2011

Smart Grid Functionality of a PV-Energy Storage System

Nenad Damnjanovic
University of South Florida, nenad.damnjan@gmail.com

Smart Grid Functionality of a PV-Energy Storage System

by

Nenad Damnjanovic

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science
in Electrical Engineering
Department of Electrical Engineering
College of Engineering
University of South Florida

Major Professor: Lingling Fan, Ph.D.
Kenneth Buckle, Ph.D.
Zhixin Miao, Ph.D.

Date of Approval:
November 2, 2011

Keywords: Optimize, Rate, Cost, Efficiency, DSM

ACKNOWLEDGEMENTS

I would like to take this opportunity to thank my supervisor Dr. Lingling Fan for her invaluable guidance and advice throughout this defense process. I want to thank my committee members, Dr. Zhixin Miao, and Dr. Kenneth Buckle for their generous advice and interest.

I would also like to thank the academic and administrative staff at the Department of Electrical Engineering at the University of South Florida. In addition, I would like to thank the researchers and professors at the Power Center for Utility Exploration (PCUE).

Finally I would like to thank my parents and my friends who have supported me throughout my graduate experience and my thesis defense at USF.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

Renewable Energy will be the key to preserving the Earth's remaining resources and continuing this surge of technological progress that we have experienced this past century. New philosophies of how/when/where energy should be consumed and produced are attempting to improve upon the current grid infrastructure. The massive advancement in communications, renewable and control systems will allow this new-age electric grid to maximize its efficiency while reducing cost. Renewable, "green" energy is now at the forefront of innovation. As the world population increases, there will be a need to free ourselves from natural resources as much as possible. Advanced Energy Storage Systems (AESS) will play a vital and large role in this new-age infrastructure. Because renewable energy is not constant (aside from hydroelectricity), this energy needs to be conserved and used at appropriate times. The Sustainable Electric Energy Delivery System (SEEDS) project features an AESS made from Lithium-ion phosphate (LiFeP04) and a Photovoltaic (PV) source connected to the grid. Every current technology has different parameters, efficiency, charge/discharge rates, lifespan, etc. The current Li-FeP04 system will be used as an example and a model. This project acts as a pilot project for future large scale smart grid endeavors. This thesis is written in conjunction with the SEEDS project and will outline and discuss in detail the findings. For the PV system, the performance is analyzed. For the storage system, the round-trip efficiency (measured)

and life cycle are broken down. The thesis concludes with a capacity sizing estimation of the storage system which is based on the renewable energy source (solar).

CHAPTER 1

INTRODUCTION

1.1 Objectives

The biggest challenge with incorporating renewable energy into the current power system is the fact that the energy they produce is inconsistent. Solar energy is only available for use when the sun is out and the sky is clear. Wind energy is only there when there is a breeze, and usually this breeze needs to exceed a certain speed in order for generation to kick in. Other than hydroelectricity, these two methods of energy production are leading the way in research and application. As stated earlier, neither one can provide a constant supply of power, and thus cannot be a true alternative to using natural resources or nuclear energy. The addition of Advanced Energy Storage Systems (AESS) solves this problem. Smart grids are now possible due to the rise in wireless technology and the aforementioned renewable resources and storage systems.

In addition, different technologies and chemical compositions are being researched and tested for AESS such as lithium ion, vanadium redox, and zinc bromide to name a few. Each technology has different parameters such as capacity, battery life, rate of charge/discharge, cost, decay rate and efficiency. Optimal usage of each system will be different from case to case. This is extremely important because the cost of the technology and the energy lost in the round-trip are not cheap. Utilities need to understand how to optimally use this technology. In order for this to occur however, it must be tested in a real time application. The SEEDS project takes it a step further by combining the PV and the energy storage projects and connecting them to the grid. This is turn forms a micro-grid. The wireless communication of components will also discussed. The purpose of this thesis is to test and observe this technology and find the limits of its performance. The observations and experiments will be documented in the following chapters as well as what needs to be done in order for large-scale integration to become a reality.

1.2 Motivation

This thesis was undertaken in conjunction with the SEEDS project and my time spent researching and gathering data at the Power Center for Utility Exploration (PCUE). After approximately 2 years, there had been much data gathered and many papers written regarding the findings. It was a logical step for me to organize everything and compile it into a Master's thesis. I am passionate about renewable energy and the new trend toward a smarter, more connected grid. There is a need to incorporate both renewable energy and a storage system in order for the smart grid to be a realization. The SEEDS project was tested in real time and real conditions. The experience gathered from this project is invaluable.

1.3 Outline of Thesis

There are 6 main chapters in this thesis. The introduction is included as an overview of the scope of the research.

Chapter 2 - Shift to Renewable Energy: How DSM is affecting the generation/transmission/flow of energy. Smart Grid will provide an overview and state of the current technology and efforts that are being undertaken to make the Smart Grid network a reality. Demand Side Management discusses the new philosophy of energy transition that will be the root of the Smart Grid system. It will explain the role of AESS in the future and the impact they can have.

Chapter 3 – State of the art: This chapter will discuss the state of the art of the battery technology, as well as PV and the current communication systems and protocols used in Smart grid.

Chapter 4 - Sustainable Electric Energy Delivery System (SEEDS) project Analysis: The implemented system will show a real-world application of a PV and an Advanced Energy Storage System working in conjunction. The performance and reliability of each system will be addressed and real data will be brought forth.

Chapter 5 - BESS Power Capacity Estimation: The power and energy capacity of the AESS are determined by analyzing the PV output. This would be ideally utilized for islanding operations.

Chapter 6 – Conclusion: Summary of all that was presented. The conclusion will wrap up the study and mention all the key analyses and contributions from this thesis. A Further Study will be to incorporate all the knowledge learned from the SEEDS project, the next step is to correctly select the optimal installation location. An economic analysis will also need to be done.

CHAPTER 2

SHIFT TO RENEWABLE ENERGY

The electric grid is an ever evolving network that is the largest infrastructure project ever undertaken in mankind's history. The entire world is covered by this network. Dating back to the war of currents between Edison and Tesla, DC vs. AC, the modern grid was eventually designed using Tesla's generators, transformers, etc. whose AC system proved to be a more economically and practically efficient way to transmit and use electricity [1]. Tesla designed the grid in 1888 (implemented in 1896), which is still the same design and infrastructure that is used today. It has evolved since its inception making use of better, bigger, and more efficient components. However, the design decisions made then are still being applied today. This is becoming a problem mainly because the demands on the grid were nothing compared to what they are now in 2011. Advanced energy storage systems, advanced communications and renewable resources are the backbone of the future smart grid. This technology will be the catalyst that shifts the grid towards a future smart grid.

2.1 Smart Grid

A smart grid system is an improvement over the current grid in every way. It allows for more reliable, efficient and distributed energy generation. The smart grid network has a completely different approach to how the energy is generated, transmitted and distributed. Smart grids offer many advantages such as: two-way communications, advanced controls, modern sensors, micro-grids and two way power flow.

Additionally, the current system does not address issues that have arisen in the past century, the main ones being cyber-attacks, keeping up with huge demand, incorporating alternative energy, and communication between consumers and producers. Changes have to be made in the production, distribution, and consumption of electricity, in order to keep up with increased demand. Economically, the utility industry is one of the largest industrial sectors in the U.S, with the value of assets in excess of trillions of dollars. The number of utilities in the US exceeds 3,273, and provides electricity to over 144 million customers [2, 4]. The primary goal of these utilities is to provide reliable and efficient electricity to consumers. “Even with the highest power quality, the direct and indirect losses attributed to power interruptions, voltage sags, surges, etc. are tremendous” [4].

The SEEDS project is a pilot project developed by the University of South Florida and Progress Energy. The project consists of an Advanced Energy Storage System (AESS) consisting of an LiFeP04 storage unit equipped with converters, inverters and power electronics that protect and control the unit. In addition, there is extra power generation with the aid of solar panels. Two identical sites were developed at the USF campus in St. Petersburg and the nearby park, Albert Whitted. The main goal is to test the compatibility, efficiency and overall connectivity to the grid. This project forms the basis of the research and models presented in this thesis.

Smart grids focus on introducing communication to all components of the grid. If everything is communicating, energy efficiency can be maximized. In addition, a smart grid expands on the ways that power is routed through the grid, and ultimately adjusts pricing of the energy used during peak hours. In essence, Demand Side Management (DSM) is only possible if a Smart Grid system is implemented. This chapter will cover smart grids and will dwell further into DSM.

2.2 Benefits of Smart Grid

The benefits of such implementations are that these technologies provide improved grid reliability & efficiency, while increasing security and power quality. This in turn reduces restoration time, adds new products and services to customers, and optimizes asset utilization. An outage at the feeder level could be autonomously corrected by the smart grid by either re-routing power, or by having a storage system to mitigate the outage. Additionally, the two way communication provides two way power flow.

Power interruptions attribute to a total cost of approximately 80 billion dollars annually[4]. One of the worst blackouts in history occurred on August 13th 2003 in the Northeast part of the country and in Canada. Approximately 55 million people were affected [3]. The reason that such blackouts occur is because the grid is overloaded and some power stations go offline for multiple reasons such as: failure, geo magnetic storms, lightning, etc. This causes a domino effect until the entire grid cannot function.

These problems could be solved if extra backup generators are built for the sole purpose of preventing blackouts. However, that is extremely expensive and would cost consumers and utilities lots of money. Another solution would be to have storage systems in place that would provide the grid with power during times of failure or extreme demand. AESS can reach their full potential using smart grid technology. With metering and two-way communication, utilities will be able to route power wherever it needs to go, thus saving money by avoiding high demand cycles. This will improve reliability and power quality.

2.3 Smart Grid Strategies

The smart grid incorporates multiple technologies, some of which will be discussed here. When they all come together, they form an intelligent system capable of increased power quality, reliability, efficiency and longevity. They do not change the core grid components (generators, transformers, transmission lines, etc.); instead they focus on integrating communication to all these components. From figure 1, the smart grid technologies can be divided into the following sections: Advanced Metering Infrastructure, Home Area Network, Distributed Generation, Plug-in Hybrid Electric Vehicles, Transmission/Substation, Distribution System Enhancements, Central Control Center, and Cyber Security [4]. Each of these will be discussed in further detail in the following section.

Figure 1. Smart Grid Technologies and Benefits

Smart Grid strategies can be summarized in Figure 1. The strategies are outlined in the inner orange circles, while the benefits are in the exterior blue circles. Some of these strategies will be summarized in the following sections.

2.3.1 Distributed Generation

Renewable Energy has been growing worldwide at an astronomical rate. As of 2008, Renewable energy accounts for approximately 19% of the world's energy production [5]. There are many forms of renewable energy, traditional biomass however, accounts for 13% of the 19% produced. Wind, solar, hydro, geo thermals and bio fuels are amongst the leaders in renewable energy behind biomass. The following sections will provide a brief overview of some of them.

However, most of these resources are isolated or not connected to the grid. With the inclusion of smart grid technology, these renewable sources can be brought into contact with the grid, and reduce the cost of resources (both capital and natural) required for building extra generators. In addition, greenhouse gases can be reduced and once installed, renewable energy is basically free since no more fossil fuels need to be used [4,5]. Not only will this renewable energy be connected, but the way this energy is used will be controlled by the smart grid, and will ultimately improve power quality, reliability and customer satisfaction. This integration of smart grid technology with renewable energy will have a tremendous impact on the job market of both fields [6]. This will increase competition between corporations which will make the technology cheaper to implement. In summary, distributed generation focuses on the large scale implementation of renewable energy sources, and the problems that arise with such implementation.

2.3.2 Plug-in Hybrid Electric Vehicles

Automobile manufacturers are trying to meet industry standards on efficiency, and consequently, many have gone on to develop their own PHEV, or even in some cases, a fully electric vehicle (PEV). PHEV greatly reduce carbon emissions since electric motors are more efficient than the mechanical engines found in cars. Tesla Motors made the world take notice when it introduced the first fully electric vehicle to market [7,8]. It packs a 56KWh AESS as well as 276 HP motor, albeit with a hefty price tag. However, the challenge will be when an entire nation has a PHEV or PEV and it needs to be charged at home, which will double the demand. There are many ongoing projects that address the issues of charging and demand. The PHEV can be charged at higher speeds if it is capable of accepting a higher rate of current. This reduces the charging time. Implementation of PHEV technology provides another means of service from the utility to its consumers.

2.3.3 Transmission/Substation Automation

A smart grid system will provide better utilization and reliability overall to the entire grid. The only way to do this will be to meter the grid and determine if things are operating in the optimal range. By installing field monitoring instrumentation devices to gather real-time telemetry information [4,9], the following benefits can be provided:

- Optimize power usage based on cost, emissions, resources and availability parameters.
- Improve power flow analyses, and have real time metering of all grid components. The energy consumption, efficiency and health specifications will be available for each component at all times.
- Improve overall efficiency of the entire grid, which reduces costs and emissions.
- Predictive analyses will foresee future areas of weakness in the grid that can be taken care of prior to an occurrence of any interruptions.

2.4 Role of Advanced Energy Storage Systems in Smart Grid

Utilities have excess power generating capabilities during off-peak hours when consumers are using less energy. The Sustainable Electric Energy Delivery Systems (SEEDS) project is a perfect pilot to test the connectivity and effectiveness of the system with the grid. The renewable SEEDS project uses renewable energy (via solar panels) and electricity from the grid to charge a 5KW AESS. This is discussed in further detail in chapter 4. AESS is a battery system with modern communication features that grants users the control over the rate of charging and discharging. This is important because it grants the utility total control of when to charge (off-peak) and when to discharge (peak). Furthermore, the system has an advanced control system that protects the components of the battery from operating outside the specifications prescribed by the manufacturer. Following Demand Side Management principles which will be discussed later in this, a model optimizing the power and energy capacity of the AESS will be presented.

With the introduction of distributed generation and two-way power flow; the complexity of the systems involved increases enormously. There will be a necessity for a method to assess reliability and have some kind of predictive system. The smart grid has the capability to respond to these issues. The unpredictability of the system can be improved by implementing a predictive system across the electrical distribution system. Smart Grid can improve reliability, predict interruptions, reduce down times, maximize resource management, and assist in self-healing the network.

2.5 Expectations from Smart Grid

Smart grids will change the modern power grid, but the cost needs to be justifiable. Expectations need to be set in order to quantify the cost. The understanding of the customer's needs and requirements is important in order to appreciate the efforts put into implementing a complex system such as the Smart Grid. The point is that the utility industry is full of experts who know the instruments and products, but the consumer angle is often lost in the process.

There is extreme capital investment in the power industry. There are many business opportunities that will stimulate the economy as well as improve our shift towards a distribute generation system [4]. Some expectations for the smart grid are:

- Overall improvement in power quality.
- Improved reliability.
- Improved efficiency
- Self-healing capabilities.
- Two way communication/power flow.
- Reduced emissions.
- Real time monitoring of power flow, health, price, demand overload, etc.

2.6 Demand Side Management (DSM)

DSM is a smart grid strategy that can only be utilized with the implementation of smart grid. DSM is the philosophy of reducing the amount of electricity that is used, and more precisely, when the customer uses it. This in turn dictates how it is generated, transmitted, consumed and managed. Supply Side Management (SSM) is the counter to the DSM approach. These two economic ideologies encompass the battles that utilities have when it comes to charging for electricity, and cutting costs. The key to implementing DSM is educating customers about the true cost of electricity and how to be less wasteful and more efficient, as well as introducing systems that are more efficient.

SSM focuses on the supplier (utilities), and cutting costs and improving the efficiencies of the way that electrical energy is generated. It creates more efficient generation and distribution systems, use fewer resources, receive tax credits from the government for reducing emissions, etc. DSM on the other hand focuses more on the consumer, and their actions. Reducing electric bills, giving incentives for consumers to use energy at off-peak times, cutbacks of consumption, and educating the public about energy conservation, are some strategies that make up DSM.

Demand Side Management (DSM) is a relatively new concept that has gained worldwide popularity in recent years. The main reasons for this are environmental and economic. We have to find better ways to utilize all the energy that is produced and to further improve on current alternative energy methods. The heart of DSM lies in the fact that every aspect of it improves efficiency for power generation and distribution. The current Supply-Side management (SSM) design of the utility grid is still the largest infrastructural accomplishment humanity has ever done. However, with the ever-growing exponential increase in population, higher demand for electronics, and the soon to be Plug-in Electric vehicles (PEV), new and more efficient power generation and distribution will have to be implemented and will eventually outdate the SSM system. This must all happen if we are to keep up with this huge demand for electricity.

The key to DSM implementation is efficiency and load management. From generation, to distribution and finally to consumption, all the energy that is made must be used efficiently. This new approach starts first with the consumers (demand side). Many people do not realize how much fossil fuels need to be burned off in order for houses to be lit, air conditioners to be run, and every appliance to work. In fact the number of Giga Watt Hours produced by burning coal is over 1.5 million in 2010 [10] alone which means that the amount of Carbon dioxide and pollution that is exhausted is too big to measure. The fact is that power generation is a bigger problem to the environment than that of the transportation industry. Present practice of turning more generators on during peak times means that this is the costliest time of the day. DSM allows for peak shaving and load shifting principles. In addition, by giving power to the consumers, they can adjust their power consumption accordingly to the times of the day they use most appliances and amenities. Such examples include using the air conditioning unit only when you are home. Most AC units are programmed to check for thermal changes in the environment and then to adjust the temperature accordingly. This is a huge waste however, if nobody is there to feel the effects! Standby power consumption occurs when an appliance is plugged in, but is not ON. This surprisingly accrues a large power waste on the utility, approximately 8% of the total household consumption [11]. This means that although the Television may be off, by being plugged into the outlet, it is using some energy. While this power may not be much, perhaps a few watts or so, over time, it all adds up. Nobody however unplugs everything. Thanks in large part to the 1 watt plan, which was introduced by the International Energy Agency (IEA), to limit all appliances and electronics to 1-watt or under for standby consumption by 2010 [12]. This will reduce CO^2 emission by 50 million tons by 2010, the equivalent of taking approximately 18 million cars off the road. Another user-friendly solution here is to make "smart" outlets that have switchgear devices that will unplug themselves from the grid at certain times of the day.

By introducing incentives to consumers regarding when their appliances are being used (more beneficially at off-peak times); the demand can be reduced on the grid. Peak times can be shifted and money can be saved by simply running autonomous electronics/appliances (AC, dishwasher, washer, dryer, etc.) at off peak times. In addition, Smart grids are a huge part of this DSM endeavor that will allow huge Power quality problems to be solved such as surges, sags, blackouts, etc. Storage units also play a big role in this process. When all these factors come together along with renewable and alternative energy, we will see a truly efficient DSM grid infrastructure.

2.7 Role of AESS in DSM

AESS' role in DSM is an important one. DSM can never fully be realized without them. Such core principles as load shifting, peak shaving, and valley filling cannot be possible without AESS. Utilities can educate the customer, and even limit and influence the time they use energy for things like Air conditioning or the oven/ dryer, but that will be difficult since people are accustomed to their freedom. Thus in order for these principles to come to fruition, AESS must be used. Charging the AESS during off peak times, and then discharging at peak times can greatly reduce costs.

2.8 DSM Principles

The following principles outline the strategy that is used in order to implement DSM theory. There are two basic strategies: Load Management- Shifting the demand profile in order to better utilize all utility components, and developing energy efficient products and systems in order to reduce energy consumption.

2.8.1 Load Management

Load Management focuses on alternating the time of day that energy is used. There are different seasons and demographics that dictate the load profile and are different all throughout the world. There is always however, a peak load time, and a min load time, and sometimes there are more than one [13]. LM is about shifting around the minimums and maximums to try to flatten the load profile as much as possible. This reduces cost and increases the lifespan on all electrical components. Peak clipping, load shifting, and valley filling are the three principles of Load management that attempt to do just that.

2.8.1.1 Peak Clipping

This LM strategy focuses on reducing the peak energy demand that occurs during certain times of the day depending on the seasons and the local demographics (commercial, residential, industrial). For instance in the summer time in warmer climates, peaks usually occur midday when all the Air Conditioning Units are running at maximum capacity. By reducing these peak times, utilities save money by not having to build peaking generators, reducing operating charges, and minimizing the use of expensive critical fuels.

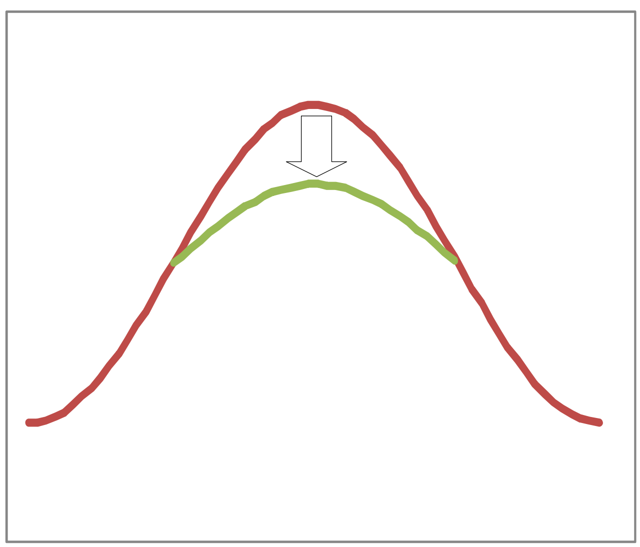

Figure 2. Peak Clipping

2.8.1.2 Load Shifting

This LM technique refers to shifting loads from peak times to lower demand periods. From a residential standpoint, high consuming devices, such as AC, dryers, ovens, etc., could be used when demand is low. For example, dryers and washing machines can be programmed to turn on at midnight, when demand is at its lowest. AC may be programmed to be off when no one is at home, and turned on half an hour prior to the homeowner's arrival. This will minimize consumption and reduce energy waste. By shifting energy consumption from peak times to off-peak times, the demand profile curve will be flattened.

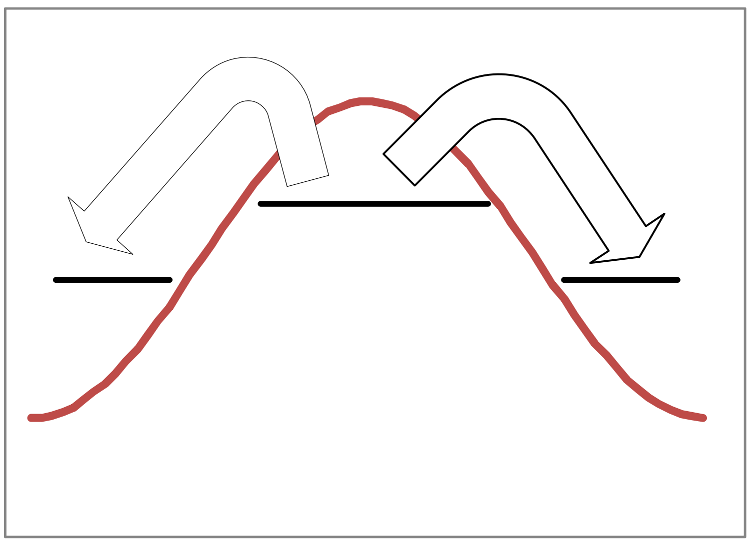

Figure 3. Load Shifting

2.8.1.3 Valley Filling

In conjunction with Load Shifting, Valley filling is simply increasing the low points of the load profile in order to reduce peaking. For example: running the dryer at night as opposed to at 6 PM (peak demand). The task is still being done, but at a different time, which reduces cost and increases the lifespan of all components. This can also be accomplished by charging an AESS during peak times and discharging during these low, valley periods. The main purpose is to make the load profile curve as flat as possible.

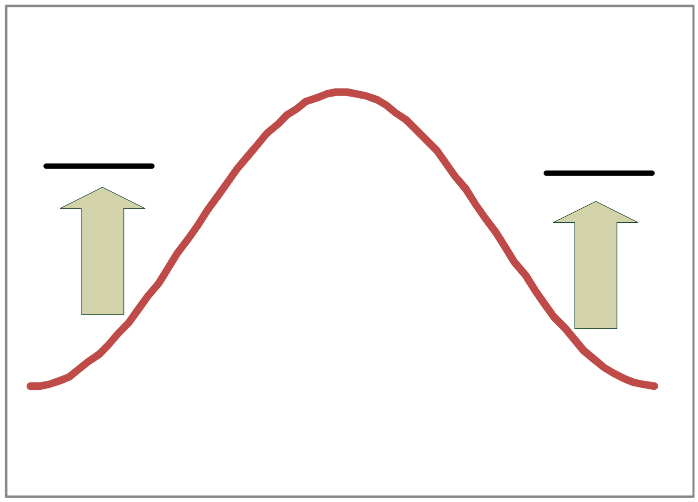

Figure 4. Valley Filling

2.8.2 Energy Efficiency

Energy Efficiency is another aspect of DSM that focuses on making appliances, electronics, motors, or anything that runs on electricity, more efficient. This strategy does not have anything to do with the grid, or shifting, clipping, filling, etc. We have all experienced this, whether it is purchasing more energy efficient fluorescent light bulbs, which are between 4-6 times more efficient, to buying energy efficient appliances (dryers, washers, microwaves, fridges, etc.) The goal behind this is to reduce the energy wasted by old technology, incandescent bulbs or instance, to make everything be as efficient as possible. This endeavor will be vital because electronics are becoming more and more widespread and as the population of the world increases, energy demand will follow.

CHAPTER 3

STATE OF THE ART

The SEEDS project has three key aspects: the storage unit, the PV system, and the communication hardware/software for smart grid application. This literature survey will discuss in greater detail the technology that was used as well as cover some other alternatives. Each of these three fields are evolving and advancing at an incredible rate. Incorporating all these technologies is a challenge that has been undertaken, and will continue to be improved upon.

3.1 Advanced Energy Storage Systems (AESS)

Advanced Energy Storage Systems have been around for quite some time now. These systems range from flywheel based energy storage to the current wave of battery (lithium ion, Nickel metal hydride, etc.) technology, even the upcoming advances sure to happen in hydrogen and fuel cell energy storage systems. Battery storage is at the forefront of technology because it presents the cheapest, most reliable form at this moment. The recent rise in popularity can be credited to the government's goals of renewable energy quotas that need to be met in the near future. Although it is fine to have distributed generation all by itself, an energy storage system provides greater use of the resources and maximizes the efficiency. The two technologies that were incorporated in the SEEDS project are reviewed.

3.1.1 Overview of Current Technology

The main uses of an Advanced Energy Storage System (AESS) are for implementing DSM principles and for reducing cost. Perhaps their biggest advantage is the ability to regulate all the energy that is being produced. Electricity operates with supply/demand economics. Generators are switched on/off according to the demand. There are many monitors of both the supply and the demand of energy. Sometimes however, demand is lower than the supply, and that energy, if not stored is wasted. By using AESS, all the energy can be stored effectively. The introduction of AESS has given utility companies the ability to conserve almost all the energy that is being produced thus making their generators that much more efficient.

Renewable energy distributed generation is not new to the market, but until the recent increases in fossil fuel prices most people were not choosing them over oil or natural gas to produce electrical energy. Now, advances in technology, utility and government subsidies along with high fossil fuel prices are helping to change that. It is not an easy task to accomplish though. One of the biggest obstacles we have to overcome may be efficiently storing our renewable energy. This task is very important because through the storage of solar-generated electricity and wind power, just to name a few, groundbreaking opportunities will emerge for the exploitation of renewable energies in residential developments, cities, regions and countries. Also this will lead to numerous technological innovations along with new prospects for industries.

By storing energy, utilities can eliminate the need for a peaking generator which will only be used when demand is at its highest, and whose capacity will never be realized. In addition, by turning on extra generators, they overshoot the market demand.

This allocation of resources will reduce the cost that consumers pay as well. In chapter 3, Demand Side Management (DSM) was covered and Advanced Energy Storage Systems are   A solution is shown in figure 5, where energy is stored at non-peak times and then distributed during peak times taking the place of peaking generators, reducing cost, and maximizing resources.

In addition to being used in Peak Shaving, AESS' can be used as a Remote Area Power Supply. Consumers who live in remote areas that are not connected to a distribution system can rely on renewable energy to supply them. Solar and wind energy are the two most popular forms. Clearly both have drawbacks since neither provides a constant supply.

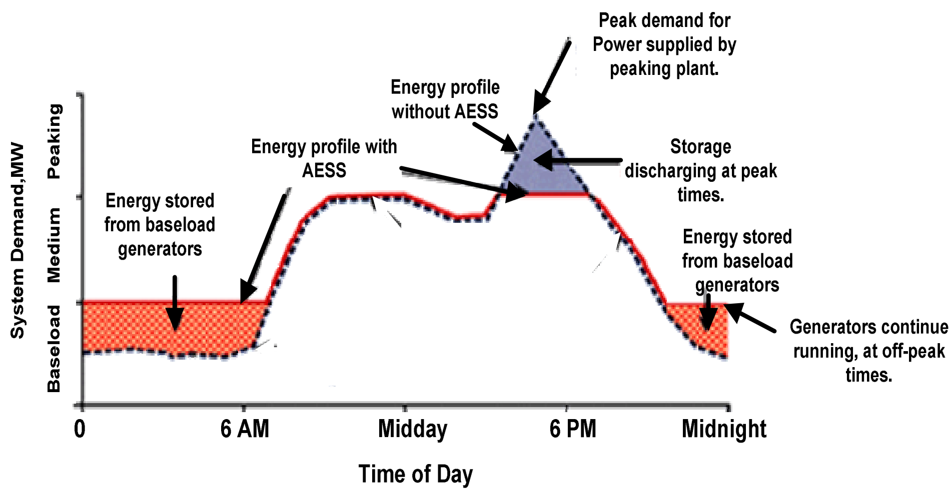

Figure 5. DSM Principles

Wind generation has a huge fluctuation in output due to the wind speed, or lack thereof. Solar has its own benefits as well as nuances however there are days where the sun just doesn't come out. Additionally, solar energy misses the peak time for residential customers, which is when everyone returns home, when the energy from the sun has diminished greatly. When connected to an AESS however, the energy can be stored and used as needed. The cycle of charging and discharging will repeat itself daily, and the consumer will only have to pay for the initial installation of the system, after that, the energy is literally free. In order to avoid a total drought, a diesel generator should be in place just for backup.

As mentioned previously in the communication section, the AESS was controlled remotely and needed to be manually scheduled. The AESS was scheduled for DSM principles (figure 5). It was charged at off peak times and discharged at peak times. The scheduling was determined not only by DSM philosophy, but also for maximum performance and safety of the AESS.

AESS can provide backup energy when a blackout occurs by pumping the grid with stored electrical energy. Keeping the infrastructure of society from collapsing even momentarily will save the extra power needed to startup all the generators. Voltage and frequency regulation can also be achieved with AESS'. Another advantage is that power surges and sags can be avoided by completely regulating the power grid.

3.1.2 Vanadium Redox Battery Energy Storage System (VRB-ESS)

The VRB-ESS is an electro-chemical energy storage system based on the patented vanadium redox regenerative fuel cell that converts chemical energy into electrical energy. Energy is stored chemically in different ionic forms of vanadium in a dilute sulfuric acid electrolyte. The electrolyte is pumped from two separate tanks into flow cells across a proton exchange membrane (PEM) where one form of electrolyte is electrochemically oxidized and the other is electrochemically reduced. This creates a current that is collected by electrodes and made available to an external circuit. The reaction is reversible allowing the battery to be charged, discharged and recharged.

Progress Energy Florida (PEF) and the Power Center for Utility Explorations (PCUE) at University of South Florida are carrying out a demonstration project to combine renewable distributed generation and an advanced battery system to supply renewable energy during the power system peak. The SEEDS project as described earlier first began with a VRB unit. To reiterate, the project consists of a photovoltaic energy system, as well as the VRB Unit rated at 5KW x 4hr.

In evaluating alternative energy storage technologies, there were several considerations that had to be taken into account.

- Long life - with no disposal issues of the electrolytes, theoretically indefinite.
- Efficiency had to be high with a low temperature of operation (typically <75%).
- Speed of response regarding waveform deviations. Had to able to compensate for flicker producing loads (typical voltage response time 5 ms).
- Must be capable of unattended operation.
- Rapid charge and discharge times were required.
- Power electronics (PCS) flexibility with programmable voltage support was required.
- Expandability – The capacity (not the rate of power flow) is easily expanded, simple increase the number of electrolyte reservoir tanks.
- Charge/ Recharge Cycle (adjustable remotely or on site): These are based on time-of-day, local time, with control override based on battery state-of-charge. The VRB-ESS controller program allows easy changes to all parameters.

Figure 6. VRB Enclosure

3.1.2.1 Advantages Over Other Systems

This systems' main advantage is that it responds almost instantaneously to load fluctuations. Also, its precise state-of-charge monitoring and extremely rapid recharge rate, the VRB-ESS is ready to perform whenever an AC utility grid outage occurs, and when power is restored it returns to backup duty faster than any other system available. Environmentally friendly and competitively priced, the VRB-ESS unit is the backup system of choice where high-reliability power is needed. Incorporating "green" technology, it has negligible ecological impact, distinguishing it from conventional energy storage systems that rely on toxic substances such as lead and cadmium. Also, it is able to discharge energy within milliseconds. In other words, it outperforms traditional batteries because it provides better power factor control and improves the quality of power on the system. but lasts longer and has a lower life cycle cost, and is ideal for wind and other applications requiring unknown cycles. Other key advantages compared to Lead-Acid batteries: VRB-ESS have a longer lifetime (discharge cycles-up to 10,000+ compared to 1,500), greater efficiency (65-75% compared to 45%), better charge to discharge ratio (2:1 compared to 1:5), and has a very low maintenance cost. Last, but not least is that its components are recyclable. The VRB-ESS met those requirements from a technical viewpoint.

3.1.2.2 Potential Risk

A main disadvantage to this system is that it requires more space than the nearest competitor does by nearly 30%, when compared by simlar storage capabilites (20KWh). Another disadvantage is that it has limited temperature ranges of between 5 and 40C. The electrolyte is a marine/water pollutant.

VRB-ESS is a flow type battery that utilized two mechanical pumps. Failure of any one would cause failure to the entire operation. The system has to be concealed properly from humidity and airborne minerals from being exposed to the electrolytes. That is an extra design constrain. The electrolytes are toxic thus require MSDS to follow up.

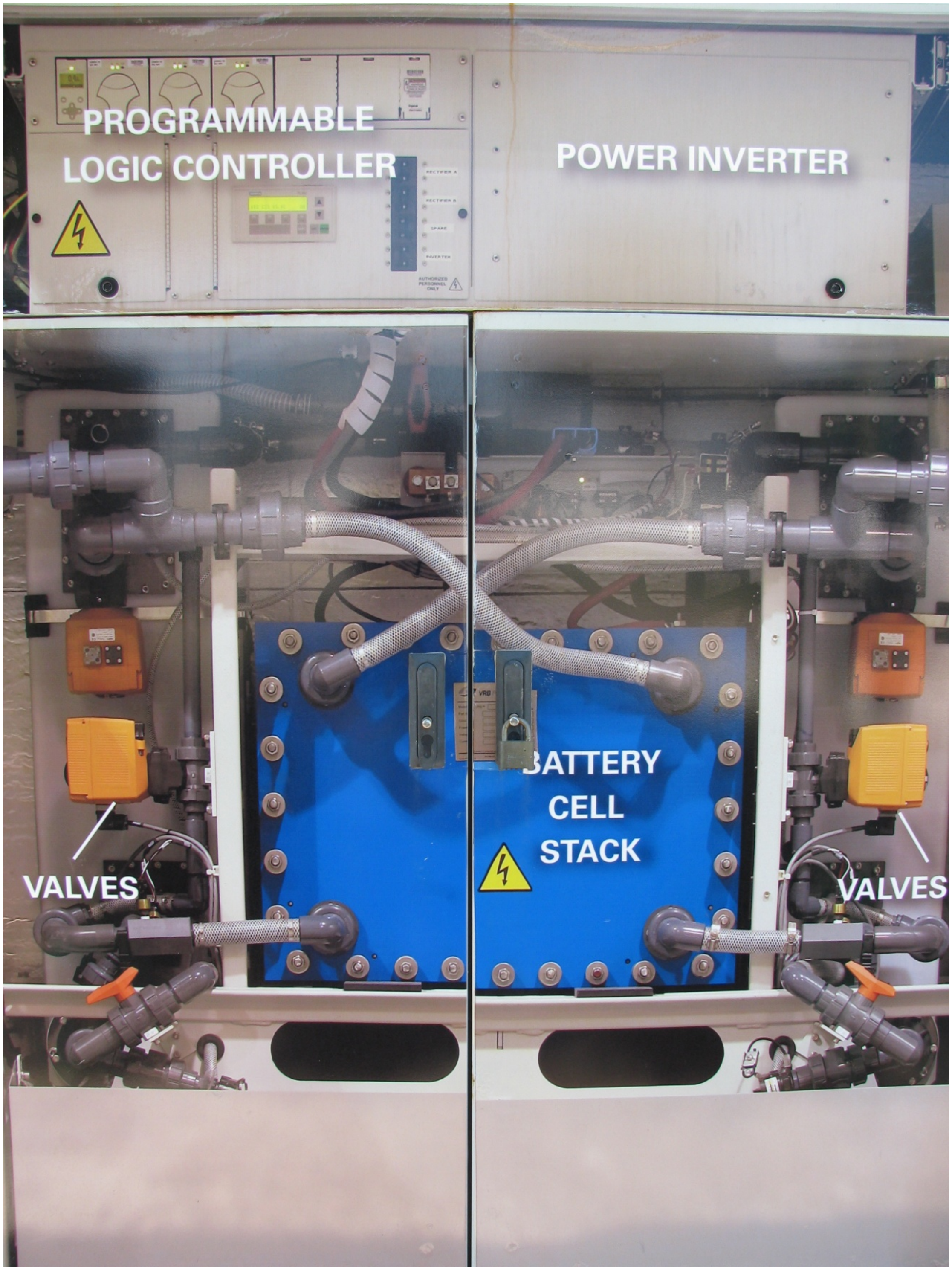

Figure 7. Picture of VRB Unit.

3.1.3 Lithium Iron Phosphate- LiFeP04

The current setup for the SEEDS project is a lithium iron phosphate system with the capacity rated at 20KWh. Unlike the VRB unit discussed in the previous section, the LiFeP04 is not a flow battery. This presents a simpler and more reliable system with less movable parts (no pumps, etc.)

Table 3.1 shows the specifications of the LiFeP04 unit as given by the manufacturer. The temperature range is sometimes beyond the set point and can reach 100° F. The time intervals and rates were followed for scheduling purposes [27].

Table 1 LiFeP04 Specifications

Control Parameter	Operation Set point	Allowable/ safe
Temperature	<95° F	upto104°F
Weather	Weather-proof enclosure	Indoor
Grid Voltage(L-L)	200~220	180~260
Time Interval between two dissimilar events	10 minutes	≥ 5 minutes
Charge rate	4KW~5KW	≤ 6 KW
Discharge rate	4KW~4.5KW	≤ 5KW

The advantages of LiFeP04 are summarized below:

- Low cost when compared to other Lithium and Vanadium based batteries.
- Environmentally safe with no risk of a spill, as in the flow batteries.
- Improved reliability.

Some disadvantages are:

- Operating temperature and diminished performance in warmer and more humid climates.
- Capacity decay trend.

The LiFeP04 technology and performance is discussed in further detail in chapter's 4 and 5. Both technologies were used in the SEEDS project. However, the VRB system failed before any data could be collected. Thus, only the lithium iron unit is analyzed.

3.2 Harnessing Solar Energy

The photovoltaic panel has become the stereotype and staple of the solar industry. There are other methods however that harness the Sun's energy. Parabolic troughs are solar thermal collectors that harness the Sun's heat, not the rays. The two methods will be briefly addressed.

3.2.1 Photovoltaic Panels

Photovoltaic panels (PV) work by converting the Sun's radiation into a DC current. They take advantage of semiconductor materials that observe the Photovoltaic effect. There are different materials that can be used. Most PV panels combine use some form of silicone. The chemical aspects and design are beyond the scope of this thesis. The smart grid must have renewable energy, and governments have imposed mandates for certain energy generation goals for the near future. In 2010, the total power generation capacity from PV's is ~2GW in the U.S and ~ 40GW in the world [14]. The PV performance is addressed in much greater detail in Chapter 4.

3.2.2 Parabolic Troughs

The only thing PV and parabolic troughs have in common is that they both use the Sun's energy. PV panels as described above use the radiation of the sun, while the troughs use the thermal energy of the Sun. The troughs work by reflecting all the sunlight onto a tube filled with heat transfer fluid. The tube is located at the foci of the parabolas. There is such a system that was installed by Florida Power and Light (FPL). The Martin Next Generation Energy Center located near Indiantown, FL. There are more than 190,000 mirrors and encompass an area of about 500 Acres [15]. The maximum output is 75 MW and is the largest solar thermal plant in the eastern United States. Figure 8 shows a row of mirrors that are part of that system.

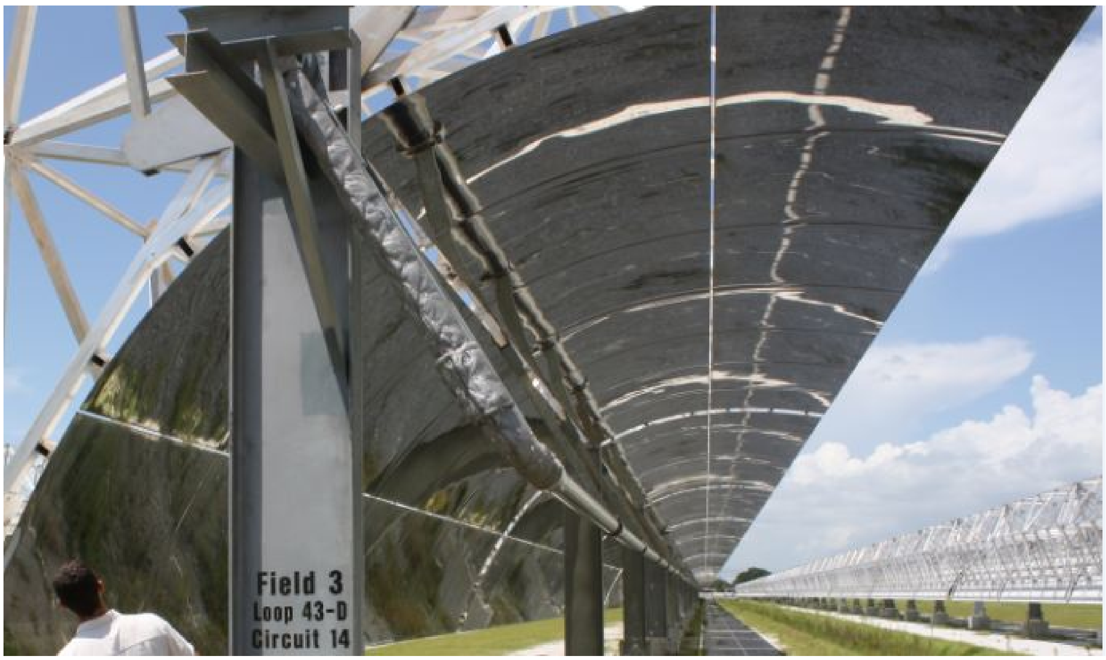

Figure 8. Parabolic Troughs at Martin Plant (FPL)

3.3 Communication in Smart Grid

The main driving force behind the surge in smart grid technology is the analogous rise in communications technology. Communications allow the grid to diagnose problems, improve reliability, maximize energy efficiency and allow control of the grid components. The recent technological advances in this field have made this possible. Wireless communication with the standards and performance of the IMT-2000 (3G), and the upcoming 4G network, has allowed for unparalleled communication in the smart grid network [16]. With the increase in transmission capacity and bandwidth, the devices can communicate with the network at blistering speeds. In this section, the standards that govern wireless communication and the lessons learned from the SEEDS project will be discussed.

3.3.1 Standards

When designing a smart grid system, there are many protocols and standards that govern the connections between the components. The installation and wiring of components is governed by the National Electrical Code (NEC), and other organizations. The communications standards are over headed by the utilities themselves and the International Electro-technical Commission (IEC) for electrical substation automation. Wireless communications are governed by TCP/IP and the standard set forth by the IMT-2000. Together, all these standards and protocols make the system run optimally and efficiently.

3.3.2 IEC 61850

A Substation Automatic System (SAS) is controlled by microprocessors, and is implemented by Intelligent Electronic Devices (IED). Manufacturers of IED's implemented their own communication protocols, which led to expensive and complicated protocol converters when using IED's from different manufacturers. The need for a common communication protocol arose that would mitigate these issues as well as provide interoperability of IED's, interoperability being the ability to operate on the same network and allowing for information sharing, etc. The IEC published standard 61850 which regulates the IED's and allows for the communication of information [17].

3.3.3 TCP/IP

Designed by the of Defense Advanced Research Projects Agency (DARPA) in the early 1970's and declared the standard for all military computing in 1982. TCP/IP merged all the existing protocols and was the main culprit towards the transition to the Internet, an interconnection of all the networks [18]. SCADA systems contain extensions to operate over TCP/IP, but there is an ongoing debate regarding internet security in which precautions must be taken [19]. TCP/IP is the protocol used in the Internet and since the BESS was controlled through the Internet, it is relevant. All the data, as well as the control of the unit was handled remotely through the Internet.

3.3.4 IMT (3G, 4G)

The International Mobile Telecommunications-2000(IMT-2000) are specified by the International Telecommunication Union (ITU). The standards regulate mobile phones and mobile telecommunication. A mobile broadband router was used to connect the BESS to the network. It was outside the range of the University's network, and the router was connected to the communication bin in the BESS unit via an RJ-45 cable.

3.4 SEEDS Implementation

The communication of the SEEDS system was done through the internet. The connection is shown below in Figure 9. The BESS communication module was connected to a mobile router. This enabled for wireless communication to the BESS from any location on the planet that has Internet connection.

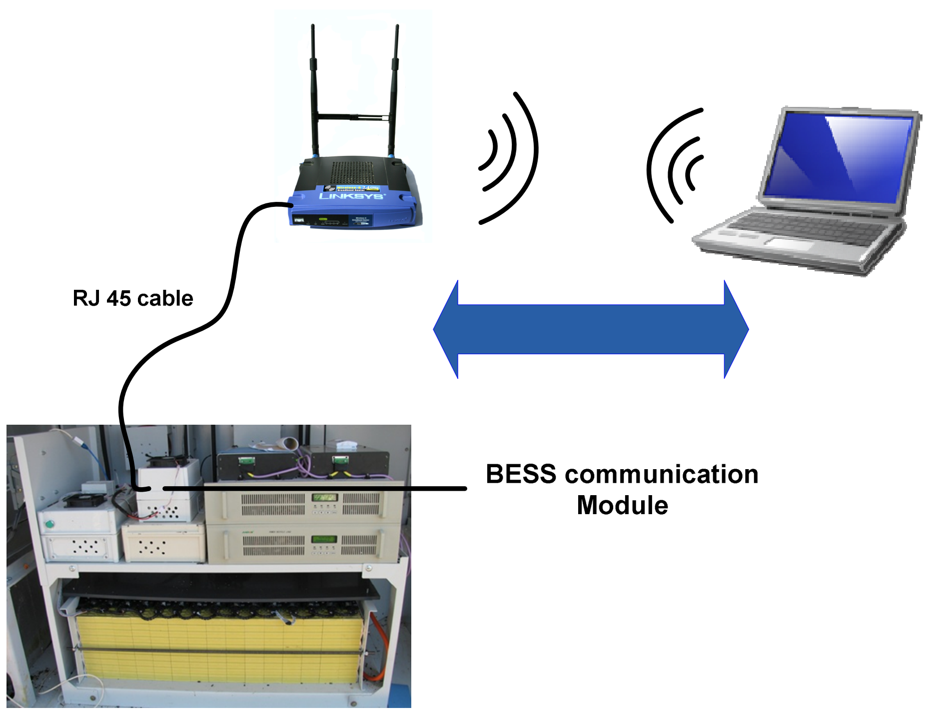

Figure 9. Wireless Connection of BESS

Figures 11 and 12 show the online interface from the manufacturer's website. It has the capability of letting the user see the real time status of the units. The health of each unit is displayed. The battery management system is in place to keep the battery safe from any overcharges, and it never lets the BESS fully discharge, this will damage the LiFeP04 cells and ultimately lead to a lower life expectancy.

Figure 10. BESS Communication Module.

Figure 11. Event History.

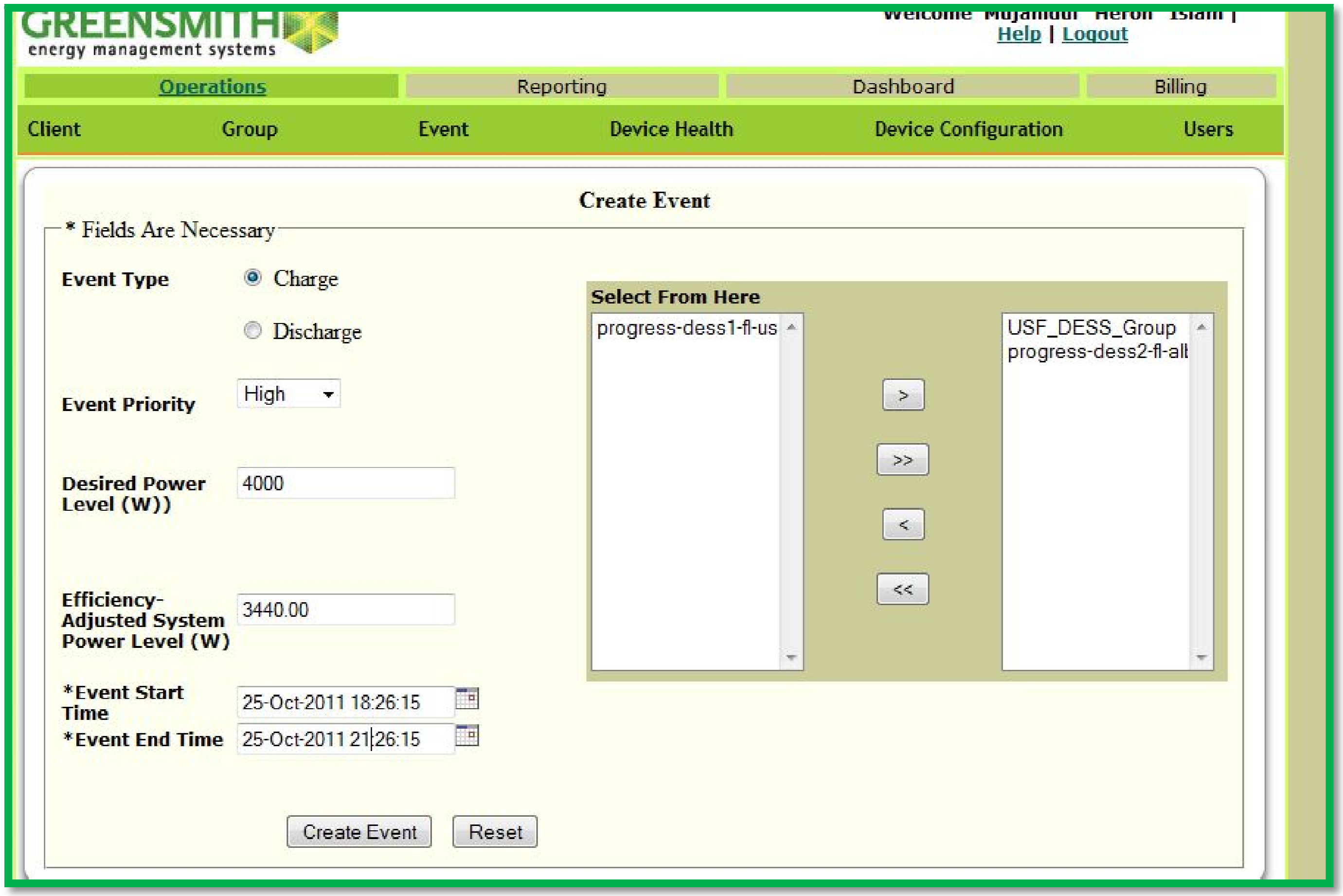

Figure 12. Event Creation of the BESS.

Charging and discharging of the BESS are all done by creating events. These events can be programmed for immediate or future execution. The unit is programmed under a self-sustaining philosophy. Meaning that it will not charge/discharge over a certain limit, and it will not drop or exceed a certain limit. The 3G network that was used proved to be sufficient in communicating with the unit, however our max memory capacity allotted (250MB) was consistently being exceeded. More storage was required due to the fact that sending the data back to our network for analysis consumed much of the memory.

Sometimes the mobile router would be down and all communication would be lost. This was due to a few factors. First, the outlet breaker would trip and the router lost power. On a few occasions, the BESS communication module was turned offline due to animal activity inside the BESS housing. The health status of the unit could not be checked and it could not receive any new commands. This placed enormous emphasis on having consistent communication with the BESS unit. The smart grid must rely on having superior communication that cannot be interrupted. The future holds promise with improving technology and the WiMAX network that will work over large areas. In the future smart grid, there must be extra precaution taken to safeguard against communication failure and cyber terrorism.

3.5 Future Smart Grid Communication

All the previously mentioned existing protocols that are in place regarding communication will evolve. Smart grid appliances and devices should use existing networks and infrastructure to minimize cost and optimize the use of the already invested capital in the network [20]. New protocols will arise that standardize the frequency and bandwidth of smart grid component communication. On a larger scale, this will aid in more efficient power generation/distribution/transmission and problem solving. The power system communication technologies and protocols are one of the main components of the smart grid. The Smart Grid will bring about a revolutionary change in the overall operation of the electric power system. It is a step forward in the long process of implementing intelligent devices into the power system. For further detail, the reader should research [21], which covers smart grid communication architecture.

CHAPTER 4

SEEDS PROJECT ANALYSIS

The SEEDS project that has been mentioned through the text has been the driving force for the research in this thesis. The purpose of this project is to act as a pilot/test project for future significantly larger storage units. The goals of the project are to check grid connectivity, troubleshoot any issues, and to record/observe the performance of the storage system. The utilities' main objective is to analyze the cost effectiveness of implementing these distributed generation and smart grid components into the current power grid. As previously stated, there are two installations of the photovoltaic and LiFeP04 storage units. One is located at the USF St. Pete campus, while the other is nearby at Albert Whitted Park. Figure 13 shows the locations and proximity of the two units. Both sites are identical, with the LiFeP04 storage units rated at 20KWh maximum (5KW x 4hr). Each site is controlled by an energy management system supplied by GreenSmith Energy Management Systems, LLC [22]. The photovoltaics are rated at 2KW maximum. The measured and observed data and results along with the grid connections are explained in the following sections. The measuring device was a power data logger supplied from Dent Instruments [23]. Figure 13 shows a picture of the AESS installation at Albert Whitted Park. Prior to the LiFEP04 unit being in the enclosure, it was used to house a VRB flow battery, hence the need for the compartment on either side. The PV panels are located on the roof of the building.

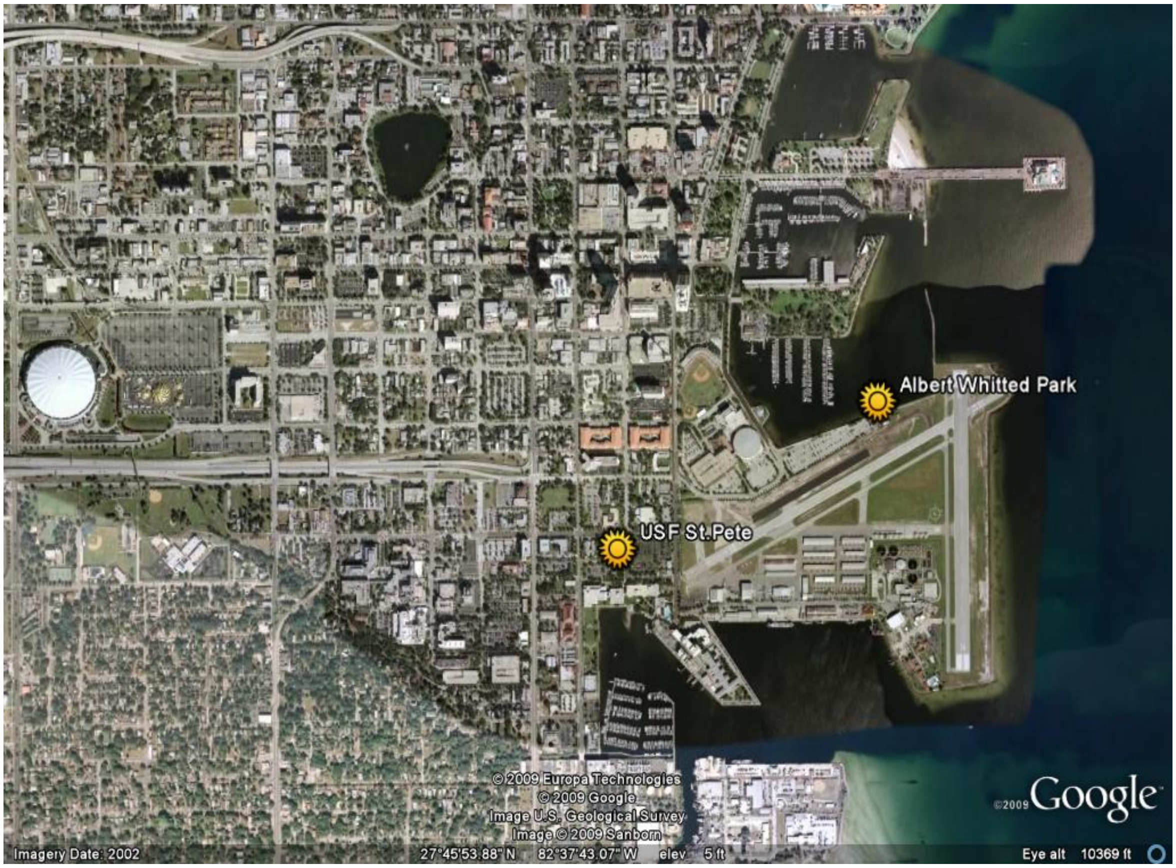

Figure 13. SEEDS Site Locations

Figure 14. LiFeP04 Unit Enclosure

4.1 Photovoltaic Performance

Photovoltaics are improving in efficiency annually. In the future, they will be smaller and be able to absorb more solar radiation. There are many factors, however, that affect the performance of the photovoltaic panels. Some important things to consider are the ambient temperature, the suns irradiance, and the angle of incidence between the sun and the PV panels. The location and facing direction of the PV panels greatly affect how much sunlight is absorbed.

The angle of incidence is crucial in maximizing efficiency. In order to convert the most sunlight into energy the most ideal situation would be a perfect 90 º angle between the sunlight and the PV panels (Figure 15). There have been ample studies that have shown that beyond an angle of 40º (sun-PV angle), the solar energy diminishes greatly, while beyond an angle of 5º, it becomes negligible [24]. A solar calculator tracks the position of the sun depending on your latitude and time of the year. This information enables the solar panels to be adjusted for optimal energy conversion. There exist solar energy trackers which track the sun and move the panels in order to always have the greatest angle of incidence. However, they raise the expense of the installation, and oftentimes the energy required to move them makes the added performance negligible.

Most installations have fixed solar panels, as are the ones at the two St. Petersburg sites. Both sites (figure 13), are angled at ~25º, and face South, South-East. In figure 15, the angle of incidence of sunlight to PV, the tilt angle of the PV, as well as the seasonal movement of the sun are shown. Table 4.1 shows, the optimal angle that the photovoltaics need to be tilted at for different months of the year. This information is only true for St. Petersburg, FL, or latitude of ~27º46'N .It can be concluded that for this installation, the most efficient times are during the Spring/Fall seasons.

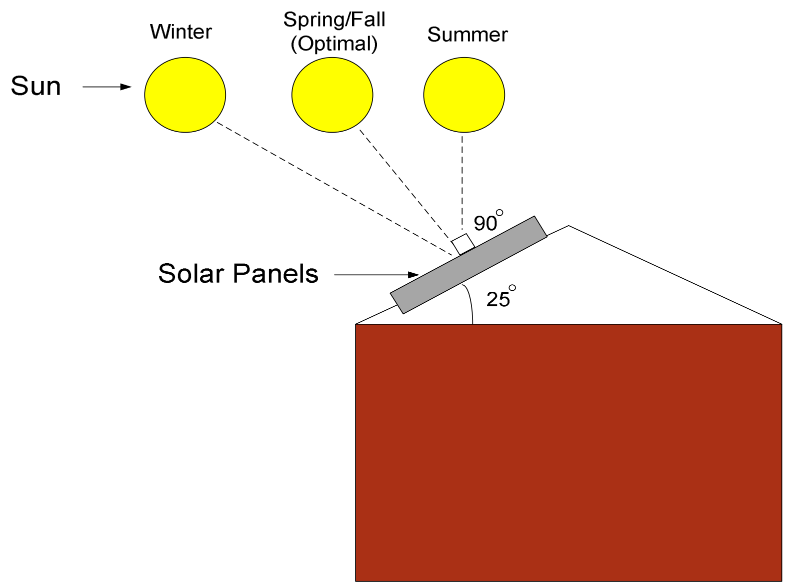

Figure 15. St. Petersburg PV Installation, Angle of Incidence.

Table 2 Optimal Angle of Incidence, St. Petersburg, FL (Latitude 27º 46' N).

Month	Optimal Angle
Jan	44
Feb	36
Mar	28
Apr	20
May	12
Jun	4
Jul	12
Aug	20
Sep	28
Oct	36
Nov	44
Dec	52

Additionally the luminescence of sunlight and the temperature at the time of incidence affect the efficiency. The greater the luminescence, the greater the efficiency of the system. Several studies have shown that PV performance decreases as ambient temperature increases [25]. Figure 16 shows the energy created by a 2 KW max rated PV unit for an ideal day (minimal cloud cover). There are very small amounts of interruptions and the curve is very smooth. The readings are taken instantaneously every 15 minutes, and show that the actual results do not exceed ~1.55 KW, even though the rated Power is 2 KW. Although there are minimal interruptions (Clouds, weather, etc), the PV unit is not operating at its maximum. This is due to the fact that it was recorded during an off-peak season (January). The other factors come into consideration such as temperature, debris buildup on the PV's, or maybe even a day that was cloudy, but sunlight was still able to seep through. PV output can be explained as a probabilistically distributed noise contaminated output. Using Riemann sums to approximate the area under the curve,

$$\int_a^b f(x)dx = \lim_{x\to\infty} \sum_{i=1}^{n} f(xi)(\frac{b-a}{n}) \quad (1)$$

Taking both left and right approximations, and averaging the two, for that particular day, 7.62 KWh were harnessed. The photovoltaic are capable of harnessing solar energy for ~7 -13 (seasonal) hours in our region of central Florida.

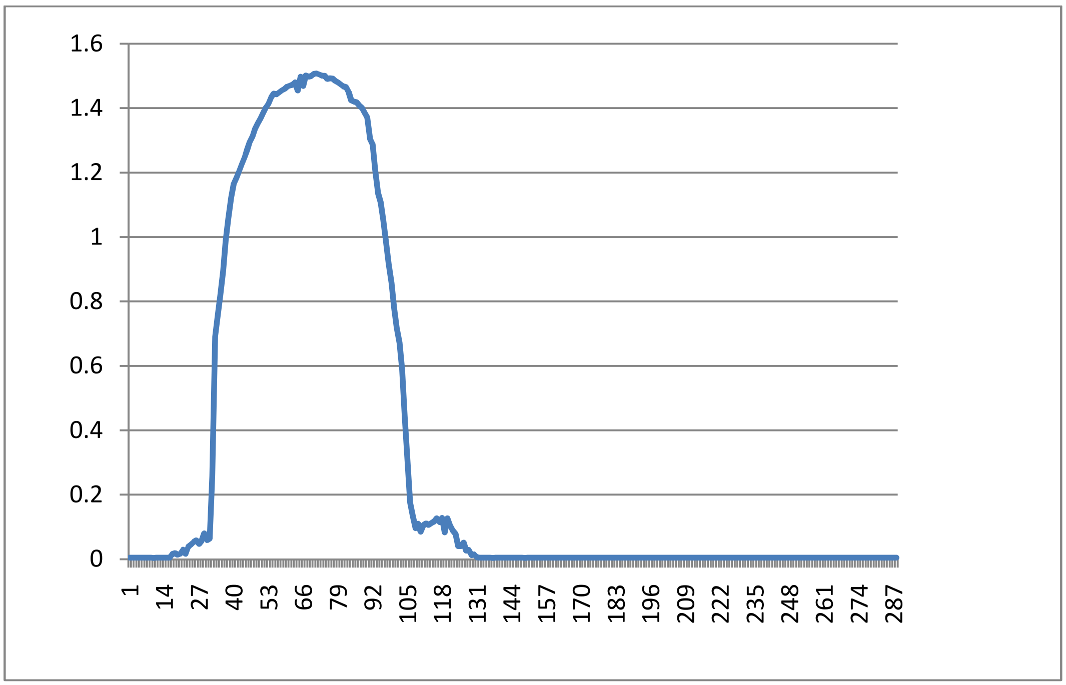

Figure 16. Instantaneous Power From Ideal Photovoltaic Conditions (2kW Unit)

Figure 17 shows the photovoltaics operating at a near optimal level. The high for this day (4/17/2009), measured at the USF site was 1.928 KW. The figure shows some mild interruptions, but it still retains the curve. The maximum energy from this day (using piecewise approximation) is ~11.94KWh. This is over 4KWh more than from the previous analysis of figure 16. It can be inferred that this day was in the Spring or Fall, had minimal cloud cover, and there was certainly no rain. This curve differs from Figure 16 because the solar energy is harnessed for approximately 11 hours as opposed to ~7 hours. It is also peculiar to note the similar “knee’ characteristic that is encountered on both graphs, right before sunset.

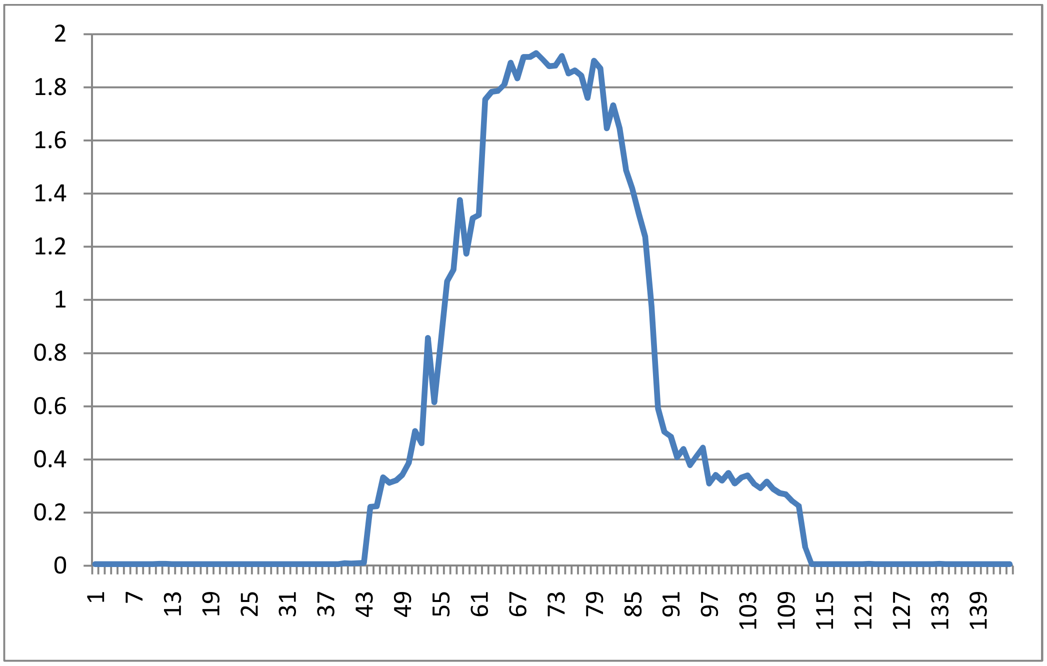

Figure 17. Near Optimal Power Capacity

Figure 18 on the other hand shows interruptions occurring for the entire day. These erratic readings can be attributed to anything that prohibits sunlight from reaching the PV’s, such as cloud cover, rain, fog, dirty panels, etc. This is one of the major drawbacks of relying too much on PV’s, which provide an inconsistent supply of energy. If it happens to be overcast the entire day, then there will be very marginal energy being generated from the PV’s. Hence, there must always be a baseline source present to be the main supply of power. Renewable energy will support this generation, but will not dominate it.

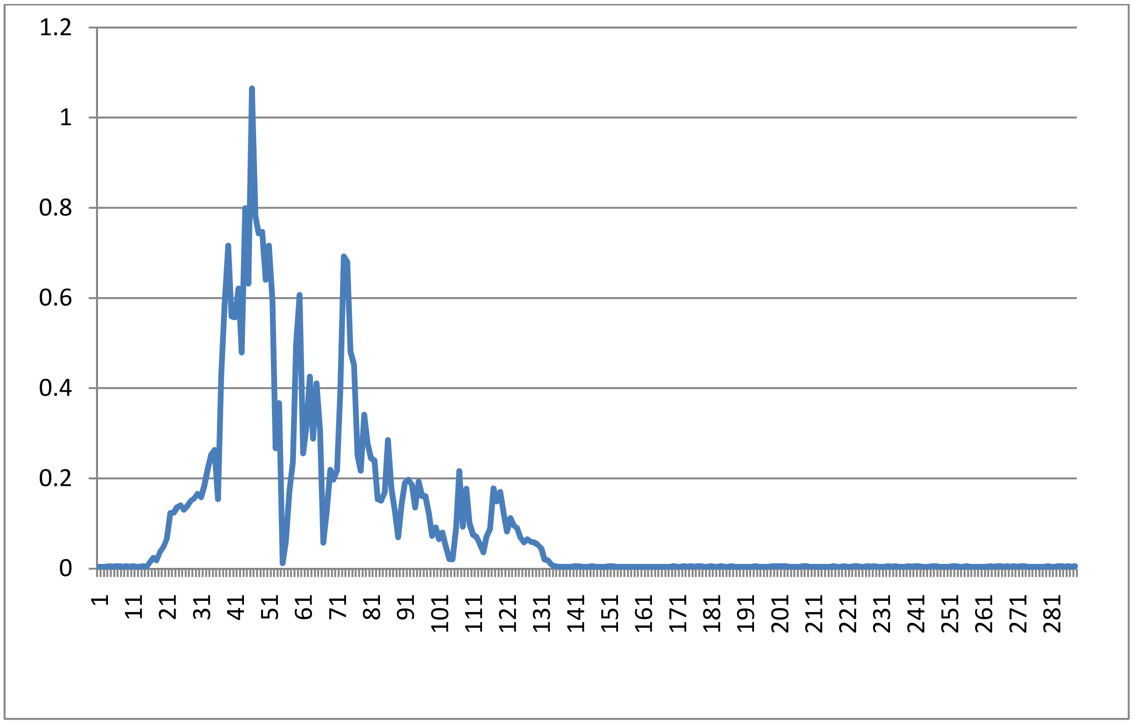

Figure 18. Instantaneous Power From Non-Ideal Conditions

Figures 19 and 20 show the solar installation at Albert Whitted Park and USF St. Petersburg respectively. There are 10 panels at each site and each panel is rated at 200W maximum power. As stated above, they are both approximately angled at 25º and face South, South-East.

Figure 19. Solar Installation at Albert Whitted Park

Figure 20. Solar Installation at USF St. Petersburg

4.2 Performance of LiFeP04 Unit

The LiFeP04 unit is pictured below in figure 21. The cell stacks are shown in yellow, while the inverters and the DC-DC converters are shown above the cell stacks on the right. The battery management system, which monitors the unit and checks that it is operating safely, is on the left. The performance of the lithium ion unit was measured mostly by the battery management system (BMS). There is a substantial amount of raw data generated from the BMS which needed to be filtered out. The main objectives in measuring the performance were its round-trip efficiency (power in/power out), and the life cycle estimation. The maximum rate of battery charging and discharging is given by the manufacturer, and is limited by the inverters and other power electronic devices. The round-trip efficiency was also given, but a real life grid application test was necessary. These tests are discussed in further detail in the following sections.

Figure 21. LiFeP04 Unit with BMS

4.2.1 Round-Trip Efficiency

AESS round-trip efficiency is the measure of its energy storage efficiency, that is, the ratio of the energy fed into the AESS from the grid, to the energy delivered to the grid from the AESS. The round-trip (RT) efficiency can be used to evaluate this system's economic viability and its suitability as a distributed resource. The RT efficiency of an energy storage system can also be used to evaluate its potential use for Demand Side Management. The round trip efficiency of a system can also be a determining factor of its suitability for absorbing power output fluctuations from an intermittent source applied to the area electrical power system (AEPS). The data that is used for this calculation was mainly compiled from two sources:

- Primary: A locally installed data/energy logger.
- Secondary: A dedicated data server (maintained by the battery package supplier) which collects data remotely via a wireless network.

Both of these data sources are used to increase the confidence level of the gathered data.

4.2.1.1 Primary Method (Data Logger)

In order to measure the AC power flow through the Point of Common Coupling (PCC) to the grid in either direction, a data logger was installed.

- Power reading with a negative sign is the power injected into the grid.
- Power reading with a positive sign is the power drawn from the grid.
- Energy is found by linear integration.

Figure 22 shows the measuring points, and the exact connections of the data logger to the system. The data logger did not take into account what was occurring inside the battery storage unit, instead, it only registered the power flow outside the unit, as can be seen with the connection to the grid.

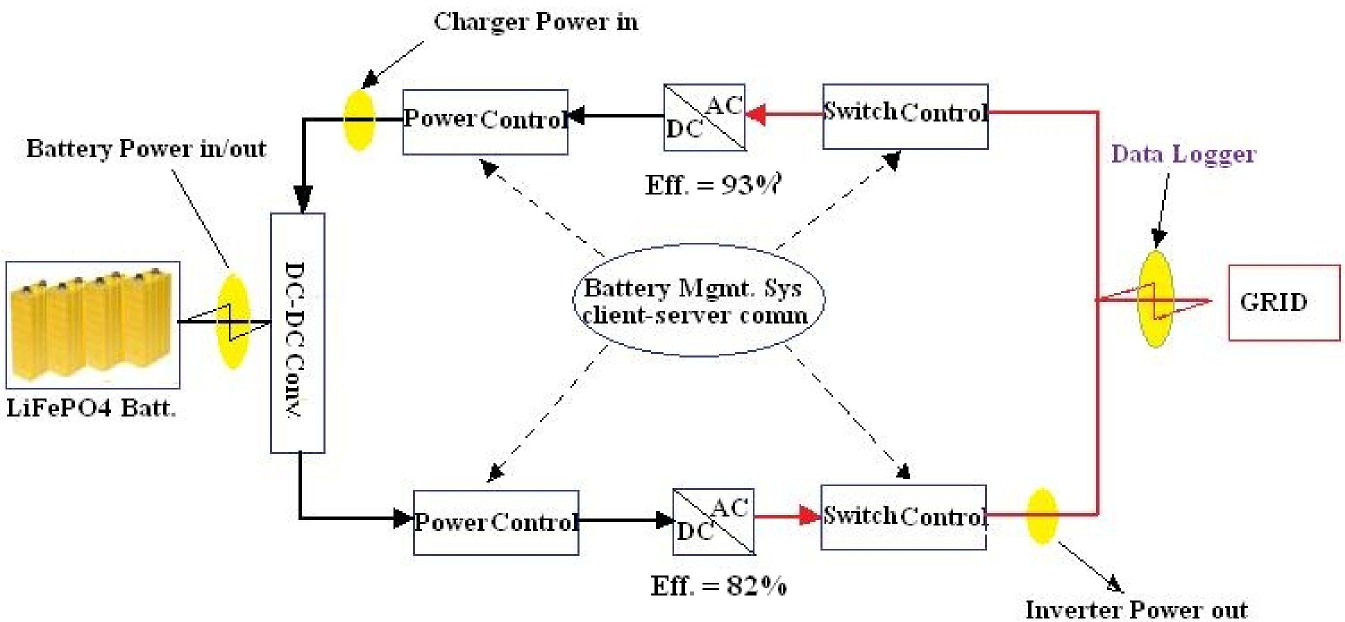

Figure 22. Block Diagram of the System Power Flow

The energy/data logger was tapped at the PCC measuring the line voltages and the load/generated current. The input/output power was estimated for multiple complete cycles. Statistical analysis was performed on identical charge and discharge events. The State of Charge (SOC) measurements are given by the BMS, but they are inconsistent in that the values round up, i.e., when the actual SOC is 94%, and the battery is full, the BMS records 100% (fully charged). Thus, the difference in the SOC is taken as the measurement to calculate the complete cycle. The phrase ‘complete cycle’ means that the AESS was charged fully and then discharged fully. It is also important to note that the lack of islanding implementation means that the system cannot intake energy from the PV system directly.

4.2.1.2 Secondary Method (DESS Server)

The BMS built-in local DESS client probed three points on the power flow path as shown in figure 22 above. One of the three is measuring the AC power delivered to the grid. However, the DESS client does not report any power at the inverter output while the system is kept on hold (either by scheduling or by the BMS’ highest priority self-operation mode). To calculate the round-trip efficiency we presumed:

- Inverter power out is taken as the power delivered to the grid.
- Power level scheduled is the power drawn from the grid.
- Idle power is considered as a loss – in the form of leakage current causing heat dissipation.

The power was integrated over a time interval to find the amount of energy transferred within the interval.

4.2.2 Calculation of Round-Trip Efficiency

The calculation of the Round-trip Efficiency is broken down into two steps. First, the charging aspect, or the power from the grid (AC), that is stored in the battery (DC). The second part is the discharge from the battery (DC), into the grid.

Charge Efficiency= $^{DC\ Power\ into\ the\ battery}/_{AC\ Power\ from\ Grid}$ (2)

Efficiency is defined as P out/P in, and in the charging case, the power into the battery comes directly from the grid (AC), while the stored power (out) is DC.

Discharge Efficiency= $^{AC\ Power\ delivered\ to\ Grid}/_{DC\ Power\ from\ battery}$ (3)

P out is the power delivered to the grid from the battery. The P in is therefore the stored DC power. The product of the two shows the round-trip efficiency, not including the internal resistances encountered. The round-trip efficiency was found to be 73.5%, close to the product of charge and discharge efficiency. In our testing, the battery charging efficiency is found to be ~82% and discharging efficiency being 93%, the product is 76%. It implies an extra loss of 2.5% in the system. The reasons for the losses are summarized below:

- The idle state, when the AESS is not charging or discharging shows a total standby power use of ~65 Watts. The total energy lost for a 24-hour period in the idle state is ~1.56 kWh.
- The losses of the inverters were taken into account. After analyzing the data, it can be shown that the inverters, when idle, are in a floating state and account for approximately 65 Watts of power with a deviation of no more than 8%.

- The standby power loss consists of 35W of continuous power for the BMS. The operating efficiency of the system (while either charging or discharging) varies minimally with the chosen rate, i.e., charging/discharging at 2KW, 3KW, 4KW, etc. However, as discussed in the next section, the overall efficiency is slowly declining.

The sources of the losses of the electrical components in the AESS are as follows. These are estimations based from manufacturer's specifications.

- While Charging (The total is estimated to be 17%):
- Contact losses at all series switches – 3%
- Rectifier loss – 10%
- DC-DC conversion loss – 2%
- Dynamic series resistance loss (heat) – 2%
- While Discharging (The total is estimated to be 7%):
- Contact losses at all series switches - 3%
- DC-AC conversion loss – 3%
- Other losses (heat, harmonics etc.) – 1%

4.2.2.1 Histograms for Charging Efficiency

The following histograms show the charging and discharging efficiency of the LiFeP04 unit and take into account the charge/discharge rate. The histograms were derived from the secondary method of using the battery management system's own data that is collected in real time. They values are instantaneous and are recorded every 10 minutes. There are 27 samples in each histogram. The measurements of the efficiency (charge and discharge), are described below and are presented individually, and not as a whole system.

The following histograms display the charging efficiency. Figure 23 was recorded on 10/30/2009, at a rate of 4500W. All but one of the values falls on 84.3% this is the mode, and the average is slightly lower at 84.28%. This is a very accurate presentation of the charging efficiency at that rate. Similarly, figure 24 shows the histogram of a recording done 4.5 months after, with a charge rate of 4000W. It also has consistent values with most falling on 81.2% and only 5 falling slightly higher at 81.7%

The disparity between the two graphs is quite apparent however. After 4.5 months, the efficiency rate has dropped by ~3%. It is possible that this is due to the decreased rate of charging (4500W to 4000W), but it is unlikely that a drop in only 500 Watts produced this much of a decrease. The most likely conclusion is that the efficiency has decreased over time.

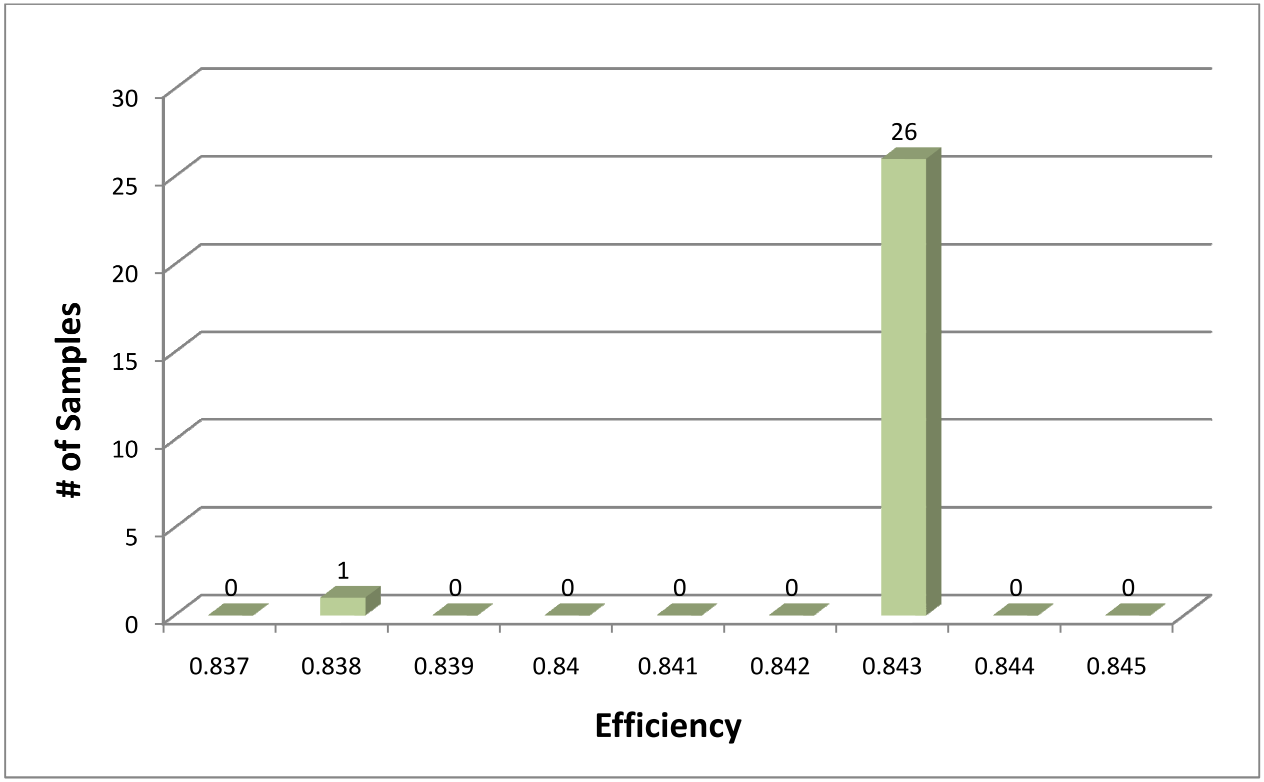

Figure 23. Histogram of Charge Efficiency Recorded on 10/30/09 @4500 W

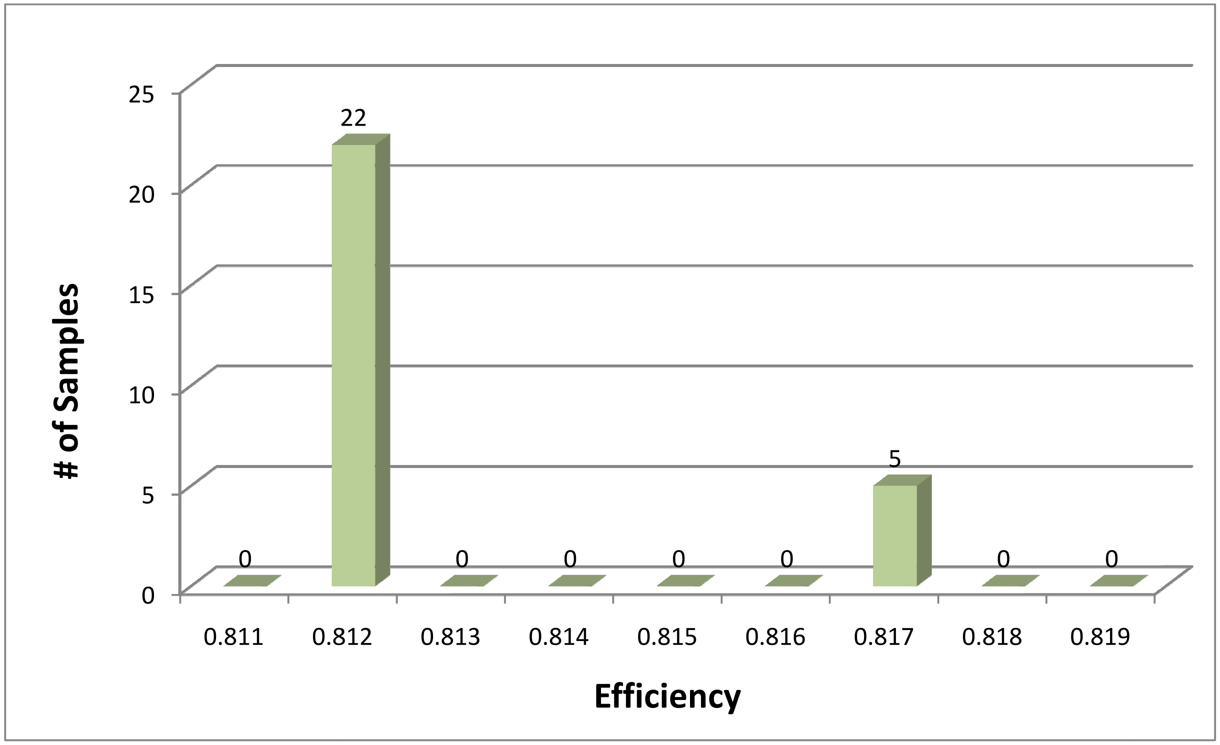

Figure 24. Histogram of Charge Efficiency Recorded on 3/17/10 @4000 W

4.2.2.2 Histograms for Discharging Efficiency

Figures 25 and 26 display two different rates of discharge efficiency (1500W and 4000W respectively), both recorded on the same day (10/28/2009). As stated above, there are exactly 27 samples in each chart. The mode for the rate of 1500W is 89% (12), and the average is slightly below at 87.88%. For the rate of 4000W, the mode is 92% (13), with the average value as 91.77%. Because these measurements were recorded during the same day, there is no disparity of losses due to time and component degradation. However, there is still ~3.9% difference in the efficiency value. This is no doubt due to the difference in discharge rates. When the AESS unit is discharging close to the maximum rated capacity (6000W), it is more efficient since all the contact switches are working regardless of rate, and thus with added power flow, the losses are generally constant. This leads to higher efficiency for a higher rate of discharge.

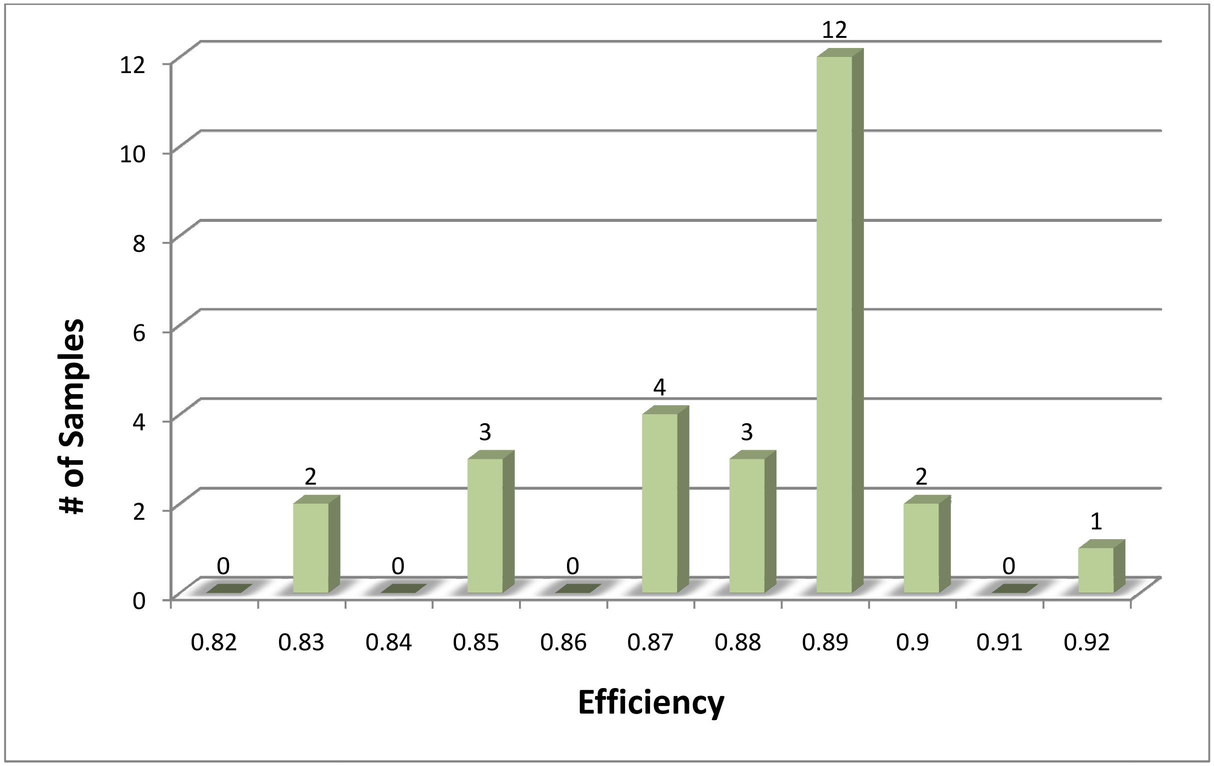

Figure 25. Histogram of Discharge Efficiency Recorded on 10/28/09 @1500 W.

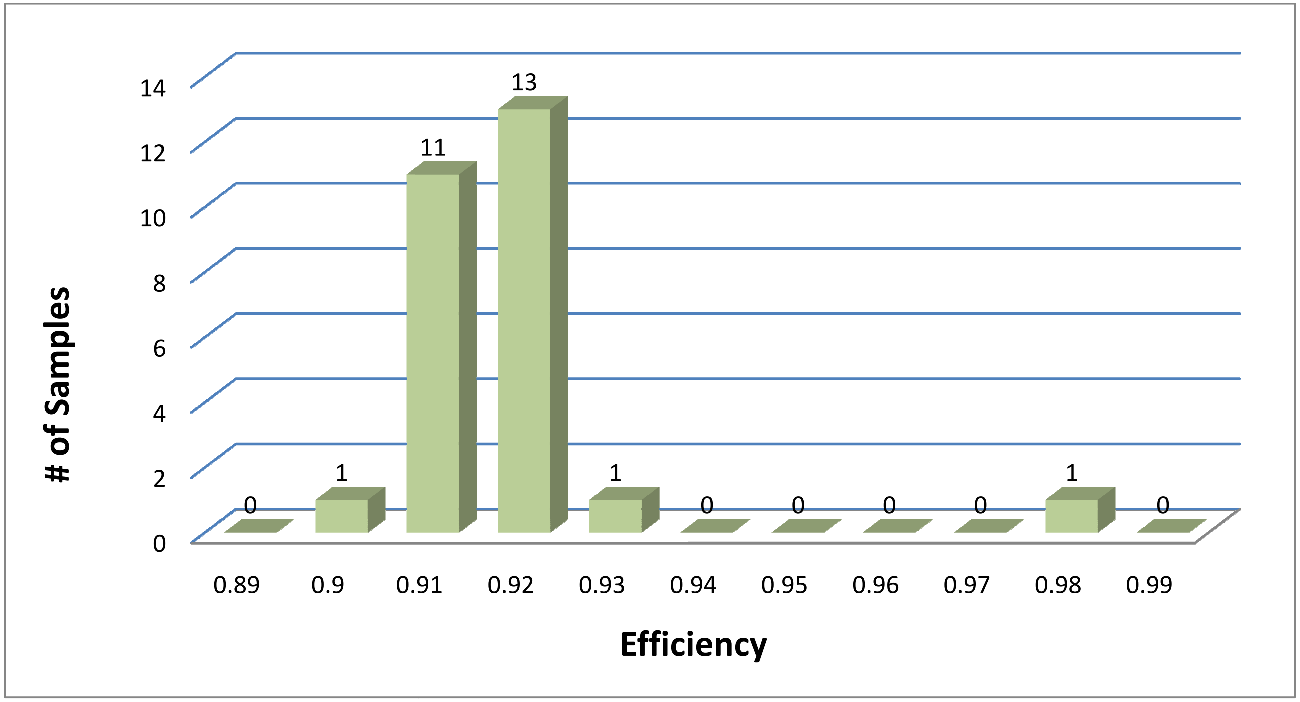

Figure 26. Histogram of Discharge Efficiency Recorded on 10/28/09 @4000 W

4.2.3. Life Cycle Estimation

The life cycle estimation is determined by retrieving the data from the full cycle charge/discharge analysis. Figure 27 below shows the analysis for ~210 days. The losses are due to:

- The shelf life of lithium batteries. It is amplified by exposure to temperatures outside the range specified by the manufacturer[26].
- Incomplete charge/discharge cycles.
- Deposits that form in the electrolyte that inhibit ion transfer.

The increase in internal resistance decreases the battery's ability to deliver current, and is more evident in higher-current applications [27]. The life cycle is a very key parameter when it comes to determining the functionality and economic value of the BESS unit.

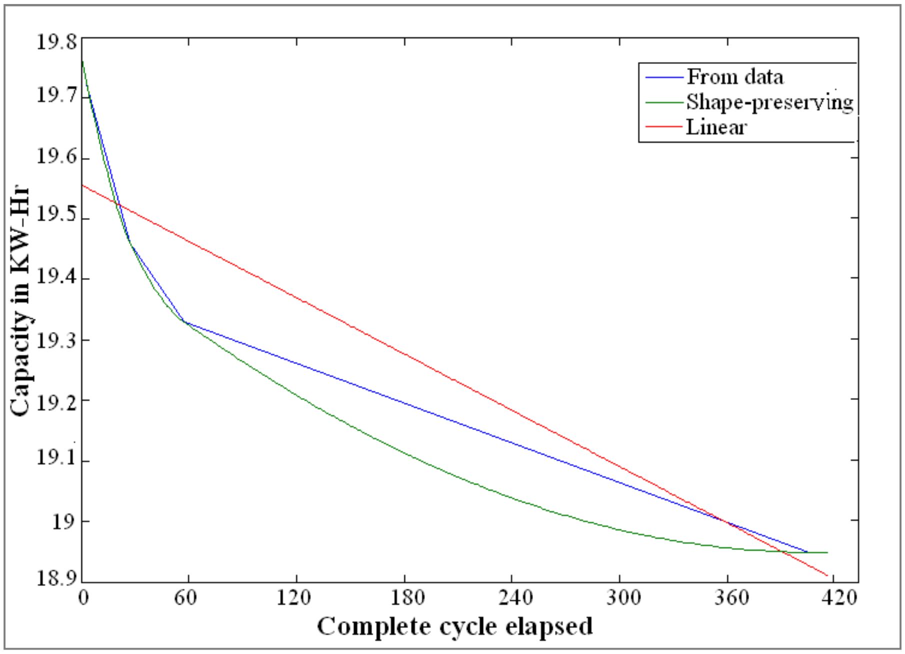

Figure 27. Capacity Decay Trend.

This plot for the capacity decay trend shows the total capacity of the LiFeP04 unit (rated max is 20kW-Hr). A complete cycle is a fully charged unit that is discharged, then fully charged again. This data is compiled on a 2 cycle/day pattern. The charge and discharge rates vary and are in the range between 3.5 kW and 4.5 kW, which is less than the manufacturer maximum limits of 6kW.

What can be inferred from the figure 27 is that clearly there is decay, but the rates vary. This could be due to a break-in period of the cells. The linear line of best fit skews the data due to this [27]. The shape preserving curve is perhaps more accurate, but it is still unknown how the AESS will fare later. From this decay trend, using linear approximation, it can be inferred that the AESS will lose 33% of maximum rated capacity (~6 KW-Hr) after 3500 cycles, or roughly 3 years. Some other important contributing factors to battery life are prolonged storage, excessive humidity causing rusty contacts and the possibility of unwanted electrolyte reaction for current transient. So regular monitoring of the battery against any sign of potential unhealthy operation is the key to long battery life.

CHAPTER 5

BESS POWER CAPACITY ESTIMATION

In order for renewable resources to be considered seriously as a major form of energy generation, they have to be harnessed and used efficiently. Harnessing renewable energy poses some problems such as voltage and frequency fluctuations, environmental changes, and availability. Power electronics are used to mitigate these issues regarding power quality. Renewable resources are currently a backup which alleviate some pressure from the rest of the grid. Solar energy is extremely variable and many factors need to be taken into account when selecting a location for solar energy harvesting. The following are some of the decisions that need to be made: What technology should be used? The location as well as the position of the sun; Should a solar tracker be installed? Cloud cover, etc. Even if one chooses the best technology and location, it remains futile to assume a consistent power output from the panels. This is of course only taking into account the times when a panel can be utilized, during the day. For more than half the time, they remain idle and unused. It is because of these reasons that a Battery Energy Storage System(BESS) needs to be installed. This analysis will focus on sizing the BESS with the power output from a PV system. It will make certain assumptions that will be addressed in the analysis. The goal of this analysis is to appropriately size the BESS according to the PV system in question. As mentioned previously, the PV system used is rated at 2kW. The analysis will take on a statistical approach.

5.1 Average of the PV Output

To analyze the BESS power capacity, the time series solar power data is analyzed. Figure 28 shows a random day. There are extreme power inconsistencies which are due to cloud cover. After a quick observation, one can conclude that since the PV system reaches only ~80% of it max. capacity, the entire day was clouded with times of minimal sunlight absorbed. In order to minimize such extremities in the data analysis, more data points need to be used which increases the confidence in the analysis. A period of 37 days were used in the analysis. The instantaneous power was taken in 10 minute intervals for those 37 days. Figure 29 shows a 15 day timespan of the data. Notice how the peaks rise and fall inconsistently, as well as the periods of no power when there is little or no sunlight. When compared to fossil fuel plants, the PV system is extremely erratic.

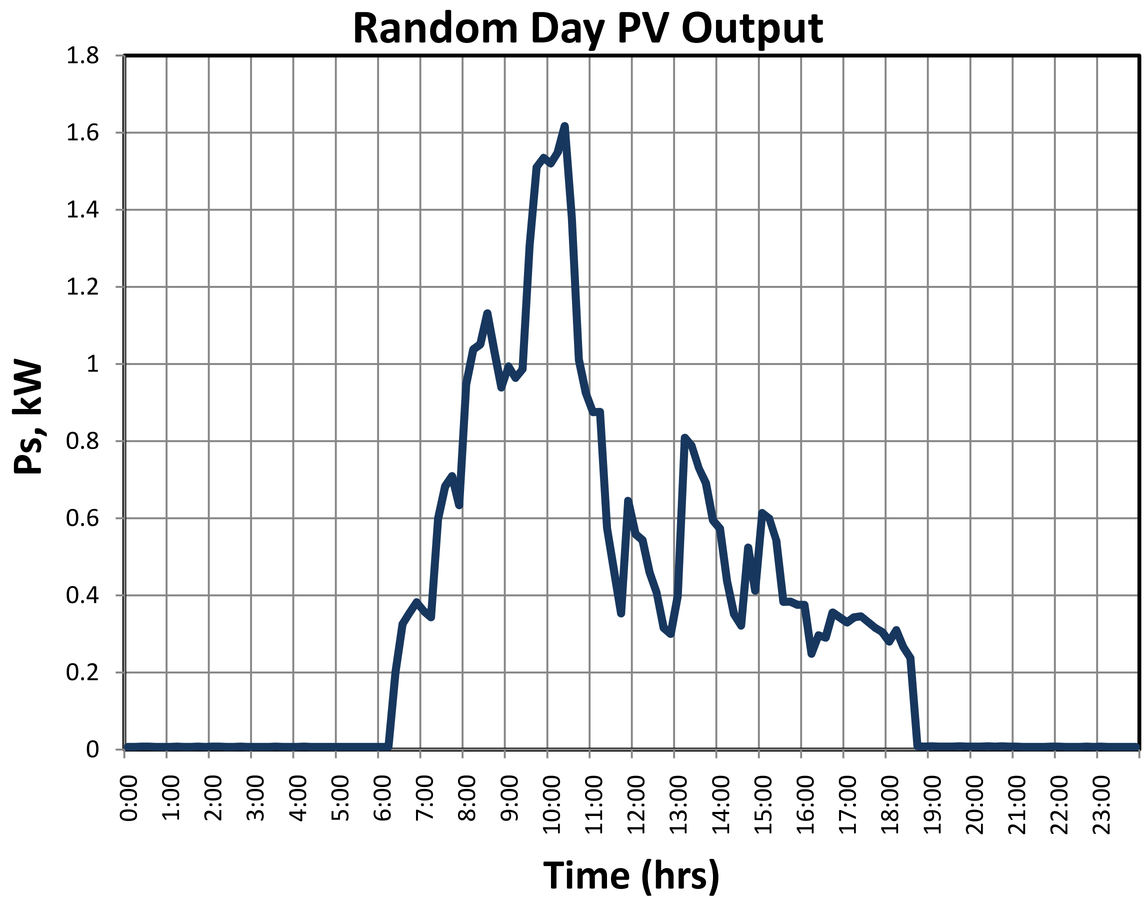

Figure 28. Random Day (Overcast)

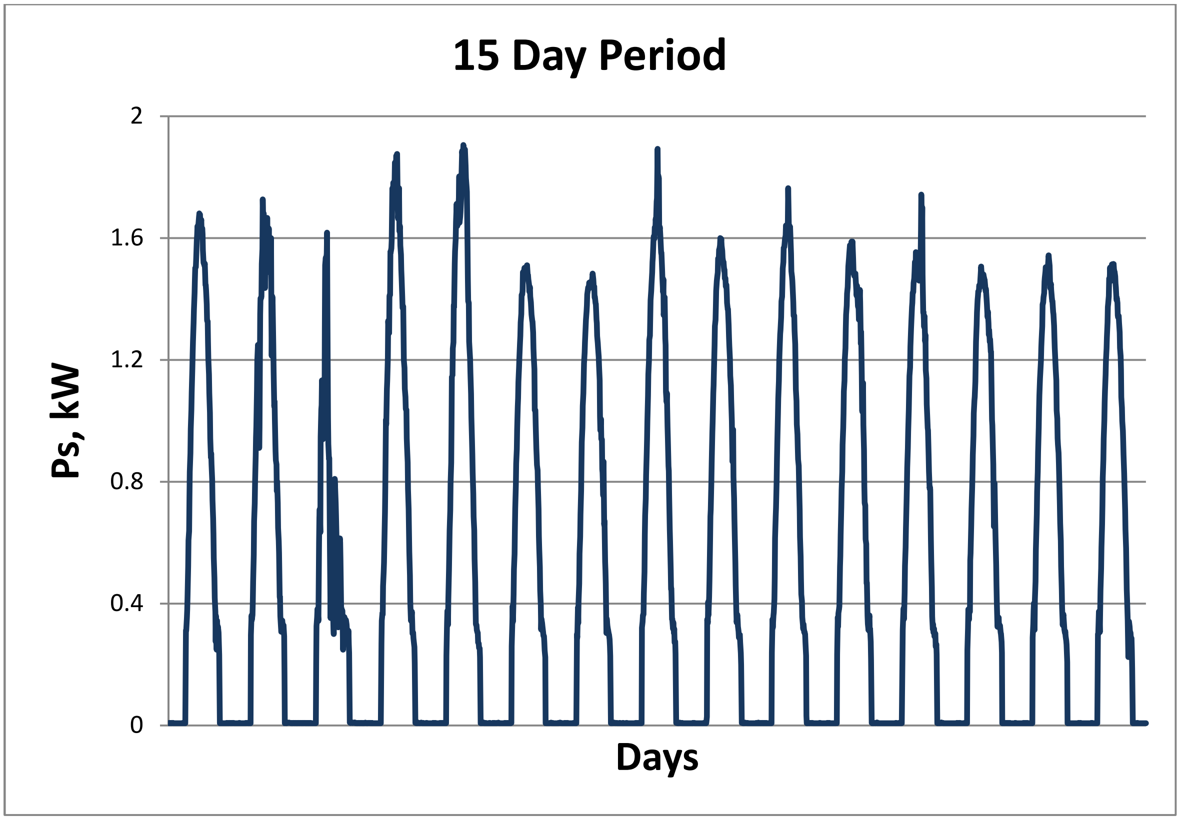

Figure 29. 15 Day Period

In order to better analyze the data, the average needed to be taken. We are analyzing a total of 5328 data points. If the average was taken for the entire period, the result will be a single value (0.49 kW). Instead, the average of every specific data point at that specific time interval was taken for the 37 day period. Since the interval is 10 minutes, there are 144 points for the entire 24 hr period. Figure 30 shows the graph of the average of all 144 data points for the 37 day period. For example, there are 37 values for the time point at 10:30 AM. The average was taken of these points. As expected, the curve is much smoother than that of figure 28. The confidence will increase as more data points are included. The maximum value is 1.504 kW. For this 37 day period, the average power is 0.49 kW and the average daily energy produced is 11.95 kW-h. It is also significant to note the the average time the panels harvest the solar power is 13 hrs and 10 minutes. Therefore, in this 13 hour span, the panels are collecting solar power at an average rate of 0.9 kW.

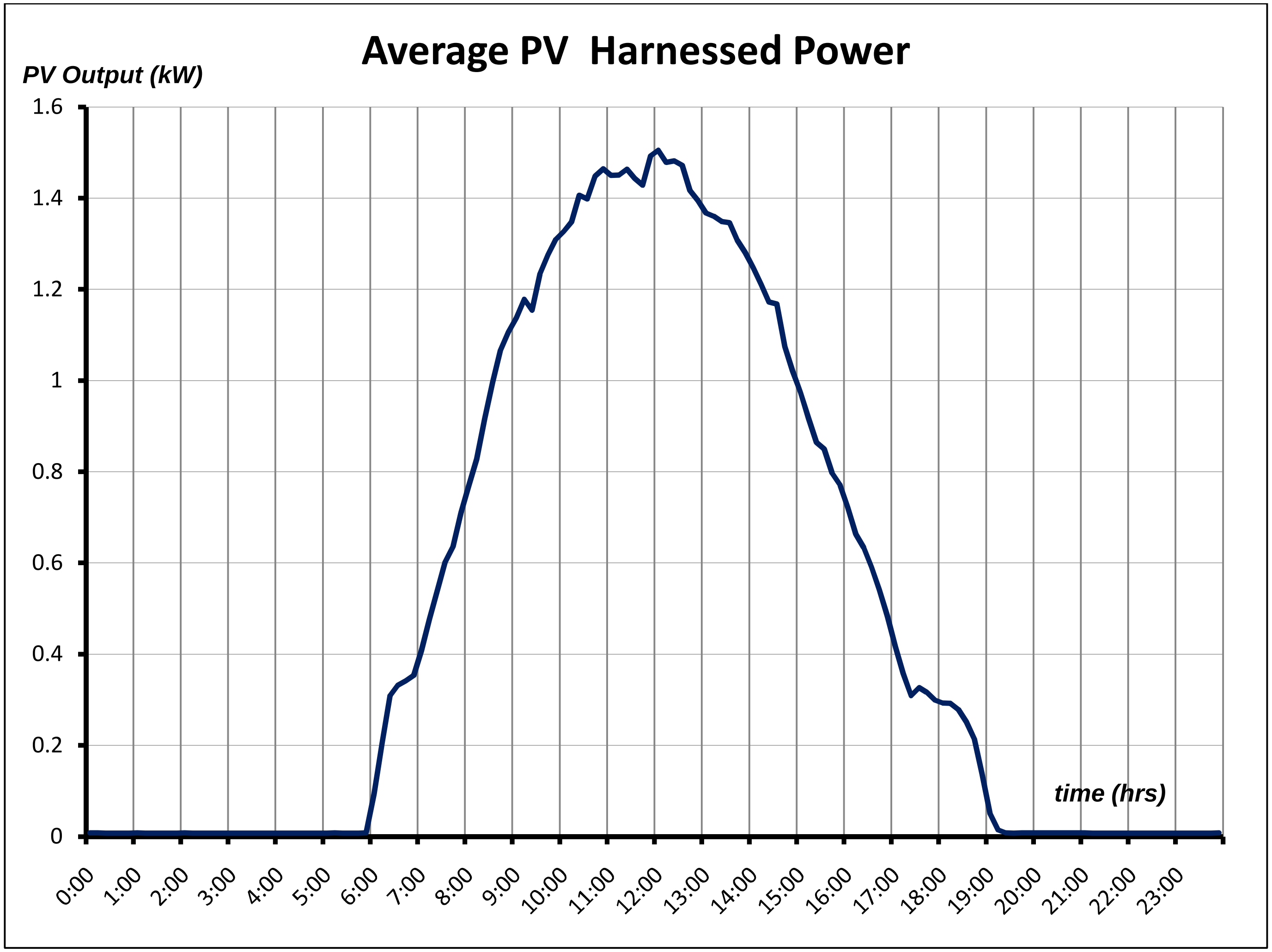

Figure 30. Average Power Harnessed by the PV System

5.2 Statistical Analysis and Power Capacity Specification

The block diagram from figure 31 below represents the connection of the PV, the power electronic components and the meter that was used to retrieve the data. The theoretical location of the BESS is also shown. This type of connection would allow for an islanded operation and for direct charging of the BESS from the PV system.

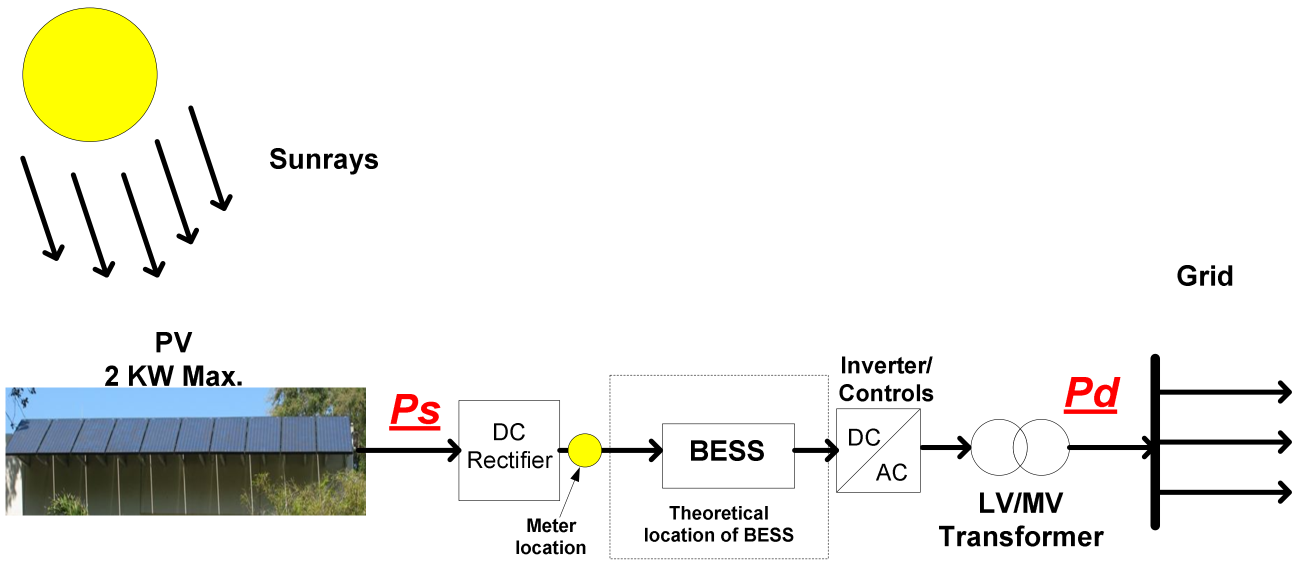

Figure 31. Block Diagram of a Theoretical BESS-PV System Connection

A few things to note about the above block diagram. Ps (solar power) is measured before entering the BESS. This is also the value stored by the data logger and is the raw data used in this analysis. Pd, or the dispatched power is the power that enters the grid directly from the BESS. In order to make the renewables more consistent, the BESS is installed to regulate the power to the grid. It will be assumed that Pd remains constant over the time interval [29]. This is beneficial because it allows for a better analysis and it thwarts Ps from impacting the power quality to the grid (voltage, frequency). The power profile of the BESS (Pbess), can be derived from:

$$P_{BESS}(t) = P_w(t) - P_d \qquad (1)$$

Because $\boldsymbol{P_d}$ will be remain constant, $\boldsymbol{P_{BESS}(t)}$ and $\boldsymbol{P_w(t)}$ will vary at the same rate. The value of $\boldsymbol{P_d}$ will be chosen arbitrarily. Using the average values obtained from figure 30, Pd was chosen to be 0.75kW.

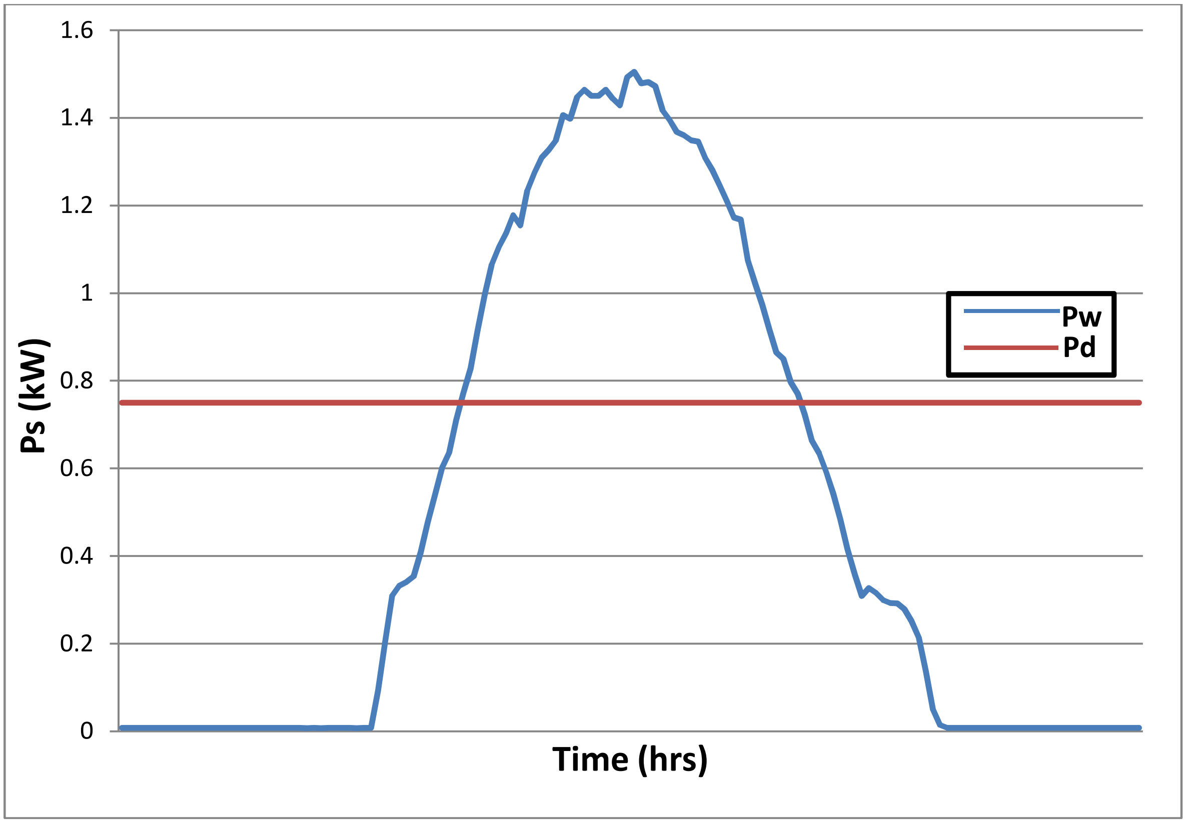

Figure 32. Average Solar Power Profile with Pd Constant

Pd is the constant dispatched power, thus the values above Pd specify that the BESS is storing, while the values below Pd specify that the BESS releases power to the grid in order to keep Pd constant.

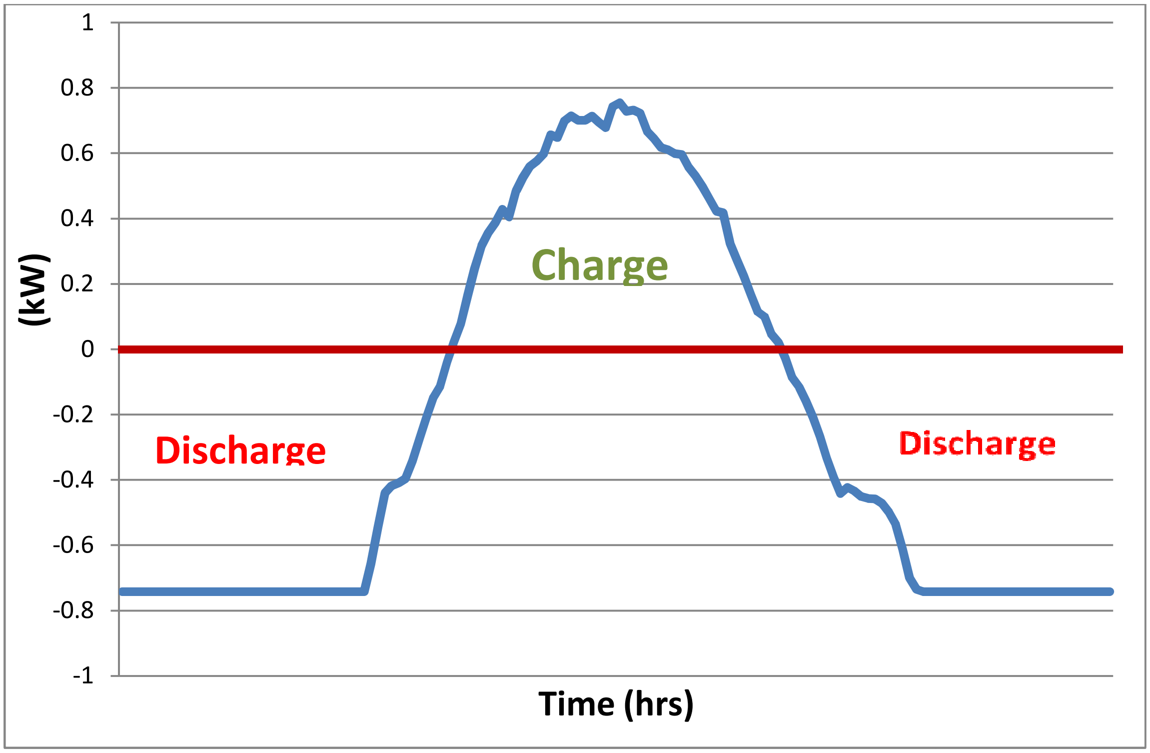

Figure 33. BESS Power Profile for Pd=0.75 kW

The above figure shows the and the positive/negative cutoff. The shape of the graph is the same as that of which follows the logic of (1). In BESS capacity sizing however, the power capacity has to be large enough to satisfy the system requirements. It is with this reasoning that we must base the BESS on its absolute value so that only positive values will appear in the design. The negative values will become absolute(positive) and will appear to be flipped about the value of 0. Figure 34 shows the absolute values of

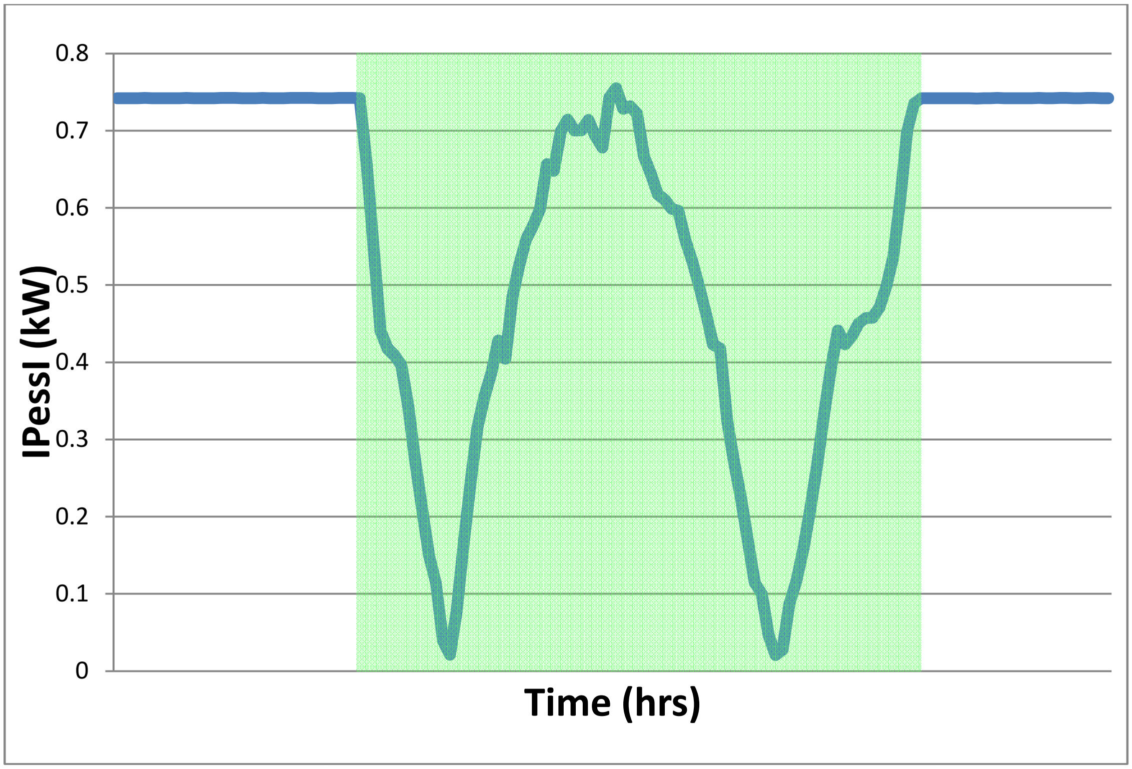

Figure 34. Absolute Values of BESS Power Profile for Pd=0.75 kW

Unlike wind farms which generate energy at all times of the day, solar energy can only be harnessed during times of sunlight. In this analysis, it was found that solar energy can be harnessed for ~13 hours and 10 minutes. The statistical analysis which follows will only take into account the times of solar energy collection. The area shaded in green will be the area used to analyze and size the BESS. Because the times of no sunlight comprise almost half the day, these would make the analysis biased and will provide uneven results.

5.3 Kernel Smoothing Density Estimation

The data comprises of continuous random variables. There are 2886 data points that fall inside the green region of figure 34. Figure 35 shows the histogram of the absolute values of the BESS power profile (figure 34) with 11 bins ranging from (0:0.075:0.825)

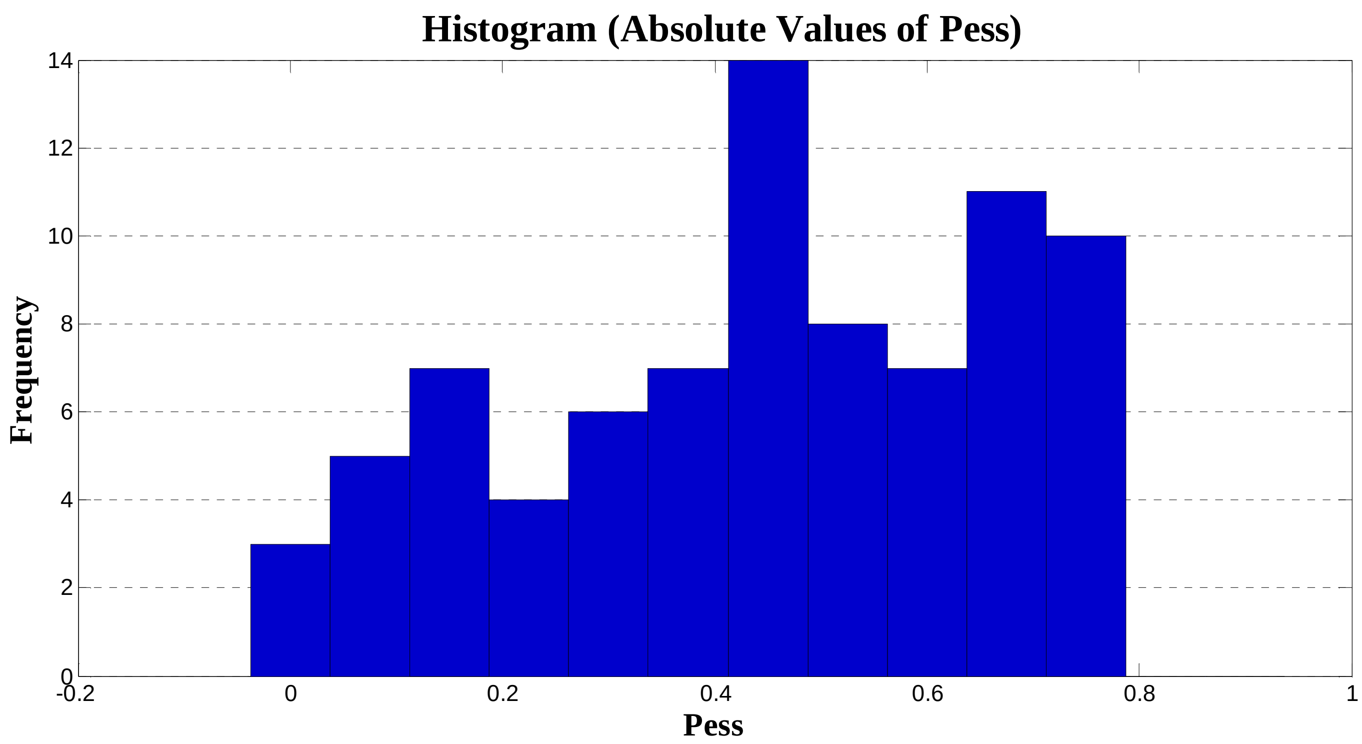

Figure 35. Histogram of the Absolute Values of BESS Power Profile

The mode falls in bin 7,(0.414:0.483) and can be seen to be 14. The probability density function (PDF) that was selected to fit with the histogram in figure 36 is derived from Kernel Smoothing Density Estimation (KSDE) [29,30]. It is a non-parametric PDF estimation method which has no dependence on parameters. It proves advantageous in this case because it can reflect the practical data more visibly. The formula for the kernal estimator is given in (2).

$$\hat{f}(x) = \frac{1}{n*h}\sum_{i=1}^{n} K*((x - X_i)/h) \quad (2)$$

K is the kernel, a symmetric function which satisfies:

$$\int K(x)dx = 1 \quad (3)$$

The variable h is for the window width of the function. The Kernel density function is related to the histogram, but has more advantages. The two most noteworthy advantages are that the sensitivity of the histogram due to the placement of the bin edges is not a problem in a Kernel smoothing estimate, and that the histogram does not display the data as efficiently as the Kernel smoothing function. By applying KSDE to the histogram in figure 35, the PDF of the absolute values is obtained and can be seen below in figure 36.

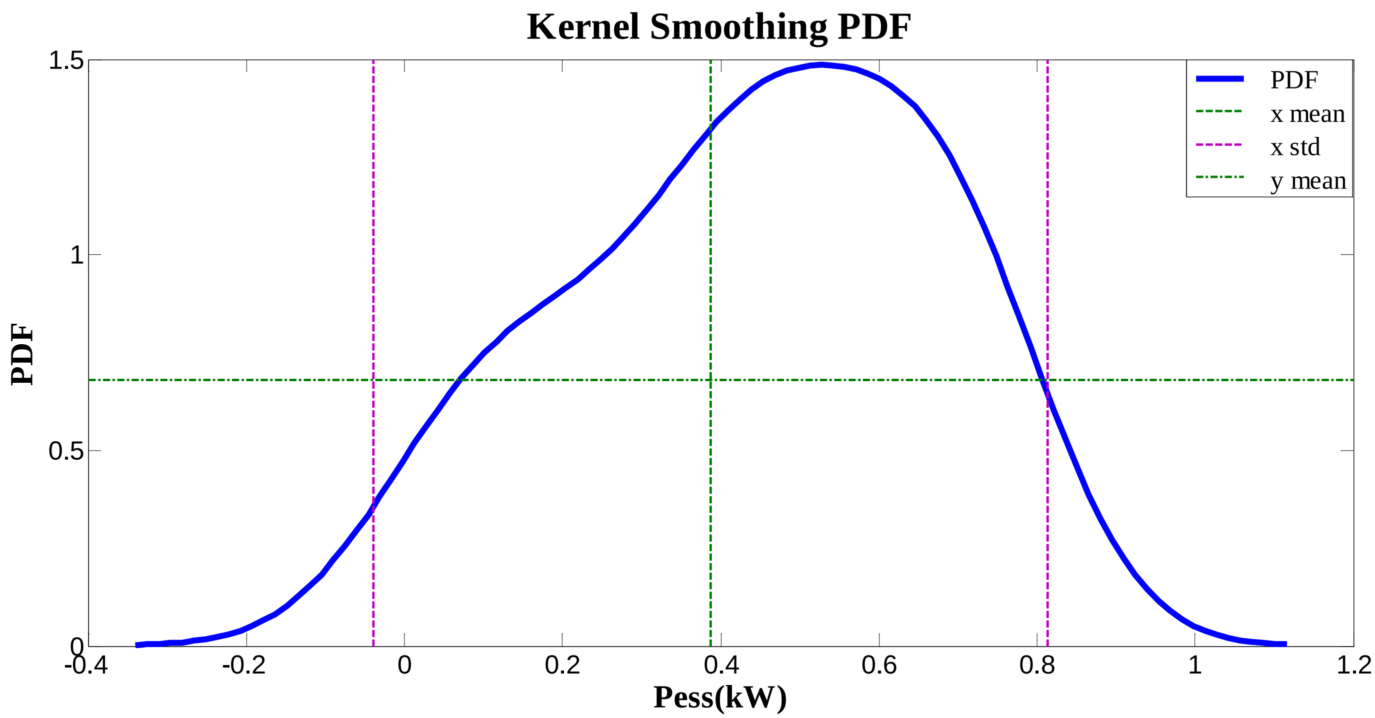

Figure 36. PDF of the Absolute Values for Pd=0.75kW

It can be seen that the curve of the PDF estimation resembles the histogram. The PDF is defined by the following equations.

$$f(x) = \int_{-\infty}^{\infty} KSDE|P_{BESS}| = 1 \qquad (4)$$

The PDF is used to evaluate probablities. This is not our goal however, and we must integrate the PDF in order to find the cumulative density function (CDF).

$$F(x) = \int_{0}^{x} f(x)dx \qquad (5)$$

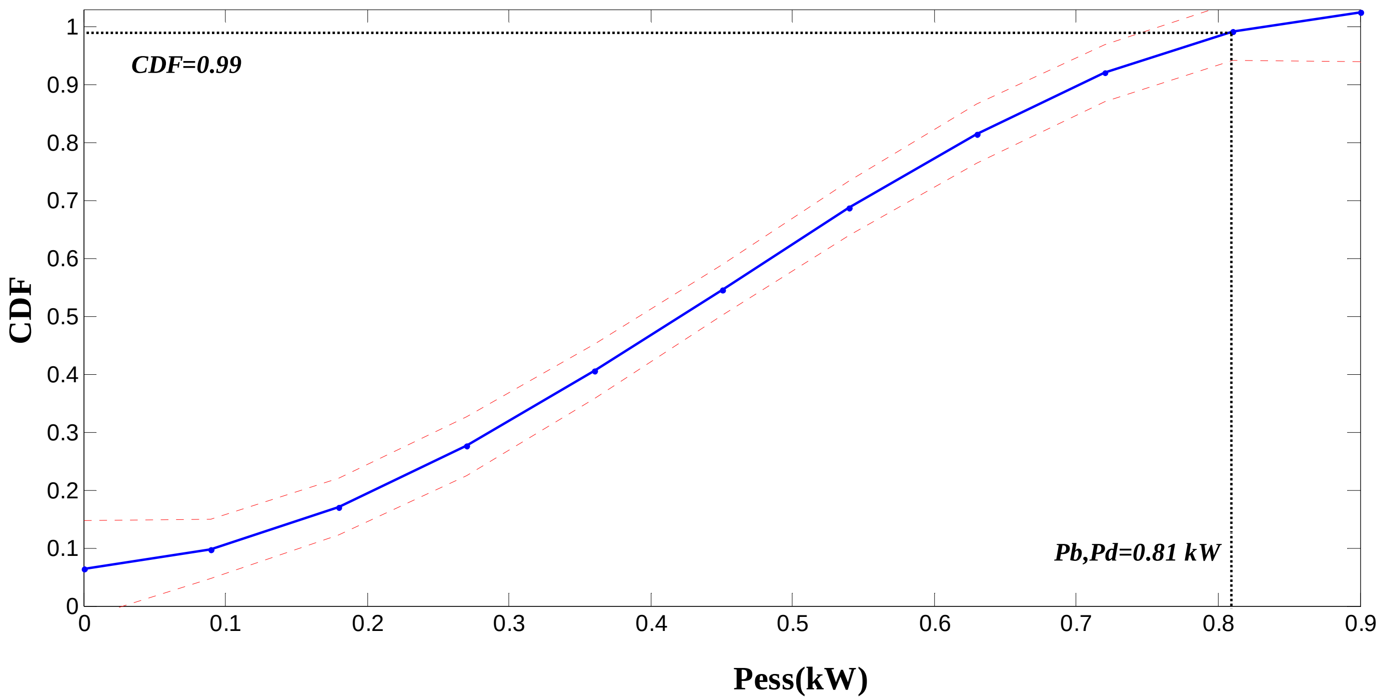

Figure 37. CDF of the Absolute Values of the BESS Power Profile for Pd=0.75kW

Figure 37 shows the CDF function. The BESS capacity can be specified to accommodate a given confidence interval. The figure shows a confidence level of 99% of the required BESS power, which corresponds to a point in figure 37 at Pb,Pd = 0.81 kW for CDF = 0.99.

$$P_{b,Pd=0.75} = F^{-1}(0.99) \quad (6)$$

What this tells us is that for a 2 kW PV unit, with a Pd set to 0.75kW, the battery needs to have a minimum power rating of 0.81kW. The energy capacity must be greater than

$$E_{BESS} = P_{b,d} * t(hrs) \quad (7)$$

$$E_{BESS} = \text{ 0.81kW*13.17hrs= 10.66 kW-h} \quad (8)$$

For this case, to constantly dispatch 0.75 kW from an isolated PV-storage system, the BESS must have a power capacity no less than 0.81 kW and an energy capacity no less than 10.66 kW-h. This is based on the average analysis as described herein. It is used as a generalization and there will be extremes that could fall outside of these ranges.

5.4 Alternate Analysis (Real Values)

An alternate analysis using the real non-averaged values provides slightly different results. There are 2753 points that will be analyzed. The remaining points are not included since they are zeros. This was depicted in figure 34. The analysis follows the same format. The histogram for this analysis is displayed in figure 38 below.

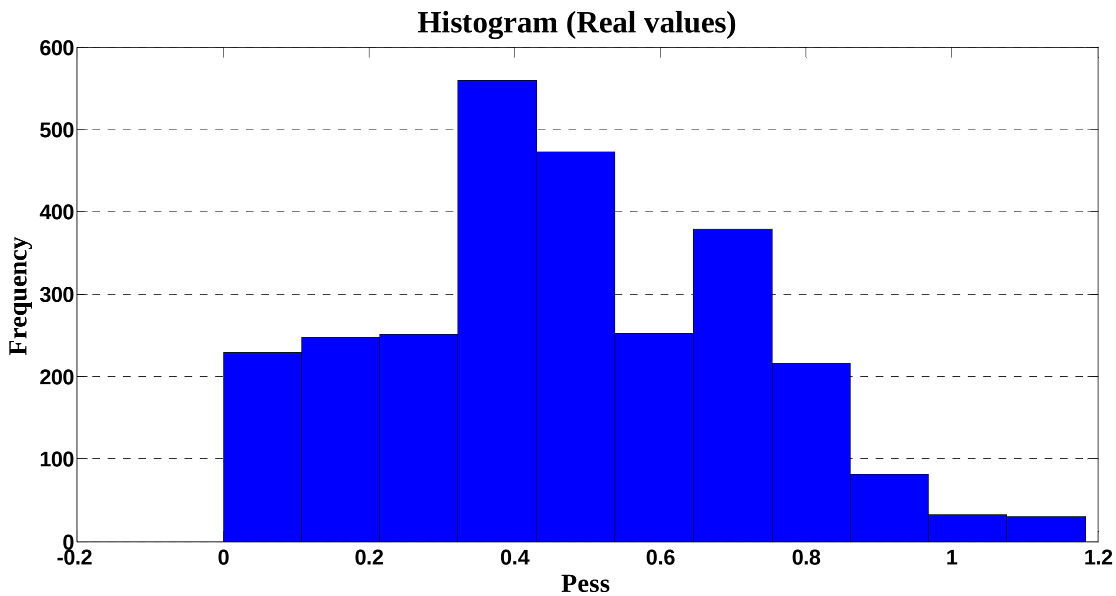

Figure 38. Histogram of the Real Values

The frequency has increased, as has the Pess values. The scale has increased from 0.8 to 1.2. All the maximums and minimums are displayed in this histogram. The pdf also changes shape since there are now 2 distinct peaks. The kernel smoothing method is used once again. The cdf is the one that changes the most. The main reason is that the range has now increased.

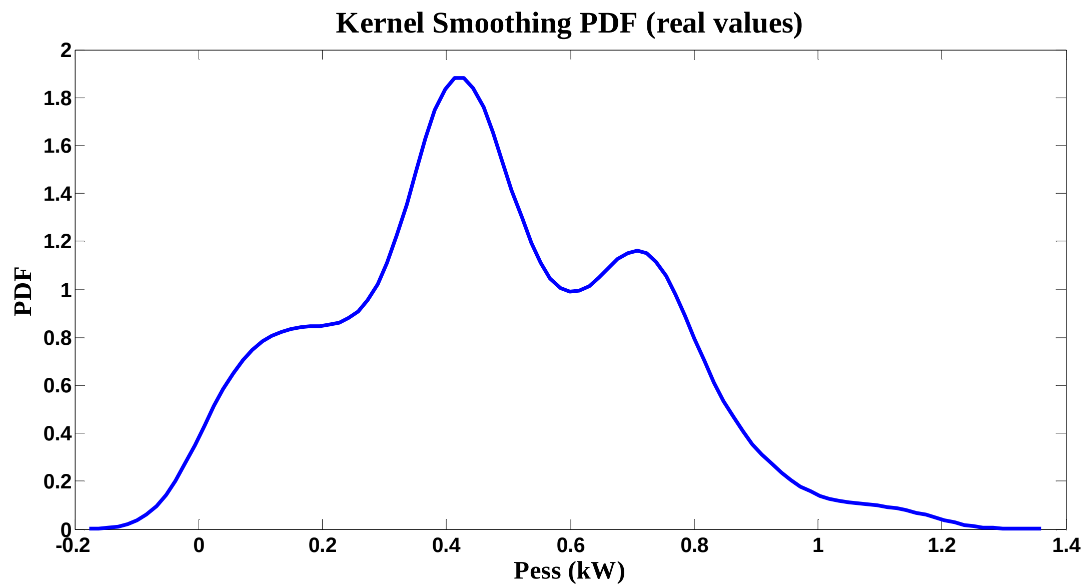

Figure 39. PDF Real Values

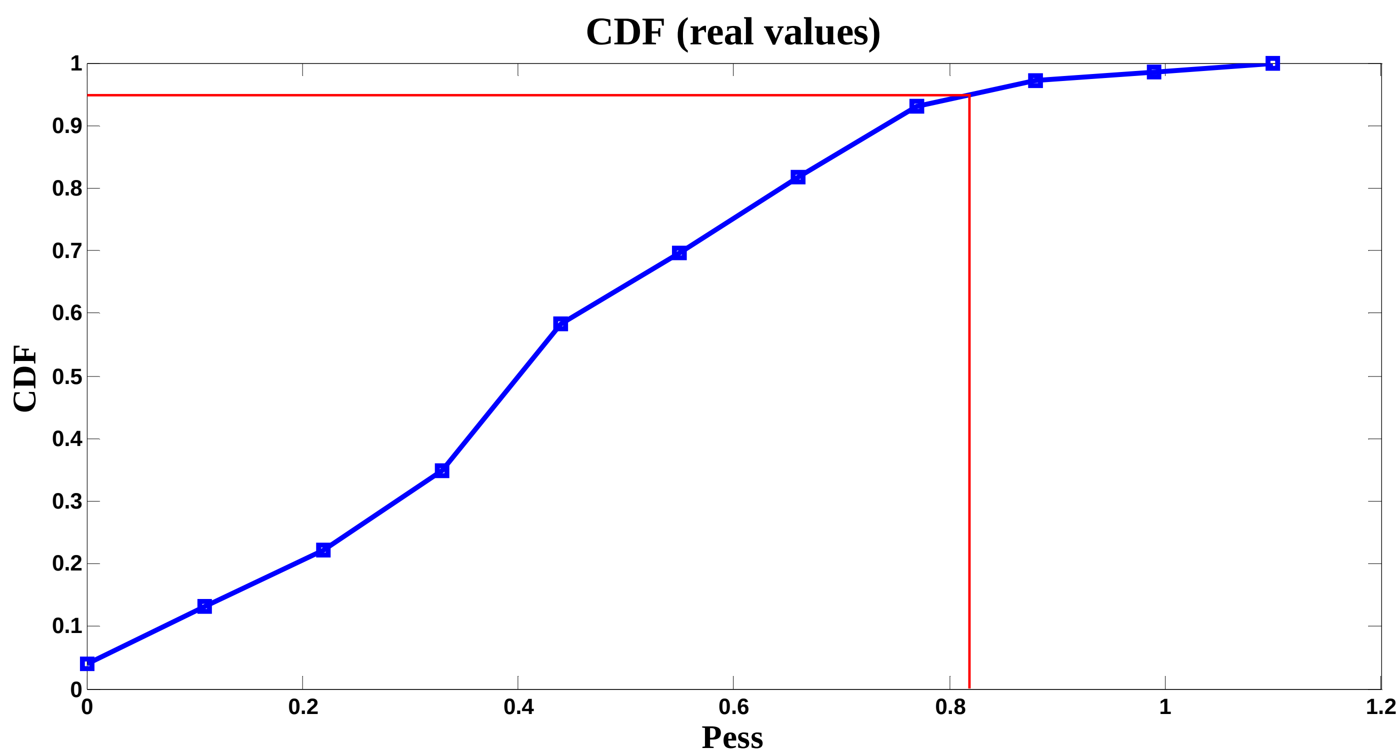

Figure 40. CDF (Real Values)

Taking a 95% confidence interval, the BESS power capacity is ~0.82 kW. When compared to the value of 0.81kW from the absolute value analysis, they are very close. Although a smaller confidence interval is taken, it is the last 5% that differentiates the two analyses. It can be omitted in the latter analysis simply because the range of the values increases which skews the study. The remaining 5% of data is >1kW.

CHAPTER 6

CONCLUSION

The aim of this research was to analyze the implementation of a PV/ AESS system to the current grid. The pilot project consisted of two identical systems installed in St. Petersburg, Florida. Each system (PV and AESS) was independently connected to the grid. The systems were to be tested and evaluated to confirm the manufacturer's specifications. After these analyses, did we then begin to develop models to best optimize the two separate systems together.

For the photovoltaics, the performance was the only thing that needed to be measured and compared to the manufacturer's claims. The systems were each rated at 2kW max generation capacity. The analyses were done over a 2 year period and during ideal conditions, the PV do reach very near their limitations. However, when the conditions faltered, i.e. during cloud cover or inclement weather, the performance faltered as expected. In summary, the panels perform best during colder temperatures, ideal tilt angles between the Sun, and finally during seasons when the days last longer.

On the other hand, testing the AESS proved more challenging and rewarding. There are many more parameters to test. Among those tested and analyzed were the round-trip efficiency and the life cycle estimation. The round-trip efficiency was below the manufacturers claims, but there are many variables at stake such as: charging/discharging rate, temperatures, cool-off time, etc. The life cycle estimation was estimated using experimental analysis of fully discharging/charging the AESS. The study was done over a 6 month period. The decay rate was then recorded for that time period, and estimated for a period of 3 years.

In addition to the performance testing, the economic side of the project was analyzed to see what the costs of future larger scale projects would be. With the current cost of PV panels and the significant cost of AESS, the economic feasibility is slightly out of reach. The life cycle estimation analysis revealed that after 3 years, the AESS is estimated to decrease in capacity by ~33%. Further study needs to be done to support or dissuade that estimate. At that rate however, the cost of replacing the unit would be too great for large scale integration. The most practical situation at this moment is for an islanded operation of the AESS, and for critical peak demand situations where the AESS will be seldom used. On the other hand, the performance of both the PV and the lithium ion technology is improving drastically, and cost is decreasing.

The smart grid can only function with the implementation of new forms of renewable power generation, improved communication and energy storage. Each of these technologies is advancing and together they will form the future grid, the smart grid which will have improved reliability, efficiency, longevity and self-healing capability.

6.1 Further Study

Continuing the research done in this thesis, the next step would be to locate ideal installation sites for larger scale AESS. The goal is to propose methods and algorithms for determining the installation site, the calculation, and analysis of financial and technical benefits. Although SEEDS will bring other benefits to the systems such as: regulation of frequency and voltage control, spinning reserve etc., we will primarily focus on the load leveling and its benefits to the power systems. We will use the experience gained from the two pilot SEEDS installations at USF St. Petersburg based on the Lithium – Ion Batteries (AESS). The round trip efficiency calculations and the life cycle estimation will be the main resource used. Firstly, the best candidate site for a SEEDS installation will be determined from the load profiles of the sites in question. Then, cost effectiveness and the financial benefits of the proposed system will be analyzed. Both steps will be in a form of optimized algorithms with proposed methods, goals, constraints, and benefits obtained from the system. The proposed methods and algorithms are not absolute. They can be modified or improved if is necessary.

6.1.1 Determination of an AESS Installation Site

The potential candidates for the AESS installation are found on the secondary side of a distribution substations' (MTr) main transformer. Figure 41, shows an example of a medium voltage substation, which then drops to low voltage after the main bus [31]. L1 through L6 represent 6 different load regions, each with a slightly different load profile. The load pattern of a main distribution transformer is analyzed and then compared with the load pattern of the total power system (regional). If the load factor improves, then the location is determined to be an AESS installation site. The transformer bank with a similar pattern will be selected as the AESS installation site.

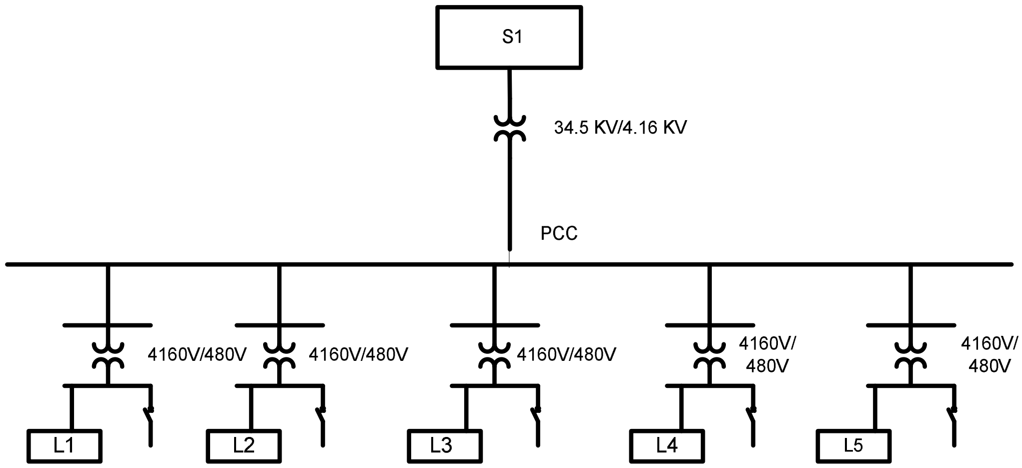

Figure 41. Substation Bus Diagram

REFERENCES

1. Tesla, N., "A New System of Alternating Current Motors and Transformers," AIEE meeting , May16, 1888

2. US Electric Power Industry Overview 2009, US Energy Information Administration, http://www.eia.doe.gov/cneaf/electricity/epa/epa_noticerev.html

3. LaCommare, K.H., and J.H. Eto. 2004. "Understanding the Cost of Power Interruptions to U.S Electricity Customers". LBNL-55718. Berkeley: Lawrence Berkeley National Laboratory. February, 2006

4. Islam, A. "Smart Grid Reliability Assessment Under Variable Weather Conditions". March, 2009

5. Renewables 2010 Global Status Report. REN, pg.15-17.

6. Pruggler, W., Kupzog, F., Bletterie, B., & Helfried, B. (2008). "Active grid integration of distributed generation utilizing existing infrastructure more efficiently - an Austrian case study."

7. Tesla Motors Inc. http://www.teslamotors.com/

8. Pecas Lopes, J.A., Soares, F.J., Rocha Almeida, P.M,"Identifying Management Procedures to Deal with Connection of Electric Vehicles in the Grid". 2009 IEEE Bucharest Power Tech Conference

9. Zhenhua, J., Li, F., Qiao, W. Sun, H., Wan, H., Wang, J. et al. (2009). A vision of smart transmission grids. Proceedings of the Power & Energy Society General Meeting. <http://ieeexplore.ieee.org/xpl/mostRecentIssue.jsp?punumber=5230481>

10. US Electric Power Industry Overview 2010, US Energy Information Administration, http://www.eia.doe.gov/cneaf/electricity/epm/table1_1.html

11. Clement, K. ,Pardon, I. ,Driesen, J. “Standby Power Consumption in Belgium”. IEEE, Electrical Power Quality and Utilisation, 2007. EPQU 2007. 9th International Conference on. 9/11/2007.

12. Standby Power Use and the IEA “1-watt Plan”. http://www.iea.org/papers/2007/standby_fact.pdf, April, 2007

13. Charles River Associates, “Primer on Demand-Side-Management”, February 2005

14. Kroposki, B.; Margolis, R.; Lynn, K.; , "Power to the People [Guest Editorial]," *Power and Energy Magazine, IEEE* , vol.9, no.3, pp.16-22, May-June 2011
doi: 10.1109/MPE.2011.940468
URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5753329&isnumber=5753319

15. “Clean Energy for the Next Generation: Martin Next Generation Solar Energy Center” ,10/1/11, http://www.fpl.com/environment/solar/martin.shtml

16. ITU global standard for international mobile telecommunications ‘IMT-Advanced’”, 10/07/2010, http://www.itu.int/ITU-R/

17. IEC 61850 Protocol API User Manual”, www.beck-ipc.com/en/.../load.asp?f=/.../IEC61850_Protocol...pdf

18. Parziale, Lydia; Britt, David T; et al; “TCP/IP Tutorial and Technical Overview”, Redbooks, Dec. 2006

19. Kwok-Hong Mak; Holland, B.L.; , "Migrating electrical power network SCADA systems to TCP/IP and Ethernet networking," *Power Engineering Journal* , vol.16, no.6, pp.305-311, Dec. 2002
doi: 10.1049/pe:20020604
URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=1159872&isnumber=26003

20. Liberatore, V.; Al-Hammouri, A.; , "Smart grid communication and co-simulation," *Energytech, 2011 IEEE* , vol., no., pp.1-5, 25-26 May 2011
doi: 10.1109/EnergyTech.2011.5948542
URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5948542&isnumber=5948497

21. Jamian, J.J.; Mustafa, M.W.; Mokhlis, H.; Baharudin, M.A.; , "Smart grid communication concept for frequency control in distribution system," *Power Engineering and Optimization Conference (PEOCO), 2011 5th International* , vol., no., pp.238-242, 6-7 June 2011
doi: 10.1109/PEOCO.2011.5970455
URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5970455&isnumber=5970379

22. GreenSmith Energy Management Systems LLC. http://greensmith.us.com/

23. Dent Instruments . http://www.dentinstruments.com/ELOG.htm

24. Wysocki, Joseph J.; Rappaport, Paul; , "Effect of Temperature on Photovoltaic Solar Energy Conversion," *Journal of Applied Physics* , vol.31, no.3, pp.571-578, Mar 1960
doi: 10.1063/1.1735630
URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5123556&isnumber=5123531

25. Farahat, M.A.; , "Improvement the thermal electric performance of a photovoltaic cells by cooling and concentration techniques," *Universities Power Engineering Conference, 2004. UPEC 2004. 39th International* , vol.2, no., pp. 623- 628 vol. 1, 6-8 Sept. 2004
doi: 10.1109/UPEC.2004.192424
URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=1492095&isnumber=32068

26. Tom Hund, "Capacity Loss in PV Batteries and Recovery Procedure", Research report from Sandia National Laboratories, under the contract between Lockheed Martin company and Department of Energy, April 2000

27. Islam, M.; Omole, A.; Islam, A.; Domijan, A.; , "Dynamic capacity estimation for a typical grid-tied event programmable Li-FePO4 battery," *Energy Conference and Exhibition (EnergyCon), 2010 IEEE International* , vol., no., pp.594-599, 18-22 Dec. 2010
doi: 10.1109/ENERGYCON.2010.5771751
URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5771751&isnumber=5771653

28. Wenzhong Gao; Xiaoyu Wang; Muljadi, E.; , "Probability-based method for power capacity specification of wind energy storage systems," *Industrial Electronics and Applications (ICIEA), 2011 6th IEEE Conference on* , vol., no., pp.2050-2055, 21-23 June 2011
doi: 10.1109/ICIEA.2011.5975930
URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5975930&isnumber=5975538

29. Bowman, A W, and Adelchi Azzalini. *Applied Smoothing Techniques for Data Analysis: The Kernel Approach with S-Plus Illustrations*. Oxford: Clarendon Press, 1997. Print.

30. Wand, M P, and M C. Jones. *Kernel Smoothing*. London: Chapman & Hall, 1995. Print

31. Kyung-Hee Jung; Hoyong Kim; Daeseok Rho; , "Determination of the installation site and optimal capacity of the battery energy storage system for load leveling," *Energy Conversion, IEEE Transactions on* , vol.11, no.1, pp.162-167, Mar 1996
doi: 10.1109/60.486591

APPENDICES

Appendix A: MATLAB Code

```
%hist(data,12);
%ksdensity(data)

histfit(finalhist,11)      %histogram plot

ldata= length(finalhist);
b=(0:0.11:1.2);
h=hist(finalhist,b);

maxh=max(h);
cs=cumsum(h/ldata);


plot(b,cs,'k-s')     % cumulative sum of (data)
%cftool

hold on


[f,xi]=ksdensity(finalhist);
%plot(xi,f)
%pdf([f,xi])
%[f,xi,u] = ksdensity(newhist);

%f=ksdensity(x,xi);
%a=cumsum(ksdensity(data));
%plot(a);

plot(xi,f,'b','linewidth',2);   %Kernel Smoothing PDF
%xlabel('Pess');
```

Appendix B: Excel Spreadsheet

Date	Point	Time	Value(Kw)	Average	Pd=0.75	Pess-Pd	Abs()
4/17/2009	1	0:00	0.007	0.00789189	0.75	-0.74211	0.742108
	2	0:10	0.007	0.00786486	0.75	-0.74214	0.742135
	3	0:20	0.008	0.00783784	0.75	-0.74216	0.742162
	4	0:30	0.007	0.00775676	0.75	-0.74224	0.742243
	5	0:40	0.007	0.00767568	0.75	-0.74232	0.742324
	6	0:50	0.007	0.00772973	0.75	-0.74227	0.74227
	7	1:00	0.007	0.00786486	0.75	-0.74214	0.742135
	8	1:10	0.007	0.00772973	0.75	-0.74227	0.74227
	9	1:20	0.008	0.00778378	0.75	-0.74222	0.742216
	10	1:30	0.008	0.00775676	0.75	-0.74224	0.742243
	11	1:40	0.007	0.00764865	0.75	-0.74235	0.742351
	12	1:50	0.007	0.00772973	0.75	-0.74227	0.74227
	13	2:00	0.007	0.00789189	0.75	-0.74211	0.742108
	14	2:10	0.007	0.00783784	0.75	-0.74216	0.742162
	15	2:20	0.007	0.0077027	0.75	-0.7423	0.742297
	16	2:30	0.007	0.00767568	0.75	-0.74232	0.742324
	17	2:40	0.007	0.00764865	0.75	-0.74235	0.742351
	18	2:50	0.007	0.00764865	0.75	-0.74235	0.742351
	19	3:00	0.007	0.00783784	0.75	-0.74216	0.742162
	20	3:10	0.007	0.00772973	0.75	-0.74227	0.74227
	21	3:20	0.007	0.00775676	0.75	-0.74224	0.742243
	22	3:30	0.007	0.00767568	0.75	-0.74232	0.742324
	23	3:40	0.007	0.00781081	0.75	-0.74219	0.742189
	24	3:50	0.007	0.00783784	0.75	-0.74216	0.742162
	25	4:00	0.007	0.00772973	0.75	-0.74227	0.74227
	26	4:10	0.007	0.00767568	0.75	-0.74232	0.742324
	27	4:20	0.007	0.00751351	0.75	-0.74249	0.742486
	28	4:30	0.007	0.00767568	0.75	-0.74232	0.742324
	29	4:40	0.007	0.00756757	0.75	-0.74243	0.742432
	30	4:50	0.007	0.00775676	0.75	-0.74224	0.742243
	31	5:00	0.007	0.0077027	0.75	-0.7423	0.742297
	32	5:10	0.007	0.00786486	0.75	-0.74214	0.742135
	33	5:20	0.008	0.00764865	0.75	-0.74235	0.742351
	34	5:30	0.007	0.00756757	0.75	-0.74243	0.742432
	35	5:40	0.007	0.00762162	0.75	-0.74238	0.742378
	36	5:50	0.007	0.00808108	0.75	-0.74192	0.741919
	37	6:00	0.007	0.09364865	0.75	-0.65635	0.656351
	38	6:10	0.007	0.20445946	0.75	-0.54554	0.545541
	39	6:20	0.312	0.30940541	0.75	-0.44059	0.440595

Appendix B (Continued)

40	6:30	0.313	0.33202703	0.75	-0.41797	0.417973
41	6:40	0.353	0.3412973	0.75	-0.4087	0.408703
42	6:50	0.38	0.35348649	0.75	-0.39651	0.396514
43	7:00	0.422	0.40789189	0.75	-0.34211	0.342108
44	7:10	0.522	0.47662162	0.75	-0.27338	0.273378
45	7:20	0.608	0.54002703	0.75	-0.20997	0.209973
46	7:30	0.638	0.60135135	0.75	-0.14865	0.148649
47	7:40	0.748	0.63567568	0.75	-0.11432	0.114324
48	7:50	0.832	0.71072973	0.75	-0.03927	0.03927
49	8:00	0.893	0.77118919	0.75	0.021189	0.021189
50	8:10	0.973	0.82802703	0.75	0.078027	0.078027
51	8:20	1.036	0.91597297	0.75	0.165973	0.165973
52	8:30	1.093	0.99632432	0.75	0.246324	0.246324
53	8:40	1.17	1.06572973	0.75	0.31573	0.31573
54	8:50	1.22	1.10597297	0.75	0.355973	0.355973
55	9:00	1.261	1.13735135	0.75	0.387351	0.387351
56	9:10	1.322	1.17821622	0.75	0.428216	0.428216
57	9:20	1.365	1.15448649	0.75	0.404486	0.404486
58	9:30	1.419	1.2342973	0.75	0.484297	0.484297
59	9:40	1.464	1.27540541	0.75	0.525405	0.525405
60	9:50	1.501	1.30927027	0.75	0.55927	0.55927
61	10:00	1.505	1.32672973	0.75	0.57673	0.57673
62	10:10	1.531	1.34797297	0.75	0.597973	0.597973
63	10:20	1.593	1.40672973	0.75	0.65673	0.65673
64	10:30	1.609	1.39786486	0.75	0.647865	0.647865
65	10:40	1.638	1.44840541	0.75	0.698405	0.698405
66	10:50	1.605	1.46437838	0.75	0.714378	0.714378
67	11:00	1.645	1.45027027	0.75	0.70027	0.70027
68	11:10	1.67	1.45048649	0.75	0.700486	0.700486
69	11:20	1.681	1.46389189	0.75	0.713892	0.713892
70	11:30	1.677	1.44372973	0.75	0.69373	0.69373
71	11:40	1.65	1.42837838	0.75	0.678378	0.678378
72	11:50	1.646	1.493	0.75	0.743	0.743
73	12:00	1.659	1.50489189	0.75	0.754892	0.754892
74	12:10	1.617	1.47843243	0.75	0.728432	0.728432
75	12:20	1.631	1.48164865	0.75	0.731649	0.731649
76	12:30	1.612	1.47202703	0.75	0.722027	0.722027
77	12:40	1.56	1.41681081	0.75	0.666811	0.666811
78	12:50	1.519	1.39464865	0.75	0.644649	0.644649
79	13:00	1.519	1.36762162	0.75	0.617622	0.617622
80	13:10	1.509	1.3607027	0.75	0.610703	0.610703

Appendix B (Continued)

81	13:20	1.516	1.349	0.75	0.599	0.599
82	13:30	1.446	1.346	0.75	0.596	0.596
83	13:40	1.444	1.30808108	0.75	0.558081	0.558081
84	13:50	1.428	1.28067568	0.75	0.530676	0.530676
85	14:00	1.382	1.24732432	0.75	0.497324	0.497324
86	14:10	1.33	1.21083784	0.75	0.460838	0.460838
87	14:20	1.327	1.17267568	0.75	0.422676	0.422676
88	14:30	1.257	1.168	0.75	0.418	0.418
89	14:40	1.204	1.07413514	0.75	0.324135	0.324135
90	14:50	1.152	1.02140541	0.75	0.271405	0.271405
91	15:00	1.092	0.97375676	0.75	0.223757	0.223757
92	15:10	1.026	0.91740541	0.75	0.167405	0.167405
93	15:20	0.942	0.86456757	0.75	0.114568	0.114568
94	15:30	0.879	0.84972973	0.75	0.09973	0.09973
95	15:40	0.892	0.79664865	0.75	0.046649	0.046649
96	15:50	0.856	0.77062162	0.75	0.020622	0.020622
97	16:00	0.807	0.72216216	0.75	-0.02784	0.027838
98	16:10	0.739	0.66316216	0.75	-0.08684	0.086838
99	16:20	0.679	0.63364865	0.75	-0.11635	0.116351
100	16:30	0.628	0.59148649	0.75	-0.15851	0.158514
101	16:40	0.55	0.54148649	0.75	-0.20851	0.208514
102	16:50	0.485	0.48302703	0.75	-0.26697	0.266973
103	17:00	0.419	0.41624324	0.75	-0.33376	0.333757
104	17:10	0.372	0.35794595	0.75	-0.39205	0.392054
105	17:20	0.275	0.30897297	0.75	-0.44103	0.441027
106	17:30	0.359	0.32686486	0.75	-0.42314	0.423135
107	17:40	0.249	0.31618919	0.75	-0.43381	0.433811
108	17:50	0.344	0.29927027	0.75	-0.45073	0.45073
109	18:00	0.309	0.29275676	0.75	-0.45724	0.457243
110	18:10	0.324	0.29232432	0.75	-0.45768	0.457676
111	18:20	0.304	0.27864865	0.75	-0.47135	0.471351
112	18:30	0.267	0.25164865	0.75	-0.49835	0.498351
113	18:40	0.232	0.21383784	0.75	-0.53616	0.536162
114	18:50	0.007	0.13724324	0.75	-0.61276	0.612757
115	19:00	0.007	0.05051351	0.75	-0.69949	0.699486
116	19:10	0.007	0.01454054	0.75	-0.73546	0.735459
117	19:20	0.007	0.00786486	0.75	-0.74214	0.742135
118	19:30	0.007	0.00778378	0.75	-0.74222	0.742216

Appendix B (Continued)

119	19:40	0.007	0.00786486	0.75	-0.74214	0.742135
120	19:50	0.007	0.00791892	0.75	-0.74208	0.742081
121	20:00	0.007	0.00794595	0.75	-0.74205	0.742054
122	20:10	0.007	0.00805405	0.75	-0.74195	0.741946
123	20:20	0.007	0.00794595	0.75	-0.74205	0.742054
124	20:30	0.007	0.00805405	0.75	-0.74195	0.741946
125	20:40	0.007	0.00818919	0.75	-0.74181	0.741811
126	20:50	0.007	0.00802703	0.75	-0.74197	0.741973
127	21:00	0.007	0.008	0.75	-0.742	0.742
128	21:10	0.007	0.00764865	0.75	-0.74235	0.742351
129	21:20	0.007	0.0077027	0.75	-0.7423	0.742297
130	21:30	0.008	0.0077027	0.75	-0.7423	0.742297
131	21:40	0.007	0.0077027	0.75	-0.7423	0.742297
132	21:50	0.007	0.00775676	0.75	-0.74224	0.742243
133	22:00	0.007	0.00783784	0.75	-0.74216	0.742162
134	22:10	0.007	0.00764865	0.75	-0.74235	0.742351
135	22:20	0.008	0.00781081	0.75	-0.74219	0.742189
136	22:30	0.008	0.00778378	0.75	-0.74222	0.742216
137	22:40	0.007	0.00767568	0.75	-0.74232	0.742324
138	22:50	0.007	0.00762162	0.75	-0.74238	0.742378
139	23:00	0.007	0.00775676	0.75	-0.74224	0.742243
140	23:10	0.007	0.00772973	0.75	-0.74227	0.74227
141	23:20	0.008	0.00764865	0.75	-0.74235	0.742351
142	23:30	0.007	0.00764865	0.75	-0.74235	0.742351
143	23:40	0.008	0.00772973	0.75	-0.74227	0.74227
144	23:50	0.008	0.00789189	0.75	-0.74211	0.742108

Appendix C: Dent Instruments Data Logger Spec Sheet

ELITE*pro*□ **Technical Specifications**

3 Voltage Channels 0-600 Volts AC or DC, Higher voltages can be measured with a Potential (voltage) Transformer

4 Current Channels 0-333 mV AC or DC, Corresponding to 5-6,000 Amps depending on current transformer selected

Current Transformers Uses voltage output CTs (0-333mV) for maximum safety. Compatible with DENT Instruments **DATA***pro* and Energy

CTs

Measurement Type True RMS using high-speed digital signal processing (DSP)

Line Frequency 50 or 60 Hz

Harmonic Sensitivity 1st through 50th

Waveform Sampling 128 times per cycle

Measurements Volts, Amps, kW, kVAR, kVA, and Power Factor

Maximum, Minimum, Average, (All Parameters) also kWh, kVARh, kVAh, Ah

Harmonics DC and Fundamental through 50th (odd and even), Total Harmonic Distortion, Crest Factor, for both Current and Voltage.

Waveform Capture Voltage, Current, Power

Accuracy Better Than 1% (<0.5% typical) for V, A, kW, kVAR, kVA, PF exclusive of sensor error

Resolution 12 bit A/D plus sign (1 part in 4,096): 0.01 Amp, 0.1 Volt, 1 watt, 1 VAR, 1 VA, 0.01 Power Factor

Memory 128 kBytes standard (~25,000 readings), or 512 kB (~100,000 readings)

Memory Types Ring (continuous, write newest over oldest), or Linear (stop when full)

Recording Intervals 3, 15, 30 seconds, 1, 2, 5, 10, 15, 20, 30 minutes and 1, 12, 24 hours

Indicators 2 LEDs: Green to signal when logging, Red to signal low battery

Communication

Direct RS-232 to PC via 9 pin null modem cable

Communication Rate 1200, 2400, 4800, 9600, 19200, 28800, 57600 baud

Modem Internal 1200, 2400, 4800, 9600, 14400 baud, auto-answer, auto-dial modes

ELOG Software Programs Logger, Displays Current Metered Values, Retrieves Data

Appendix C (Continued)

Data Formats ASCII and Binary

Power Internal Lithium Battery; For external power use a Listed (US/Canada) or Certified (non-US) power supply rated 9 VDC minimum 150 mA

and marked ‘Class 2,’ ‘Limited Power Source,’ or ‘LPS’

Battery Life ~3 years, LED indicator of low battery charge

Analog Sampling Rate 3 seconds on external DC power, 1 minute when on internal battery

Clock Crystal controlled internal Real Time Clock, 20 ppm (<1 min/month)

Mechanical

Operating Temperature -7 to + 60 oC (20 to 140 oF)

Humidity 5% to 95% non-condensing

Enclosure Indoor: High Impact ABS Plastic, UL 94-V0 flame rating

Outdoor: Weather tight enclosure, Polycarbonate UL 94-V2 flame rating

Weight 0.4 kg (11 ounces) without modem

Dimensions 8 X 15 X 6 cm (3.2" X 5.9" X 2.4") Indoor Enclosure

Connections To The ELITE*pro*

The **ELITE***pro* has four wire leads for making temporary connections to voltage sources. On the end panel with the voltage leads there is a two

piece, eight (8) pin phoenix connector where sensors are terminated. The section with the screws and wire terminations may be removed by

grasping both sides of the connector and pulling firmly away from the logger. Each pair of pins is a channel input as indicated on the logger.

each pair, the left-most pin while facing the logger is the (+) or high side and the right-most pin is the (-) or low side. The 2nd, 4th, 6th and 8th

are connected together and to the logger ground which is the same as the ground pin on the RS-232 port. The other end panel of the logger

DB-9 connector that is the RS-232 serial port.

Two other connectors may appear on the long side of the logger. An RJ-11 jack provides access for a telephone line if the logger is equipped

modem. A 3.5 mm jack is also provided to allow for connecting external DC power to the logger.

Appendix C (Continued)

Minimum System Requirements

For The ELITE*pro*□

Computer: IBM PC or equivalent

Operating System: Windows 95, 98, 2000, XP, NT 4.0 or higher

CPU: Pentium Class 100 MHz or higher recommended

RAM: 16MB minimum (32MB recommended)

Hard Drive: 5MB minimum available

Graphics: SVGA or higher resolution (800X600) required for Harmonic Analysis

Serial Port: One Serial Port

CD Drive: One CD or DVD drive required for software installation.

DATA*pro*□ **Technical Specifications**

Model 1T/3P: 1 Temperature & 3 Pulse Recording Channels

1 Temperature Channel -40 to +70 oC (–40 to 160 oF) Extended Range Sensors: -50 to +125oC

0.1 oC Resolution, Uses interchangeable, high-accuracy Thermistors

3 Pulse Channels Interrupt driven, Maximum input frequency 10 Hz

Model 2T/2P: 2 Temperature & 2 Pulse Recording Channels

2 Temperature Channels -40 to +70 oC (–40 to 160 oF) Extended Range Sensors: -50 to +125oC

0.1 oC resolution, Uses interchangeable, high-accuracy Thermistors

2 Pulse Channels Interrupt driven, Maximum input frequency 10 Hz, □ 1 Count Resolution

Model 4C: 4 Channel Current Recorder

4 AC Current Channels 0.05-6,000 Amps, Depending on Current Transformer, .01 A resolution

Current Transformers Uses voltage output CTs (0-333mV) for maximum safety.

Compatible with DENT Instruments **ELITE***pro* and Energy Logger CTs

Measurements True RMS using high-speed digital signal processing (DSP) techniques

Line Frequency 50 or 60 Hz

Harmonic Sensitivity 1st through 50th

Appendix C (Continued)

Waveform Sampling 128 times per cycle

Model 4P: 4 Channel Pulse Recorder

4 Pulse Channels Interrupt driven, Maximum input frequency 10 Hz, Resolution □ 1 Count

Model 4Vdc: 4 Channel Low Voltage DC Recorder

4 DC Voltage Channels 0-10 Volts DC, 0.01V Resolution

Model 4Ma: 4 Channel Milliamp Recorder

4 Milliamp Channels 4-20 mA or 0-25 mA inputs, 0.025mA Resolution

Model 4T: 4 Channel Temperature Recorder

4 Temperature Channels -40 to +70 oC (–40 to 160 oF) Extended Range Sensors: -50 to +125oC

0.1 oC resolution, Uses interchangeable, high-accuracy Thermistors

Specifications Common To All Models Of DATA*pro*

Number of Channels 4

Measurements Maximum, Minimum, Average, Instantaneous (Temperature, Current, Milliamps and Volts DC), Count, Run-Time, Duty-Cycle,

On-Time (Pulse/Digital)

Resolution 12 bit A/D Plus Sign (1 part in 4,096): 0.01 Amp, 0.1 oF or oC, 1 Count

Analog Sampling Rate 1 second on external DC power, 1 minute when on internal battery

Digital Sampling Rate 10 Hz Maximum, Interrupt driven

Accuracy Better Than 1% (<0.5% typical) exclusive of sensor error

Memory 128 kBytes standard (~25,000 readings), or 512 kB (~100,000 readings)

Memory Types Ring (continuous, write newest over oldest), or Linear (stop when full)

Recording Intervals 3, 15, 30 seconds, 1, 2, 5, 10, 15, 20, 30 minutes and 1, 12, 24 hours

Indicators 2 LEDs: Green to signal when logging, Red to signal low battery

Communication

Direct RS-232 to PC via 9 pin null modem cable

Communication Rate 1200, 2400, 4800, 9600, 19200, 28800, 57600 baud

Modem Internal 1200, 2400, 4800, 9600, 14400 baud, auto-answer, auto-dial

ELOG Software Programs Logger, Displays Current Metered Values, Retrieves Data

Appendix C (Continued)

Data Formats ASCII and Binary

Power Internal Lithium Battery, For external power use a Listed (US/Canada) or

Certified (non-US) power supply rated 9 VDC minimum 150 mA and

marked ‘Class 2,’ ‘Limited Power Source,’ or ‘LPS’

Battery Life ~3 years, LED indicator of low battery charge

Analog Sampling Rate 3 seconds on external DC power, 1 minute when on internal battery

Clock Crystal controlled internal Real Time Clock, 20 ppm (<1 min/month)

Mechanical

Operating Temperature -7 to + 60 oC (20 to 140 oF)

Humidity 5% to 95% non-condensing

Enclosure Indoor: High Impact ABS Plastic, UL 94-V0 flame rating

Outdoor: Weather tight enclosure, Polycarbonate UL 94-V2 flame rating

Weight 0.4 kg (11 ounces) without modem

Dimensions 8 X 15 X 6 cm (3.2" X 5.9" X 2.4") Indoor Enclosure

Connections To The DATA*pro*

The **DATA***pro* has four connectors. On one of the two small ends of the logger there is a two-piece, eight (8) pin phoenix connector where

are terminated. The section with the screws and wire terminations may be removed by grasping both sides of the connector and pulling firmly

from the logger. Each pair of pins is a channel input as indicated on the logger. The left-most pin while facing the logger is the (+) or high side

the right-most pin is the (-) or low side The 2nd, 4th, 6th and 8th pins are connected together internally and also to the logger ground which is the

same as the ground pin on the RS-232 port. If the logger accepts more than one type of sensor, the location and type of sensor is indicated on

logger panel as follows: T = Temperature sensor; P = Pulse or digital sensor, C = Current transformer.

The other small end-panel of the logger has a DB-9 connector, which is the RS-232 serial port. Two other connectors may appear on the long

of the logger. An RJ-11 jack provides access for a telephone line if the logger is equipped with a modem. A 3.5 mm jack is also provided to allow for connecting external 9VDC power to the logger.

Appendix C (Continued)

Minimum System Requirements

For The DATA*pro*

Computer: IBM PC or equivalent

Operating System: Windows 95, 98, 2000, XP, NT 4.0 or higher

CPU: Pentium Class 100 MHz or higher recommended

RAM: 16MB minimum (32MB recommended)

Hard Drive: 5MB minimum available

Graphics: SVGA or higher resolution (800X600) required for Harmonic Analysis

Serial Port: One Serial Port

CD Drive: One CD or DVD drive required for software installation.

ABOUT THE AUTHOR

Nenad Damnjanovic was born in Pirot, Serbia. He attended high school at East Lake H.S in Tarpon Springs, Florida. He obtained his B.S degree in Electrical Engineering from the University of South Florida in 2009. He joined the Master's program immediately after and worked under the supervision of Dr. Domijan and Dr. Fan at the Power Center for Utility Explorations (PCUE). Nenad is a member of IEEE and his area of interest include power systems, magnetics, energy storage and renewable energy.