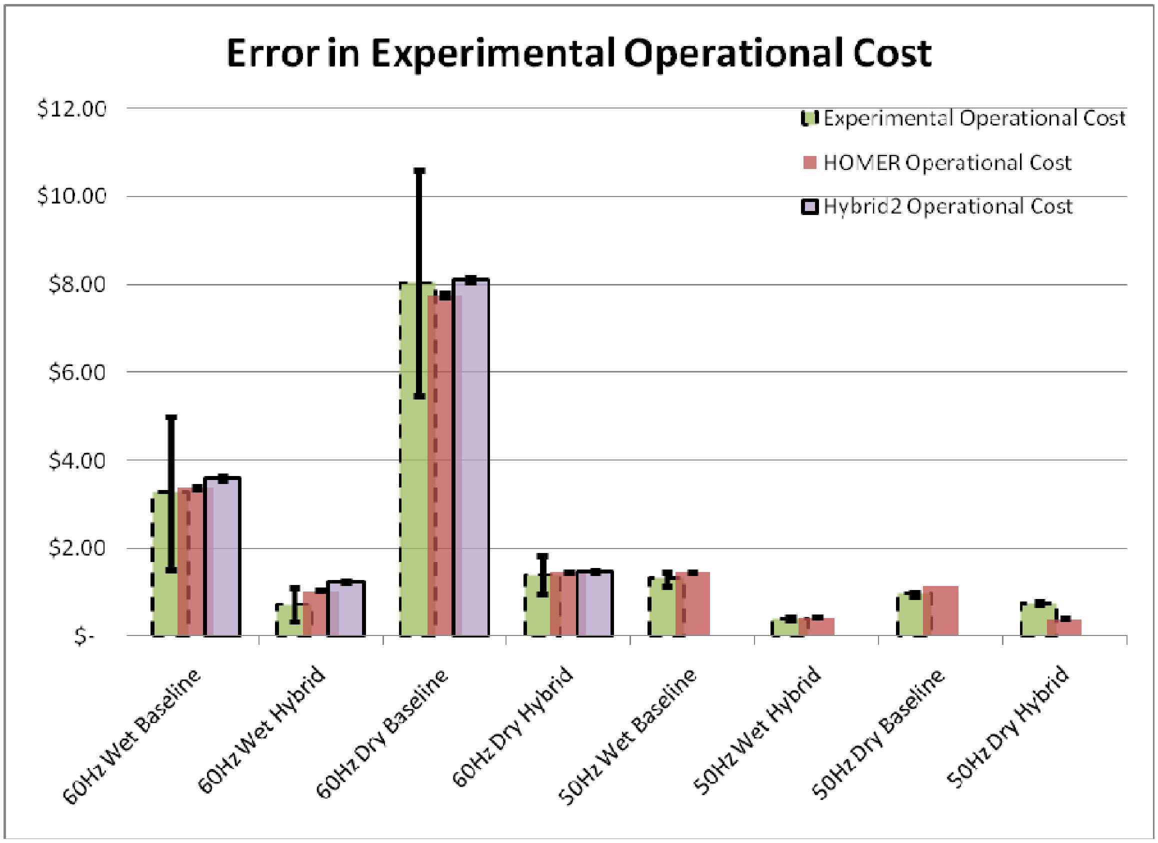

Figure 23: Experimental Measurement Error for Operational Cost

The uncertainty ranges associated with the experimental 50 Hz Operational Costs are much tighter than those associated with the 60 Hz system. While the HOMER Operational Costs for the 50 Hz Wet Season fall within the experimental uncertainty range, the fact that the HOMER values for Dry Season are outside the experimental uncertainty ranges suggests that there is a problem with how the model is set up. One possibility is the way in which grid electricity availability, or lack thereof, is modeled in the HOMER model. In order to mimic the partial availability of BKPS, the model assumes that the electricity is available from 8:00am to 2:00pm in March and from 12:00pm to 6:00pm in September. There is, however, a problem with this method: the availability of BKPS electricity is completely unpredictable. Figure 24 shows the cumulative electricity difference between the HOMER model and the experimental datasets. A positive difference means that the HOMER predicts more electricity is consumed by the system than the experimental data shows. Figure 24 shows that the experimental setup uses 319 kWh less than HOMER's prediction resulting in a higher experimental Operational Cost than predicted by HOMER.

For most datasets and system configurations HOMER's Operational Cost predictions falls within the 95 percent uncertainty bounds of the experimental data suggesting that HOMER is more accurate in predicting Operational Cost than can be measured by the current setup. In the exceptional case of the 50 Hz dry season, our inability to predict the [random] availability of BKPS power means that HOMER over predicts the hybrid system's consumption of BKPS and under predicts the Operational Cost. If HOMER had the ability to input an hourly datalog of when electricity is available, then it would probably be within the 95 percent uncertainty bounds of the 50

Hz Dry Season as well. The Hybrid2 is as accurate as HOMER, but due to a slightly different dispatch strategy that requires a larger fraction of the system's annual electricity to be generated by the Lister-Petter diesel generator, it calculates a slightly higher Operational Cost for all 60 Hz systems in Figure 23. Hybrid2 also predicts higher Operational Cost than HOMER for the 60 Hz Optimum system shown in Figure 12.

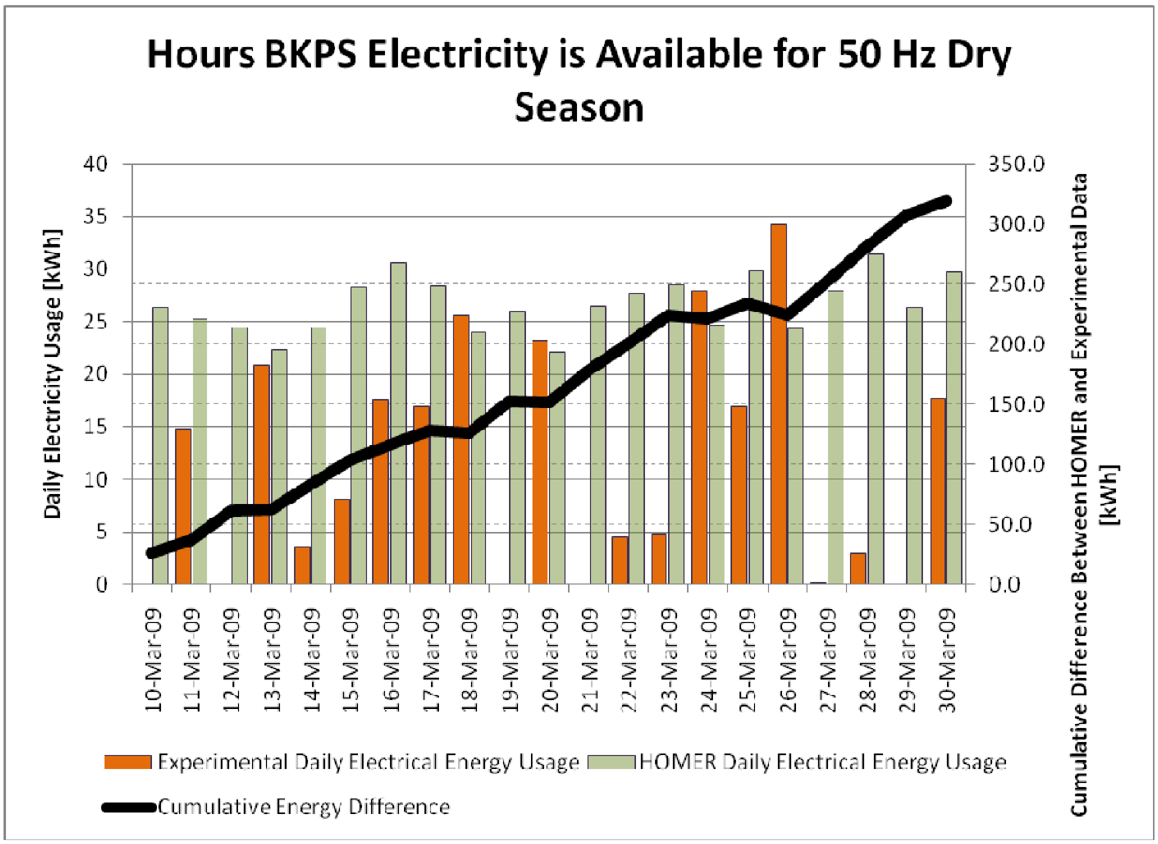

Figure 24: 50 Hz Dry Season Electricity Comparisons

Comparison between the 50 Hz and 60 Hz Experimental Data with Literature

Most of the literature on hybrid power systems is software optimization studies; only a few papers publish the performance of experimental or commercial hybrid systems. The four papers that do include experimental data are written by Ruther [9, 12], Nayar [11], and Phuangpornpitak and Kumar [10]. Ruther reported on the conversion of a diesel-only powered mini-grid in Northern Brazil into a Diesel/PV hybrid system through the addition of a 20.5 kW array. The mini-grid served a small rural community rather than a hospital, so electricity demand the Ruther's hybrid system served was much higher than that at Mercy Hospital; roughly 700 kWh/day compared to 32 kWh/day. Prior to installing the solar array two 54 kW diesel generators ran continuously. Following the solar array installation, the load on the two generators was reduced during the day to the point where one could be shut down saving the operators both fuel costs and maintenance costs. The solar array was designed so that it would produce 10 percent of the daily electricity demand. In a second paper, Ruther does on to estimate the fuel savings resulting from installing this type of hybrid system across Northern Brazil, but he does not provide cost data which can be compared to Mercy Hospital's Operational Cost.

In 1997, Nayar installed hybrid PV/battery/grid systems into two separate sites in India. The components within his hybrid system were: a 2.5 kW_p solar array, a 10 kVA inverter, and a 28.8 kWh battery bank. Nayar stated that the solar array that was installed was able to provide about 40 percent of the load connected to the inverter and the balance was provided by the grid. Nayar's inverter also provided power factor correction for the load. Although Nayar does not mention the system's average load, data within the paper suggests that continuous draws of 2 to 2.6 kW were typical. The value of this paper lies more in its statement of concept rather than data it actually provides; Nayar provides very little data. The main interest is that his hybrid UPS system is similar in size to the optimized hybrid system designed for the hospital. Due to the lack of financial data presented, it is not possible to calculate if Nayar's hybrid system resulted in Operational Cost savings.

Phuangpornpitak and Kumar [10] detailed the technical and financial performance of two hybrid power plants in Thailand: Phu Kradung and Tarutao national parks. Each system incorporated roughly 10-17.5 kW of both solar and wind power generation, and derive roughly 75 percent of their electricity needs from renewable sources. Phuangpornpitak calculated the efficiencies of various components within the both hybrid system, but the only parameter that can be directly compared to data taken at Mercy Hospital is the battery roundtrip efficiency. Phuanpornpitak found that the average battery roundtrip efficiency to be 88.5 percent for both plants. The data collected at Mercy Hospital indicate that the average battery roundtrip efficiency is 86.0 percent. These values are close to the 87 percent roundtrip efficiency value reported by the battery manufacturer. It is Phuanpornpitak's financial analysis of the hybrid systems at Phu Kradung and Tarutao that make the paper extremely useful. Based on system records she stated the capital cost for each system, in 1999 dollars, was US$198,500 and US$201,500 for Phu Kradung and Tarutao respectively. Between 1999 and 2000, the operation and management expenses for each system totaled to roughly US$2,900. Although Phuangpornpitak does not explicitly calculate Operational Costs for the two sites, it is possible to estimate them after assuming a constant average demand. The resulting

Operational Cost estimation is about US$0.22/kWh for both systems. This value is on par with the Operational Cost of US$0.15/kWh expected from the 50 and 60 Hz optimized systems at Mercy Hospital. The savings over a diesel baseline systems obtained by installing hybrid systems at Phu Kradung and Tarutao were calculated to be $1,800 and $3,200 per year. Phuangpornpitak admitted that the system at Phu Kradung had lower savings because of increased diesel generator usage to offset a larger than anticipated average electricity demand. Table 20 compares the systems described in these experimental papers with the system install at Mercy Hospital.

Table 20: Literary Comparison Table

	Renewable Generator	**Backup Generator**	**Average Load**	**Renewable Penetration**	**Capital Cost**	**Annual Savings**
Ruther	20.5kW Solar	2x 54kW diesel	~700 kWh/day	~10 %		
Phu Kradung	7.5kW Solar 2.5kW Wind	42kVA diesel	36 kWh/day	~75 %	$198,500 (1999 US$)	$1,800 (1999 US$)
Tarutao	7.5kW Solar 10kW Wind	48kVA diesel	36 kWh/day	~75 %	$201,500 (1999 US$)	$3,200 (1999 US$)
Nayar	2.5kW Solar	Grid		~ 40 %		
Mercy Hospital 50 Hz	—	12.2kW diesel Grid	20-31 kWh/day	—	$44,700 (2008 US$)	~$3,600 (2008 US$)

Inverter and Battery Modeling

It is important for modeling programs to accurately account for DC bus losses for reasons other than the obvious desire to reclaim energy that was being wasted as heat within inefficient components. In situations where system designers use battery banks for short-term "ride though" capacity while the system transitions from one generational source to another, unexpectedly high losses can severely damage a battery. Lead acid batteries are not designed to be discharge in less than an hour, but designers who are cost sensitive may try to push their battery bank beyond what they are normally designed for. When a system is designed to discharge a battery bank in less than an hour, the batteries are subjected to high rates of discharge and large energy dissipation within the battery itself. Figure 25 shows the percent of energy stored within a Rolls/Surrette 4KS25PS battery that is dissipated into the battery for a given discharge current. Note that if a designer is intending to discharge the 4KS25PS at 450 amps, roughly 75 percent of the battery's stored energy heats up the battery's temperature. If a designer under predicts that the DC bus losses, due to inaccurate modeling, and designs a system that routinely requires large discharge currents available on the DC bus then the current leaving the batteries can be much larger than those predicted by software. The unexpectedly large discharge current can quickly raise the battery above safe operation temperatures and possibly destroy the battery.

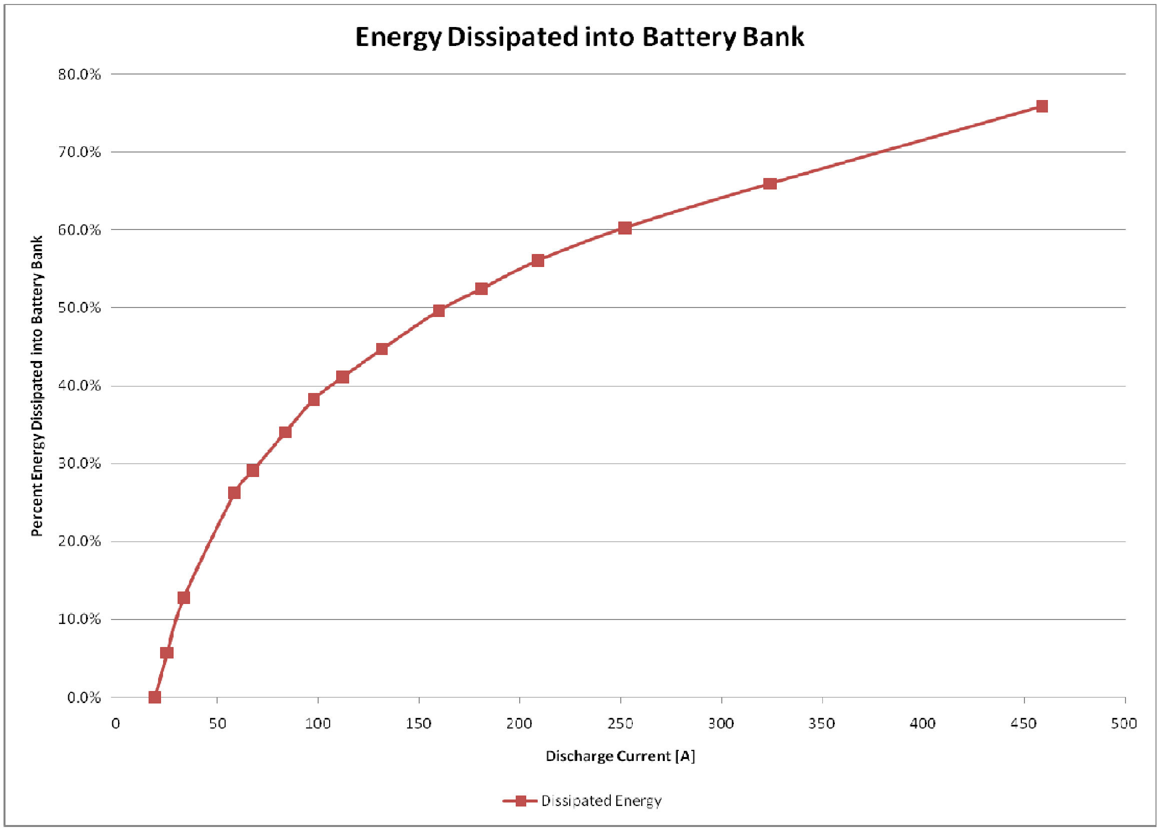

Figure 25: Energy Dissipation into a Rolls 4KS25PS

In order to understand how HOMER and Hybrid2 account for the losses on the DC bus, it is necessary to understand how they model both the inverter and the battery bank. Both programs use the same battery model – the Kinetic Battery Model (KBM) [19-20]. The KBM splits the energy stored in the battery into two categories: available energy and bound energy. Figure 26 shows a diagram of how the KBM separates the total electricity stored in a battery into available and bound energy. Available energy can be released to the DC bus within a timestep, while bound energy must be transformed into available energy before it can be discharged. Three parameters are inputs into the model: Qmax, battery bank's total storage capacity; k which relates the rate at which energy is transferred between energy categories; and c, the ratio of the available energy to the bound energy with the battery.

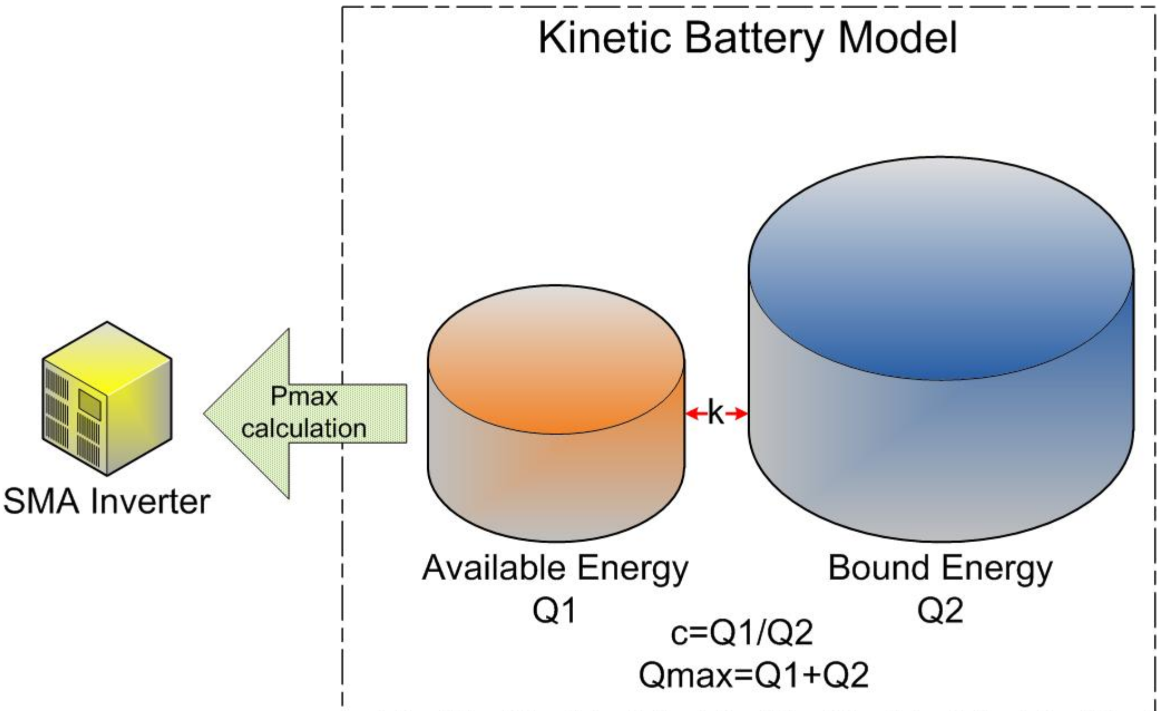

Figure 26: Kinetic Battery Model Diagram

Hybrid2 takes the KBM one step further by calculating the battery terminal voltage (and by extension the DC bus voltage) as a function of SoC and current. It does this by assuming a hypothetical internal cell voltage that is a linear function of the battery bank's SoC. The internal voltage source (E) is connected in series with a constant resistor. If the battery is being discharged the voltage drop in the resistor reduces the terminal voltage (V) to a value below that of the hypothetical cell voltage. A diagram of Hybrid2's model for the battery bank's terminal voltage is given in Figure 27. The theoretical internal voltage calculation is based on work presented by Hyman [21-22] and is dependent on having detailed battery terminal voltage data during charging and discharging.

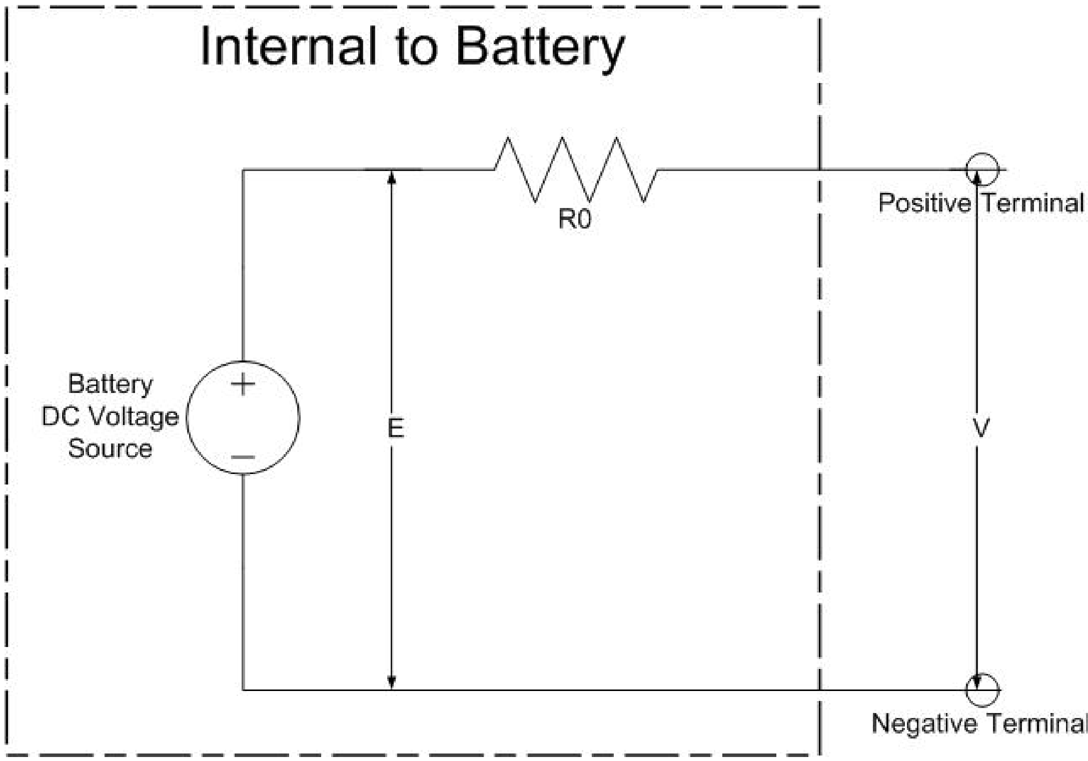

Figure 27: Hybrid2's Terminal Voltage Model Diagram

Due to the different approach to battery bank modeling, the two programs calculate the battery losses differently. HOMER simply assumes that the battery bank's discharge losses are given by:

$$Loss_{discharge,HOMER} = \sqrt{\eta_{B,round}} * V_{nom} * I_{discharge} \qquad \textbf{Equation 18}$$

$\eta_{B,round}$ is HOMER's user inputted value for the battery roundtrip efficiency, V_{nom} is the DC buses nominal voltage, and $I_{discharge}$ is the current removed from the battery in amps. The value for $\eta_{B,round}$ in HOMER is 80 percent for the Rolls/Surrette 4KS25PS. Hybrid2 calculates the losses associated with discharging the battery by:

$$Loss_{discharge,Hybrid2} = (E - V) * I_{discharge} \qquad \textbf{Equation 19}$$

E is the hypothetical internal cell voltage and V is the terminal voltage shown in Figure 27, and $I_{discharge}$ is the battery's discharging current in amps.

Both HOMER and Hybrid2 calculate the inverter losses by assuming the inverters are black boxes with an associated loss. HOMER assumes inverter efficiencies are constant and requires the user enter a value. An efficiency value of 91 percent is used for the SMA SI5048 inverter based on calculations from preliminary experimental results. HOMER's constant efficiency leads to a linear increase in losses starting from zero Watts at no load up to a maximum value at 100 percent load. Instead of assuming constant inverter efficiency, Hybrid2 assumes losses in the inverter increase linearly from a constant no load value (25W based on data available from the manufacturers of the SI5048) up to a known maximum when the inverter is fully loaded (again based on manufacturer's data). As can be seen in Figure 28, the losses predicted by Hybrid2 are similar to the losses predicted by HOMER, but neither accurately predicts the actual losses shown in Figure 28. The actual inverter losses graphed in Figure 28 are derived from Figure 29 which is published in SMA's installation and operation manual for the inverter [14]. According to Figure 29, the highest efficiency does not occur at full load, but rather at 20 percent load. The inverter is designed this way to maximize the efficiency for an inverter which spends the majority of its operation at partial load.

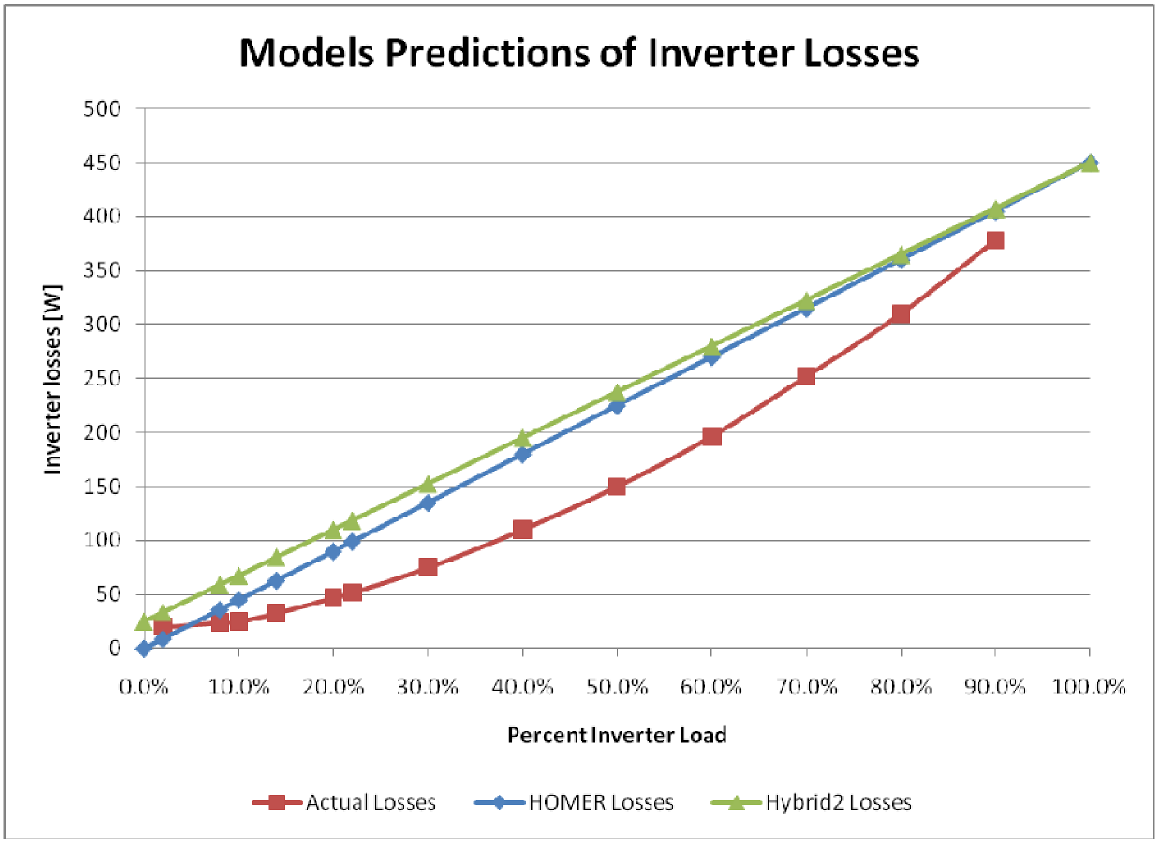

Figure 28: Loss Prediction and Actual losses within the SI5048 inverter

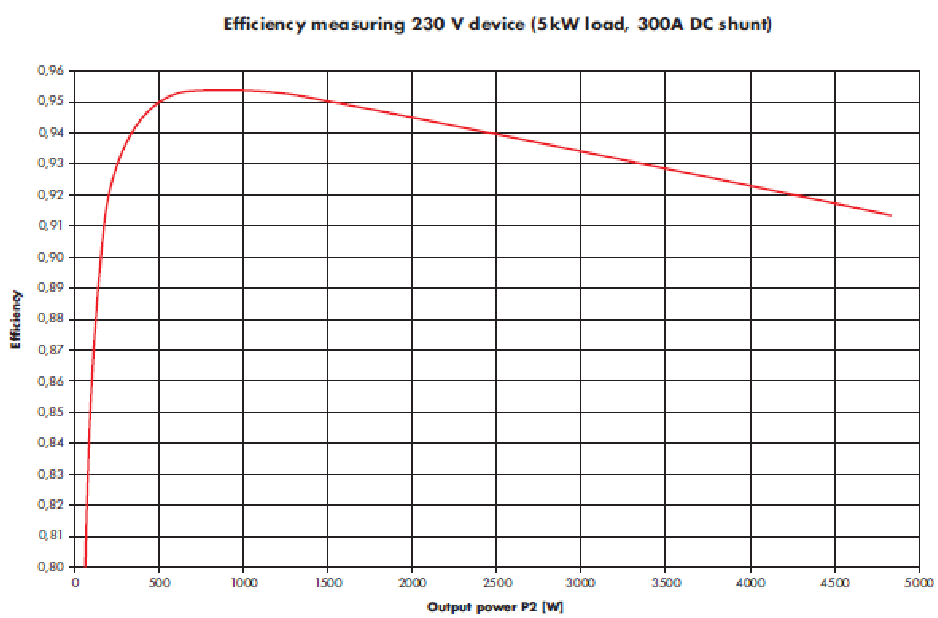

Figure 29: Inverter Efficiency Curve published by SMA Solar Technology AG

Comparison between the efficiency results for HOMER, Hybrid2, and the experimental results in Table 16 show that the average round trip battery efficiency is somewhere between the values used by HOMER and Hybrid2. HOMER assumes a constant round trip battery efficiency of 80 percent and an inverter discharge efficiency of 91 percent. When compared to the experimental data, HOMER always overestimates the losses on the DC bus. When the four experimental datasets are averaged together the battery bank round trip efficiency is to 86.0 percent and an inverter discharge efficiency of 92.0 percent. The Hybrid2 predicts round trip battery efficiencies around 88.7 percent and an average inverter discharge efficiency of 85.8 percent. Hybrid2 is predicting a higher battery roundtrip efficiency than the experimental results, thus is under predicting the losses associated with the battery bank. Closer investigation reveals that the cause of these low efficiencies is excessively low discharge rates, not the excessively high discharge rates that have the potential to damage batteries.

The reason for this over estimation in battery bank round trip efficiency by Hybrid2 may lay in the breakdown of its assumed linear relationship between the theoretical cell voltage and battery bank SoC as the battery bank approaches 100 SoC. Due to differences in the manufacturing process, each cell within the battery bank has a different charge and discharge characteristic. This leads to differences in each cell's SoC when the battery is recharged. Some cells reach 100 percent charge before others. These cells start to dissipate energy in the form of gassing, which is when the water within the sulfuric acid electrolyte begins to be electrolyzed into hydrogen and oxygen. As more and more cells start to gas, the charging efficiency of the battery drops because energy is not going to increase the battery bank's SoC, but in electrolyzing the battery's electrolyte.

Expected Operational Costs

Hybrid systems are able to reduce the high Operational Costs of traditional diesel power plants that have been one of the hurdles to rural electrification. Hybrid systems do this in two ways: generation of electricity using local resources, and intelligent dispatch of electricity to the load. Conventional diesel plants require large quantities of diesel fuel to be transported to the power generation site. Not only is diesel expensive in its own right, but the transportation costs of the fuel to remote areas is a significant expense. Using renewable energy sources like wind, solar, hydro, and biomass to generate electricity, the burden of "fueling" the electricity generation is shifted from distant resources to local ones. The system controller is then able to maximize the benefit of the local generation of energy by ensuring the system utilizes electricity that is generated by the lowest cost source available at any given time.

If the social cost of supporting an electrification project is not explained to the stakeholders who will be in charge of supporting it, the project may fail. These stakeholders can include local and national governments, the community members, local electricity users, and the system installers. While a community may be lucky enough to get continuing subsidization of their electricity from the other project stakeholders, they need to be prepared for supporting the project costs if those subsidies are withdrawn. The main reason behind examining Operational Cost rather than the levelized Cost of Electricity (COE) is the difficulty of quantifying the replacement cost of all the system components, which is required for the calculations of the COE, during the operation of the project. By examining the Operational Cost of a hybrid system with differing configurations and loads, this thesis generates insight into the potential cost of a system to a community.

The experimental data recorded at Mercy Hospital and the models developed to support the design and installation of Mercy Hospital hybrid system can provide insight into the Operational Cost savings that other communities can expect to realize if they switch to hybrid power. This thesis uses data from two hybrid power systems to generate two baseline diesel-only power systems: one providing up to 10 kWh a day and a second providing up to about 30 kWh a day. HOMER and Hybrid2 are also used to model baseline systems with demands up to 70 kWh per day. It is clear from the results in Table 18 that the Operating Costs of remote power plants relying on diesel generators are very costly. The Operational Cost of diesel-derived electricity varied between US$1.14 to US$5.65 per kWh. The later is from the lightly loaded 60 Hz Cummins generator and the former is from the more heavily loaded 50 Hz Lister-Petter generator. Generator loading plays a large factor in the Operational Costs realized by a system. The O&M cost of a diesel generator significantly adds to the cost of diesel-derived electricity because it is accrued whether or not current is flowing through the wires. Compounding the problem is that diesel generators running under light loads are less efficient and so use more fuel to generate each kWh as well. Finally lightly loaded diesel generators may also never reach their designed operating temperature which increases wear within the engine. Generators with low loads are producing fewer kWh's, but are still accruing costs just by running yielding large per kWh costs.

Shutting down diesel generators during parts of the day when they would be running at low loads reduces Operational Cost. One method to do this is to only run the generator during the hours that electricity is most needed. In one of the datasets, the 50 Hz Dry Season dataset, the hospital reduced the diesel generator runtime to only 12 hours a day. This resulted in a US$0.35 drop in the Operational Cost, from US$1.31 to US$0.96 per kWh. That is a 27 percent drop in Operational Cost solely from using load management to shift the load to when it is most economical to run the diesel generator. While restricting generator runtime is a low cost method to reduce Operational Cost, it is possible to reduce Operational Cost further by having the generator charge a battery bank and then turning off to allow low loads to be satisfied by the battery bank. This approach also has the advantage of providing 24 hours power. The 60 Hz system benefited the most from the addition of a battery bank. The Operational Cost dropped from an annual average of roughly US$5.21 per kWh down to US$1.17; a drop of 77 percent. The 50 Hz system already had a lower Operational Cost than the 60 Hz system resulting from the larger loads placed on the 50 Hz generator. Although not experimentally measured, a HOMER model was created to quantify the Operational Cost resulting from adding a battery bank into the 50 Hz baseline system. A hypothetical 50 Hz "Diesel/Bat" system results in an Operational Cost reduction of 35 percent, from US$1.39 down to US$0.91.

After adding a battery bank to create a "Diesel/Bat" system, the natural progression is to add PV solar arrays to create a "Diesel/Bat/PV" system. There is no experimental data for either system in a "Diesel/Bat/PV" configuration, but HOMER and Hybrid2 models are developed to help provide insight. For both the 50 Hz and 60 Hz systems a 0.85 kW_p solar array is added. The fuel reduction realized by adding a PV array depends on the PV penetration of the system. PV penetration is the total annual solar output divided by the total annual electricity demand. For the 60 Hz system the PV penetration for a 0.85 kW_p array is 48 percent. For the 50 Hz system, with the larger load, the PV penetration for the same array is only 10.6 percent. The percentage savings in Operational Cost due to offset fuel costs cannot be larger than these values. The addition of the solar array results in 33 percent drop in Operational Cost for the 60 Hz system, from US$1.17 to US$0.82 per kWh, and a 9 percent drop for the 50 Hz system, from US$0.91 to US$0.83 per kWh.

The 50 Hz system grid connection allows for the examination of how being attached to a grid can reduce Operational Costs. It is expected that access to a grid, even an unpredictable grid, has the potential to drastically reduce system Operational Costs provided that the kWh price of grid power is substantially lower than that of the diesel generator. Experimental data on the 50 Hz system is from the “Diesel/Bat/Grid” configuration. This yielded an average calculated Operational Cost of US$0.55 which is a 39 percent reduction from the Operational Cost of the 50 Hz “Diesel/Bat” configuration. A HOMER model for a hypothetical 60 Hz “Diesel/Bat/Grid” configuration yielded a similar reduction in the Operational Cost, 46 percent, when compared to a “Diesel/Bat” configuration.

The lowest possible Operational Cost that the 50 and 60 Hz systems can obtain are given by the optimum system configuration found in **Part 1** of this thesis. Table 7 states the Operational Costs for both the 50 Hz and 60 Hz optimal configurations are US$0.15 and US$0.16. These both represent Operational Cost reductions of 82 and 81 percent over the “Diesel/Bat/PV” system for both the 60 of 50 Hz systems. There are two main reasons for these reductions: 1) the optimal configurations have higher loads such that time dependent costs (e.g. salary, meter rental charges, and generator O&M

costs) are spread over a larger demand resulting in lower per kWh costs and 2) the PV penetration for both optimal systems approach 100 percent. Figure 30 shows the average HOMER, Hybrid2, and experimentally derived Operational Costs of the systems discussed in this section. The percentage reductions created by adding each component into the 50 or 60 Hz systems are given in Figure 31.

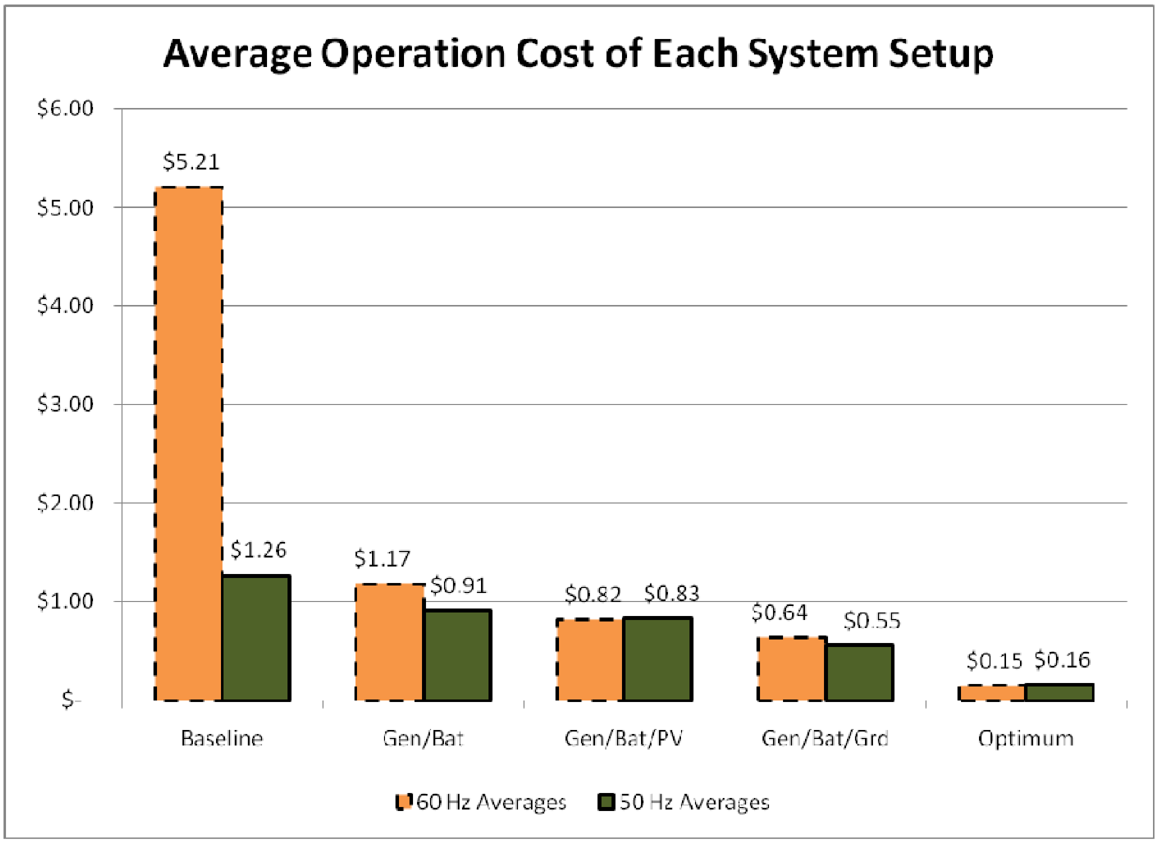

Figure 30: Savings of Additional Hybrid System Components

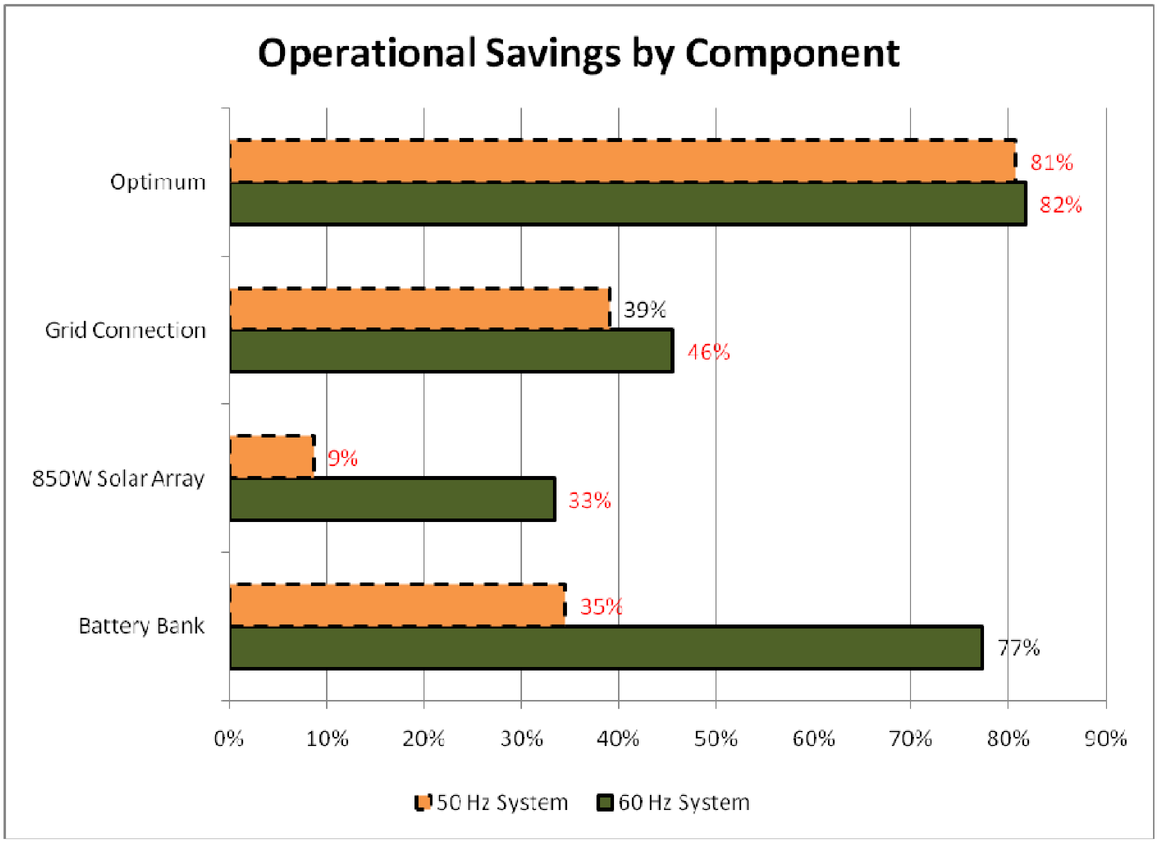

Figure 31: Percentage Reduction of Operational Cost by Component

If a designer wishes to covert a diesel-only system into a hybrid power system in stages, they have a decision to make in regards to the order in which components are added to the re-designed power system. Most likely, the systems users are eager to realize the largest Operational Cost savings as fast as possible. The major conversion decision hinges around should PV or battery be added to a system first. A secondary conversion decision is whether to incorporate unreliable or unregulated grid power if it is available to a hybrid system. The purpose of a battery bank is to correct for a temporal mismatch between electricity generation and electricity demand. This makes battery banks superfluous for sources of energy that have relatively low O&M costs and can be continuously run at a required power level. Neither PV nor diesel generators fall under these two categories, so they greatly benefit from having a batter bank. In addition, Ruther mentions in his paper that grids will become unstable in a PV array with a PV penetration of greater than 10 percent is added without a battery bank [9]. Momentary fluctuations in solar radiation on the solar array occur too quickly for the diesel generator to compensate for and the grid voltage and frequency will fluctuate as more or less power is generated on the AC bus. The ultimate effect of adding a battery bank is to reduce the overall O&M cost of a generation system. As opposed to a battery bank, a PV array directly offsets the energy that needs to be generated thereby reducing the fuel costs of a system. However, in order to take advantage of the electricity generated by the PV array the electricity demand must overlap with the array's generation when the sun is out. When transitioning a system from a diesel generator to a PV/Diesel hybrid system, it is usually recommended to add a battery bank before the PV array unless the system fuel costs are high in relation to the O&M costs and the solar array is planned to have a penetration of less than 10 percent.

The inclusion of grid power into the hybrid power system depends on several factors; some of which are hard to explicitly quantify in terms of Operational Cost (e.g. spontaneous loss of power or poorly regulated voltage.) The cost of protecting the system from voltage surges and unregulated power from a utility company can be significant. The cost to protect the 50 Hz system from poorly regulated BKPS power was approximately US$8,300 not including replacement parts. The per kWh price of the utility power is usually lower than the Operational Costs calculated for the "Diesel/Bat" or "Diesel/Bat/PV" systems in Figure 30, so inclusion of grid power into a hybrid system is usually recommended provided that the system design and maintenance technician are knowledgeable about the local requirements and the additional design complexity associated with a grid-tied hybrid system.

Conclusion

Designing a hybrid power system is a complicated systems engineering problem. A hybrid system is comprised of multiple technologies each mature in their own right, but it is their combination that allows for significant reduction in the cost of electricity to communities currently far from the grid. In most cases, hybrid power systems are flexible platforms that can provide cheaper electricity than systems using only one energy source. While there are many papers describing new optimization techniques and optimized hybrid power system designs, none couple optimization with experimental validation. This thesis fills that literary gap by generating an optimized hybrid system design for Mercy Hospital and subsequently collects and compares the system performance with that predicted by HOMER and Hybrid2. The second contribution of this thesis is quantifying the savings engendered by the conversion of the diesel-only power system in Mercy Hospital as components such as batteries and solar panels are added. Due to the need to compare the system's experimental performance with HOMER and Hybrid2's predicted performance, a metric for the combining the O&M and fuel costs of generating electricity is created: Operational Cost.

By comparing the predicted and actual Operational Cost of the Mercy Hospital hybrid system, it is possible to validate HOMER and Hybrid2's predictive accuracy. It is shown that HOMER and Hybrid2's accuracy is greater than the experimental data measured by the system's dataloggers. HOMER's Operational Cost predictions largely fell within the 95 percent uncertainty range of the experimental data except for one instance: the 50 Hz Hybrid System Dry Season. Analysis on that dataset showed that HOMER's accuracy is limited by our ability to predict the availability of electricity from BKPS, the local utility company. HOMER predicts the availability of BKPS power is such that the operation of the diesel generator is not necessary, when in fact the 50 Hz experimental system generates 264 kWh, roughly 52 percent, of the demand using the diesel generator. This results in HOMER predicting a significantly smaller Operational Cost than that of the experimental data: US$0.41/kWh versus US$0.77/kWh. Hybrid2 predicts higher Operational Costs than HOMER as a result of an addition of a bi-monthly full battery recharge which increases the proportion of electricity that is generated by the relatively expensive diesel generator.

Validating HOMER and Hybrid2 also involves searching for inaccuracies in the way either program models the components within a hybrid system. It was observed that HOMER's battery loss model typically over predicts the losses associated with the storage and conversion of electricity, while Hybrid2's under predicts them. Experimental data yields an average roundtrip battery efficiency of 86.0 percent, while Hybrid2 predicts battery efficiencies of 88.7 percent, and the value inputted into HOMER is 80 percent. In specific hybrid system designs where battery discharge currents are very large in comparison to the capacity of the battery bank, Hybrid2's underestimation of the internal battery losses could result in battery bank overheating.

The thesis also predicts the Operational Cost reductions that one can expect when building a PV/diesel hybrid system and provids experimental data on battery performance for others to incorporate into their modeling. Diesel generators have the highest

Operational Costs primarily as a result of the O&M cost that is accrued irrespective of the generator's power output. Operational Cost for the 60 Hz diesel-only baseline system is calculated to be higher than US$5/kWh while the baseline 50 Hz system is calculated to produce power for roughly US$1.25 per kWh. By adding an inverter and battery bank, these Operational Costs can be reduced between 35 and 77 percent depending on system loading and temporal mismatch between the generation and consumption of electricity. Other authors who have built hybrid power systems have used them as grid-tied UPS systems, so it is of interest to evaluate the reduction of Operational Cost due to incorporation of grid power into our hybrid system. The result is an additional 39 percent reduction in Operational Cost. Although solar arrays were not added to the experimental system in Mercy Hospital, models are used to show that the inclusion of solar arrays offers less cost savings than adding a battery bank. Through the use of HOMER and Hybrid2, it is seen that optimized hybrid systems are expected to obtain Operational Costs of US$0.16 per kWh.

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