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An Experimental Study of Potential Residential and Commercial Applications of Small-Scale Hybrid Power Systems

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AN EXPERIMENTAL STUDY OF POTENTIAL RESIDENTIAL AND COMMERCIAL APPLICATIONS OF SMALL-SCALE HYBRID POWER SYSTEMS

A Thesis

by

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ABSTRACT

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The research presented in this thesis provides an understanding of small-scale hybrid power systems. Experiments were conducted to identify potential applications of renewable energy in residential and commercial applications in the Rio Grande Valley of Texas. Solar and wind energy converted into electric energy was stored in batteries and inverted to power common household and commercial appliances. Several small to medium size hybrid power systems were setup and utilized to conduct numerous tests to study renewable energy prospects and feasibility for various applications. The experimental results obtained indicate that carefully constructed solar power systems can provide people living in isolated communities with sufficient energy to consistently meet their basic power needs.

DEDICATION

I would like to dedicate this thesis to my family. I appreciate the loving support from my parents, Miguel and Elisa Acosta, and my brothers Orlando and Edgar Acosta. I thank you guys for everything and know that I am very proud of every one of you. I thank my wife, Eloi Acosta, for her love and encouragement to achieve great things by hard work. I feel grateful to have always been driven to succeed in what I do and never give up and I thank God for that blessing.

ACKNOWLEDGEMENTS

I would like to take this opportunity to thank some very important people who have helped me throughout my graduate career. A very special thanks goes to my advisors Dr. Constantine Tarawneh and Dr. Horacio Vasquez. Without these two gentlemen, none of my academic success would have been possible and their never ending support has helped me reach my dreams. I am very grateful to have had them as professors, mentors, and friends throughout my undergraduate and graduate years at The University of Texas-Pan American. Dr. Constantine Tarawneh and Dr. Horacio Vasquez are two of the hardest working individuals in the university and are a huge part of the success of the Mechanical Engineering Department. I would also like to thank fellow mechanical engineering students Roy Villanueva and Eloi Acosta, who helped me build part of the hybrid power system and also supported me throughout my education. A sincere and heartfelt thanks to Dr. Hashim Mahdi, who will never be forgotten for his kindness and passion for the Mechanical Engineering Department. Finally, I would like to thank the Department of Mechanical Engineering and its unmatched support for academic excellence.

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CHAPTER I

INTRODUCTION

Even though research in alternative energy has been a hot topic of study, recently it has become more enticing due to various issues that have risen in the present days. The unstable economics of the oil industry is one strong example that supports further research in other energy sources. It is commonly known that there is a vast number of resources that can be utilized to produce energy for everyday use. The problem lies in how to harness, store, and utilize the energy in the most efficient and optimal way. The sun is a source of energy that has nourished the Earth for billions of years, yet solar energy is not used to its fullest potential. An immense area of the Earth's surface is exposed to sunlight that can be used to generate electricity. Solar panels and other technologies exploit this aspect and are currently being used. Wind is another viable option for electricity production that has recently received a lot of attention. Depending on the location, wind is a source of energy that can be captured and utilized by various methods. A system that can simultaneously capture solar and wind energy has an advantage over others due to how the two energy sources would complement each other. Therefore, in a time when the cost of energy is constantly on the rise, a hybrid power system which produces power using the sun and wind provides a viable option of renewable energy.

The problem lies in the fact that people have not been presented with other options of producing electricity for use in their homes or businesses. Current sources of energy do not provide a practical solution to relieve the cost of electricity. High energy costs require the design of systems that can convert the abundance of sunlight and wind into electricity and at the same time reduce the consumption of fossil fuels. These systems must be able to self regulate their energy storage and energy usage using smart controllers with minimal human interaction. Homeowners find their electric bills unusually high, especially in the summer, and occasional blackouts are a nuisance since without electricity, businesses cannot operate efficiently, refrigerators are not able to keep food from spoiling, and much needed air-conditioning systems stop functioning. There is no electricity to power important appliances needed during these annoying disturbances. Therefore, research and development of hybrid power systems has become an important factor in solving the energy crisis at hand, and in mitigating the environmental damage that the utilization of fossil fuels creates due to the generation of CO_2 and its effect in global warming. In spite of the relatively high initial investment cost, a hybrid power system could provide great benefits, especially in regions where there is abundant sunshine and wind throughout the year.

The main purpose of this work is to provide a complete understanding of the performance of small to medium size hybrid power systems in the Rio Grande Valley. The study presented here gives a thorough investigation into hybrid power system performance and sustainability for several applications. Chapter 2 provides some background information and a literature review is given. In Chapter 3 the theoretical development and algorithms used in the experimentation is given. A complete description of the experimental apparatus and procedure followed for every experiment is provided in Chapter 4. Chapter 5 presents a thorough discussion of results, which is followed by Chapter 6, in which the conclusions, future work, and recommendations are provided. Finally, Appendix A contains a sample of a MATLAB m-file used in the analysis of the experiments, whereas, Appendix B lists the plots for all of the experiments conducted for this study.

CHAPTER II

BACKGROUND AND LITERATURE REVIEW

2.1 Background

Solar energy converted to electricity that can be stored and used at a later time seems to be a viable solution to the rising energy concerns. However, since solar energy is only available for less than twelve hours a day, renewable wind energy could complement in the form of a hybrid power system that benefits from both energy sources. Solar or photovoltaic (PV) cells are made of semiconductor materials and convert sunlight into electricity. A typical silicon solar cell 100 cm^2 can produce 0.5 Volts and generate up to 3 Amps of current [1]. The rated power (in Watts) of a solar cell or solar panel is specified by its characteristic output voltage multiplied by the electric current flowing out of the cell under specific operating conditions. Solar cells have relatively low efficiency (generally between 15% and 20%) because part of the sunlight energy striking the solar cells is required to make the electrons move and leave holes which are to be occupied by other electrons, thus producing electricity. New technology has resulted in the creation of new solar cells that are about 40% efficient, and researchers are continuously trying to make them cheaper and better [2]. A solar module is an array of solar cells, and a solar panel is made up of several solar modules that produce a specific output voltage, current, and power. Solar panels usually have diodes to protect them against reverse flow of current. PV panels produce silent, pollution free, renewable energy wherever sunlight is available. PV technology is a convenient electricity source in remote places that lack a power infrastructure. However, PV output power depends on several factors such as solar irradiance, incidence angle, ambient temperature, reflectance, tracking, operating voltage, and current. Solar energy production has a parabolic shape with a maximum occurring at about 1 p.m. and little to no energy production between approximately 7 p.m. and 7 a.m., depending on the geographic location [3]. Wind energy production is generally irregular, peaking at variable times depending on location [4]. The kinetic energy from wind is captured using different types of blade designs with varying attack angles, geometry, and surface area. A wind generator converts this kinetic energy into electrical energy using electromagnetic induction. Since it is relatively simple to put together a wind generator, there are an immense number of designs that are being put into use. The power output varies according to the wind availability of a specific location, size of the generator, quality of the magnets, blade design, and configuration. Solar and wind are two energy sources that complement each other, allowing us to generate renewable energy under a variety of atmospheric conditions in rural and urban settings [4]. About 80% of PV systems are used in stand-alone applications with energy stored in batteries [5]. Batteries are charged and discharged daily, and the state of charge (SOC) is usually estimated by measuring their voltage and current history [5]. A low SOC for extended periods of time will cause sulphation and reduce the life of the batteries. Batteries experience self-discharge, and therefore must continuously be recharged to prevent low SOC. Since batteries are one of the major costs of a renewable energy PV system, a battery management system is required to optimize its performance without any over- or under-charging. Optimization and predictive algorithms are required to avoid wasting renewable energy as well, in particular during periods when the SOC of the batteries and the renewable energy availability are both high. In such cases, unless the energy demand is equivalent to or exceeds the electricity being produced, the renewable energy will be wasted because batteries will have reached their full storage capacity.

Even though there is an immense amount of information regarding renewable energy systems, further investigations are important to fully understand the capabilities of hybrid power systems. The current curiosity in such systems will positively affect the number of studies focused on generating a greater understanding. With the vast amount of knowledge that will be obtained from these studies, renewable energy systems will play a crucial role in directing the world to cleaner, more advanced methods of obtaining electrical energy for consumption.

2.2 Literature review

Research into the components that make up a hybrid power system is currently being conducted all over the world. At present, research is focused on developing better ways to acquire and store energy, like in the form of more efficient PV panels, wind generators, and hydrogen for fuel cells. As was previously mentioned, the more efficient technology can be found in the work from the National Renewable Energy Laboratory, where they have created a solar cell that is 40% more efficient than current standards [2]. It is safe to assume that with further advances in technologies that support PV panels, their efficiencies will increase over time making them more enticing as a renewable energy option. At present, one major concern with renewable energy systems is the variability of the energy source utilized to generate electricity. A gas turbine can be controlled to produce a fixed amount of power by adjusting the rate of fuel being consumed by the turbine. With renewable energy systems, the energy source is dependent on the weather conditions. These conditions are a function of the region, environment, and various other uncontrollable factors. Therefore, it is very important to consider the performance of PV arrays and wind generators while taking into account the variability of the energy source. According to Wang, power fluctuation is a major disadvantage of wind generators, and therefore research is needed to find a way to reduce this variability and provide smooth flowing energy [6]. Another concern with renewable energy systems is the method of storing the renewable energy for future consumption. Storing electricity is both difficult and expensive, which is one of the main limitations to implementing reliable renewable and sustainable energy systems using solar and wind power sources [7]. Even though lithium-ion batteries have better performance than lead batteries, because they cost more lithium-ion batteries are used mainly for low energy capacity systems, while lead batteries are better suited for higher energy storage applications [7]. At present, research is focused on developing better ways to store the energy in hydrogen fuel cells like the work from Ulleberg and Chaparro [8,9]. However, regardless of how the energy is stored, a smart control system strategy, constructed with culturally-informed human factors research, is required to manage the renewable energy system, protect the system components, and prevent over-use from unplanned consumption.

Research is also focused on implementing smart controllers using different control techniques that act as a “brain” to oversee every portion of the renewable energy system. Such work can be seen in the research of Valenciaga and Puleston [10]. The controller that they consider switches into different modes of operation according to the conditions that are taking place in order to increase the efficiency. The first mode of operation (Mode 1) occurs while there is enough wind (considered the primary energy supply) to power the load and the battery which also acts as a load during the recharge cycle [10]. Mode 2 comes into play as soon as the load exceeds the power that can be provided by the wind. In Mode 2, the solar panels are activated to supplement the wind generator and provide any excess power necessary to meet the load requirements. Once the batteries become saturated, Mode 3 goes into effect by which the wind, solar, and batteries all provide the energy needed to supply the demand. The controller continuously monitors the SOC of the batteries and disconnects the load if necessary to keep from damaging them. Controller research combined with feasibility studies of renewable energy systems, will generate important knowledge for widespread implementation of these systems.

The research of Reddy provides an insight into a working hybrid wind and solar power system with a simple controller implemented to provide power from the grid if needed [11]. In his study, Reddy builds and tests a working system to gain information of energy production for 2 years in Hyderbad, India (2001 and 2002). His system is capable of producing 1.4 kW·h per day using a series of PV panels rated at 840 W in conjunction with a wind generator capable of producing a maximum power of 400 W [11]. The system powered three fans (3x50= 150 W), four tube lights (4x30= 120 W), and three compact fluorescent light (CFL) bulbs (3x10= 30 W) for a total of 300 W for about eight hours per day during peak power production (6 a.m. - 6 p.m. in Hyderbad, India) [11]. Furthermore, he includes a cost benefit analysis for his system.

Efforts to develop, research, implement, and teach renewable energy technologies have amplified in recent years and continue to grow as focus has been directed towards solving problems related to the lack of power infrastructure in remote places, and dealing with the numerous drawbacks affecting fossil fuel technology [12,13]. Pecen et al. (2004) fabricated an instrumented renewable energy unit to teach undergraduate and visiting high school and community college students about power generation, relationships between steady state voltages and currents, energy storage, power quality, and data acquisition systems [14]. Al Kalaani indicated that even though there is great enthusiasm for renewable energy, there is a lack of understanding the benefits of using renewable energy sources [15]. Hence, it is essential that some engineering courses at the University level incorporate sustainable energy concepts and applications to encourage education and implementation of these technologies. One such effort directed towards educating students on potential residential and commercial applications of a small-scale hybrid power system is the work presented in this thesis.

Another driving factor for small-scale hybrid power systems is to support isolated areas of civilization that lack an energy infrastructure to power basic needs. These smaller systems could be implemented to provide electricity for a few essential purposes that could drastically improve the quality of life for these people. To emphasize the worldwide importance of renewable energy projects, Zahnd et al. explained how in poor villages in Nepal, and in many other countries including developed countries, about 2 billion people endure harsh living conditions in part because of the lack of electricity [16]. For instance, in many villages, people prepare meals on open fireplaces that require burning logs inside their houses, generating smoke clouds that create respiratory problems with negative health consequences manifesting in increased morbidity and a shortened lifespan. Deforestation problems are also caused because of the logs needed for the fireplaces and tree resin extraction needed to create candles. As an example of small-scale electricity generation, Zahnd et al. installed a 150 W hydropower generator to provide 30 houses with three 1 W white LED lights which, although a seemingly small contribution, tangibly benefiting people of that village [16]. Increasingly, developing countries are realizing the importance of using renewable energy systems to provide distance learning programs to children and parents in rural communities without education access, as exemplified by the works of Ross et al. and Foster et al., whose projects were funded by the U.S. Department of Energy (DOE) and the U.S. Agency for International Development (USAID) [17,18].

2.3 Relevance of current work

To that intention, a small-scale hybrid power system (solar panels and wind generator) has been implemented in the mechanical engineering department at The University of Texas-Pan American (UTPA). Initial experimental efforts in a previous study were focused on investigating the charging and discharging performance of the batteries with varying load, solar panel power, panel inclination angle, and sun tracking effect [19]. The experiments conducted for this thesis examined the amount of charging energy acquired for a different number of days, the effect of adding supplemental wind charging, and the sustainability of these systems. A series of current and voltage transducers and signal conditioning components were installed and monitored using a data acquisition system, which allowed for the system performance to be quantified. In addition, the data collected were analyzed to determine the peak hours of electric generation. The main objective of the initial study was to identify potential residential and commercial applications of small-scale hybrid power systems. It is important to understand that these types of systems do not effectively replace current power sources. The amount of monetary savings that they generate will require a large amount of time to pay for the initial investment and cost of maintenance. On the other hand, these systems do provide benefits that are very valuable to households and small businesses. For a household located in an area with electrical infrastructure, a hybrid power system with current technology does not provide much energy savings. The benefit becomes apparent in natural disaster or blackout situations where there is no electricity available from the grid. Even in these scenarios, there are several other more cost effective alternatives such as gas powered generators. However, in cases where gasoline or diesel are not readily available, a hybrid power system will be very beneficial. Families in remote areas where there is no electrical infrastructure, will greatly increase their quality of life with a hybrid power system. This system can be utilized to power a couple of lights and even a refrigerator that will keep vital food and medicine from spoiling. To lay a foundation for eventually establishing consumption and management expectations, a working relationship was established with Ciudad Valles decision makers through the Mexican Consul of McAllen, TX, coordinated by the Office of the Dean of the College of Social and Behavioral Sciences. UTPA researchers and administrators (lead by the University Provost) visited Ciudad Valles, whose decision makers in turn visited UTPA to view and learn about the system in its proof of concept stage and to discuss human factors issues with researchers in the College of Social and Behavioral Sciences. Ciudad Valles, located in San Luis Potosi, Mexico, is home to more than 150,000 people, and is the third largest municipality in the state. At its center is the populated city of Ciudad Valles proper, surrounded by small towns, villages, and isolated homesteads inhabited by people of Huastecan ethnicity, with Huastec the first language and Spanish second. The region is equipped with an electric power grid; however, government planners deemed it unfeasible to extend power lines to the county's outer rural regions, meaning that substantial percentage of the overall population does not have electricity for basic needs (e.g. light, refrigeration, and emergency equipment). The people living in these remote communities want electricity, understanding that it will give them access to services that do not currently exist for them. The current work presented in this thesis is an extension of an earlier study conducted and is also aimed at exploring renewable energy prospects and feasibility for these types of isolated communities and remote areas.

CHAPTER III

EQUATIONS AND ALGORITHMS

In this chapter, the theoretical development and algorithms used in this study is presented. A thorough discussion of circuit design calculations, programming algorithms, energy computations, and system capability calculations is given in the following sections.

3.1 Circuit design calculations

In this section, the required circuit design calculations are shown in detail. The hybrid power system was capable of producing anywhere from 0 – 35 Volts and 0 – 78 Amps, which necessitated the use of voltage and current transducers to produce low measurable signals for the data acquisition system. To this effect, the transducers selected provided a maximum 5 V signal to the data acquisition device. These signals were then multiplied by a conversion factor and stored into the hard drive of the computer for future performance evaluation. Figure 1 displays the circuit board built to house the current and voltage transducers.

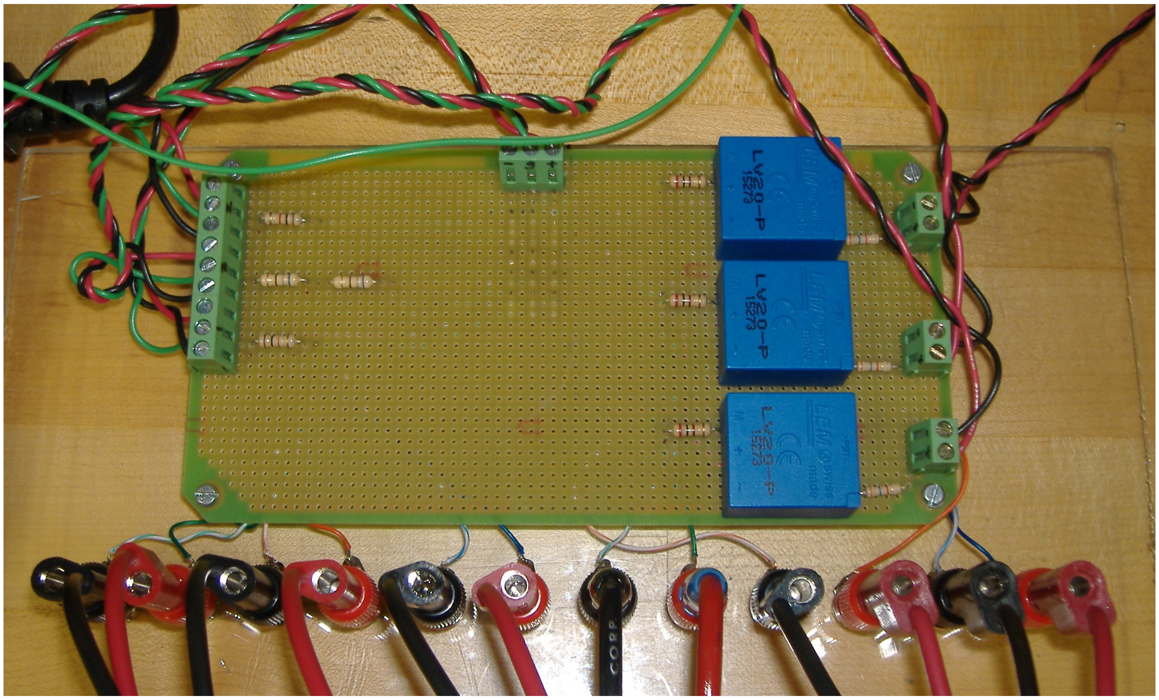


Figure 1: Circuit Board for Voltage and Current Transducers

All of the transducers were designed using the relationship between I_P and I_S, which are the primary and secondary currents. Using Ohm's Law which is given by,

$$V = I \cdot R \tag{1}$$

where V is the voltage, I is the current, and R is the resistance, the resistors were determined using the range of voltage supplied and the manufacturer's required nominal current. Figure 2 shows the locations of the primary and secondary currents for the voltage transducers.

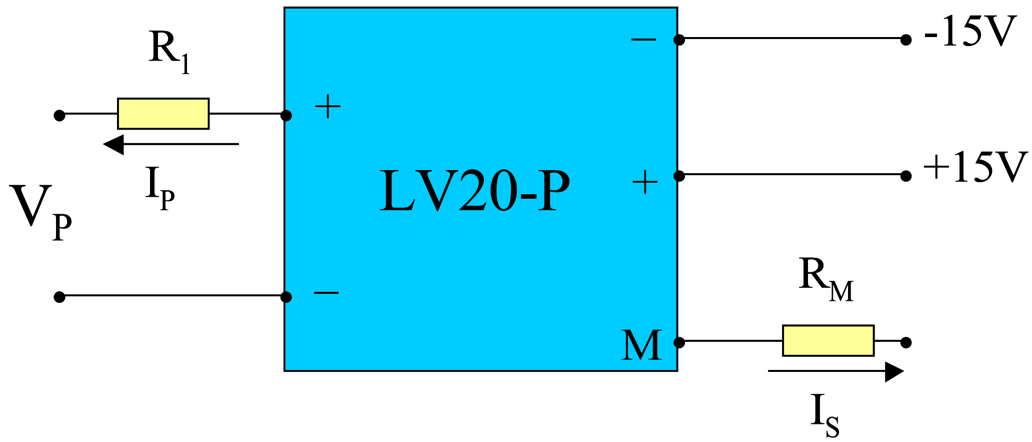


Figure 2: LV20-P Voltage Transducer Schematic

For the LEM LV 20-P voltage transducers, the nominal secondary current (I_S) is equal to 25 mA, while the nominal primary current (I_P) is rated at 10 mA. Using these conditions, one can select the corresponding resistance values for R_1 and R_M (see Fig. 2) depending on the voltage range. Assuming the maximum voltage of the system was 35 V at the nominal current value of 10 mA, R_1 is calculated as 3500 Ω using Eq. (1). It should be noted that a resistor was selected with the understanding that there is an additional small resistance value between the positive and negative terminals on the primary side of the voltage transducer. If this resistance value is not taken into account, there can be some small error that will be evident in the signal to the data acquisition system. Since R_1 was selected using a maximum voltage of 35 V, the transducer is now specified to measure any value between 0 and 35 V. The secondary side of the voltage transducer requires that there be a mandatory input supply of ±15 V, and therefore a voltage supply capable of providing such voltages was included in the system. The resistor, R_M, was selected by applying the condition that the maximum voltage input to the data acquisition device should 5 V. The latter ensures that the data acquisition system is protected (the absolute maximum voltage cannot exceed 10 V DC for the data acquisition system), while maintaining enough data resolution. Assuming 5 V and using the required 25 mA, Eq. (1) was used to find the value for R_M which is 200 Ω. Choosing appropriate resistors to be used with the voltage transducers will permit the data acquisition system to log a primary voltage between 0 to 35 V as a secondary voltage anywhere between 0 and 5 V. All voltage transducers in this setup were designed in this manner.

There were two types of current transducers used within the hybrid power system due to the difference in measured currents. One was the LEM LA 100-P and the other was the LA 55-P model which is shown in Fig. 3.

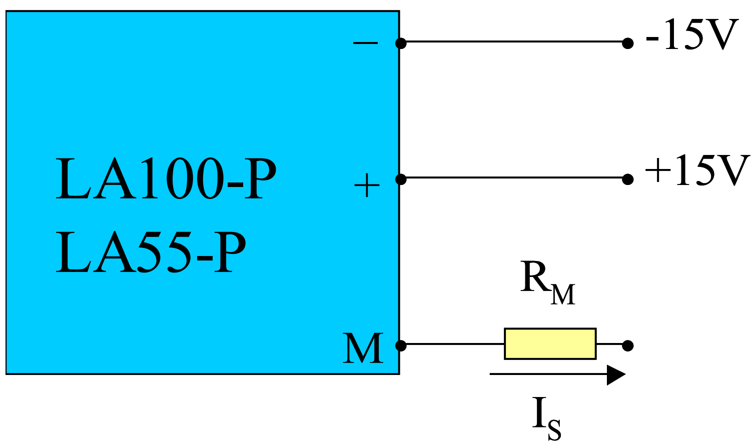


Figure 3: LA100-P and LA55-P Current Transducer Schematic

The only difference between the two transducers is the current threshold of each model and the relationship between the primary and secondary currents. The LA 55-P transducer has the following relationship between the primary and secondary currents

$$\frac{I_P}{I_S} = 1000 \qquad (2)$$

Equation (2) is the governing relationship of the LA 55-P transducer where the nominal secondary current (I_S) is equal to 50 mA, and the nominal primary current (I_P) is 50 A. To maximize resolution, the current of the primary circuit (i.e. current within the system, I_{PV} in this example) was theoretically calculated using Eq. (3)

$$P = V \cdot I \quad (3)$$

which is the equation of electrical power where P is the power, V is the voltage, and I is the current. For example, to design a current transducer for the 650 W solar panels Eq. (3) was used, where P = 650 W and V = 24 V, and therefore the primary current is found to be 27.08 A. Since the LA 55-P current transducer is rated for 50 A, it can be used to measure the current of the 650 W solar panel. Using Eq. (2) and the primary current of 27.08 A, the secondary current is found to be equal to 27.08 mA. Then from Eq. (1) and using a maximum data acquisition voltage of 5 V, the resistance becomes 184.6 Ω.

$$R_M = \frac{5\,V}{0.02708\,A} = 184.6\,\Omega \sim 185\,\Omega \quad (4)$$

The same approach was followed when designing the LA 100-P current transducer, where the relationship between the primary and secondary currents is given by

$$\frac{I_P}{I_S} = 2000 \quad (5)$$

The LA 100-P current transducer was required to measure the current from the loads powered by the inverter. Assuming the inverter was powering a load at maximum capacity (i.e. 1500 W), using Eq. (3) and a voltage of 24 V, the current was calculated as

62.5 A. This value is higher than the rated 50 A for the LA 55-P, therefore the LA 100-P was chosen.

Conversion factors were calculated and added to the ChartScan program in order to record the actual data values rather than the 0 to 5 V signals from the transducers. There are two ways of calculating the appropriate conversion factors for the system. One way is to go through the selection of the resistor and use the same relationships to go back and compute the factor required to provide the most accurate values of data. The other way is to actually measure the voltage or current using an accurate device and dividing the actual value by the 0 – 5 V value shown in the acquisition device. The second method was utilized because it requires less iterations to obtain accurate data for this study. The factor was calculated by measuring the actual voltages using an Omega SUPERMETER and dividing it by the value given by the voltage measured across the secondary resistor R_M as shown in Eq. (6). A full description of the data acquisition circuit can be found in Chapter 4.

$$Conversion\ Factor = \frac{V_{ACTUAL}}{V_{SECONDARY}} \tag{6}$$

3.2 Programming algorithm

In this section, the necessary programming algorithms are discussed. All of the experiments performed with the hybrid power system were recorded using an Omega OMB - ChartScan - 1400 data acquisition device. Figure 4 shows the real-time display of the ChartScan device software that displays voltage and current information while also storing it for later analysis.

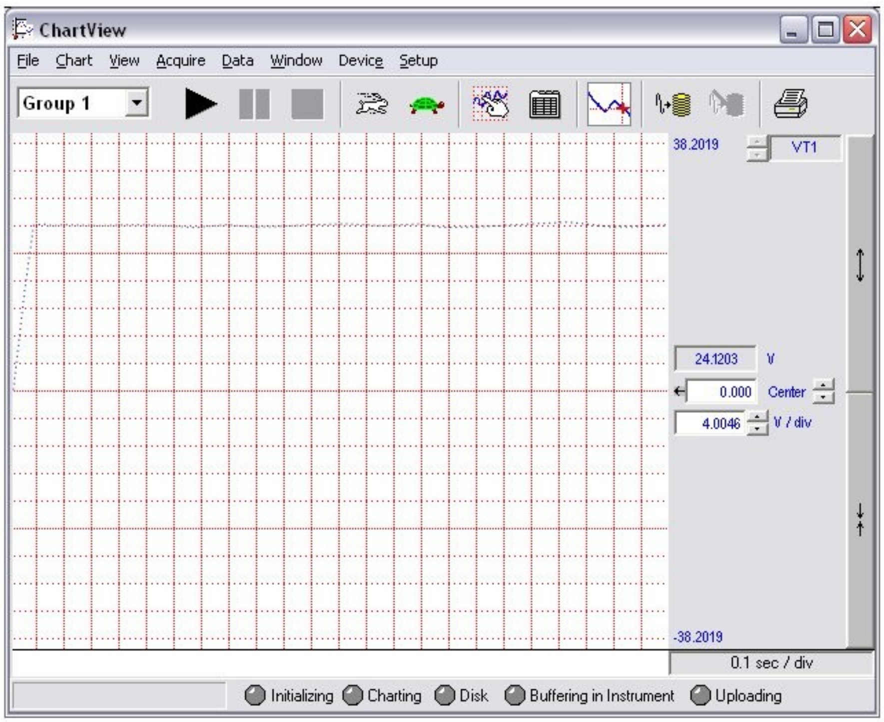
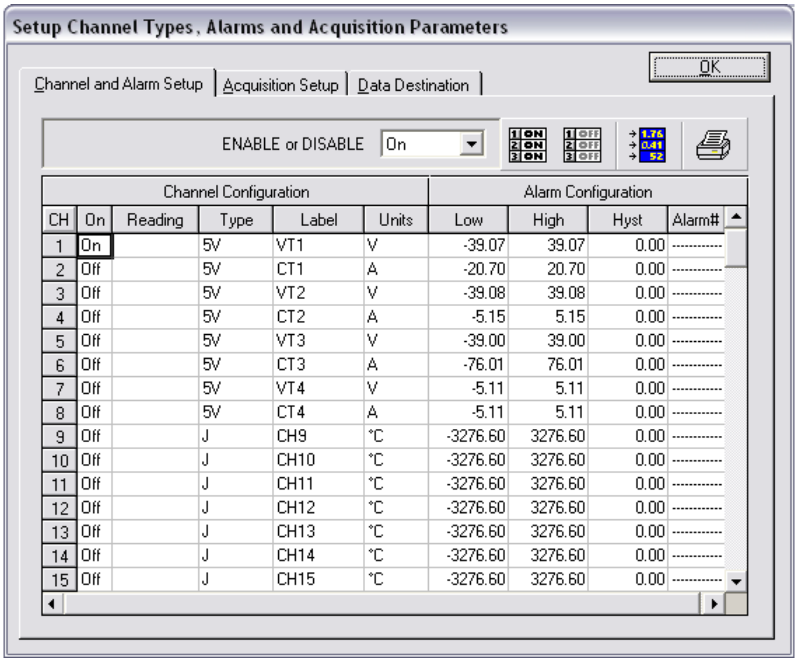


Figure 4: Omega ChartView Program Interface

Upon initiating the ChartView program, all the channels used were configured to read up to a 5 V signal through the Channel and Alarm tab located under Setup tab. Each channel was then given a specific label along with the Scale Factor (Conversion Factor for the transducers) and Unit Value along the Units column (see Fig. 5).



Channel Configuration						Alarm Configuration			
CH	On	Reading	Type	Label	Units	Low	High	Hyst	Alarm#
1	On		5V	VT1	V	-39.07	39.07	0.00	----------
2	Off		5V	CT1	A	-20.70	20.70	0.00	----------
3	Off		5V	VT2	V	-39.08	39.08	0.00	----------
4	Off		5V	CT2	A	-5.15	5.15	0.00	----------
5	Off		5V	VT3	V	-39.00	39.00	0.00	----------
6	Off		5V	CT3	A	-76.01	76.01	0.00	----------
7	Off		5V	VT4	V	-5.11	5.11	0.00	----------
8	Off		5V	CT4	A	-5.11	5.11	0.00	----------
9	Off		J	CH9	°C	-3276.60	3276.60	0.00	----------
10	Off		J	CH10	°C	-3276.60	3276.60	0.00	----------
11	Off		J	CH11	°C	-3276.60	3276.60	0.00	----------
12	Off		J	CH12	°C	-3276.60	3276.60	0.00	----------
13	Off		J	CH13	°C	-3276.60	3276.60	0.00	----------
14	Off		J	CH14	°C	-3276.60	3276.60	0.00	----------
15	Off		J	CH15	°C	-3276.60	3276.60	0.00	----------

Figure 5: Omega ChartView Channel Setup

Under the Acquisition Setup tab, several other parameters were chosen. In the event configuration box, the trigger was set to “keyboard”, while the stop was set to “count from trigger”. The count from trigger option allows the user to control the amount of scans wanted depending on the scan intervals. Every time the device would scan, it would take the average weight of 64 samples in one scan interval under the normal mode. The scan intervals used were between every 1 to 15 seconds depending on the length of the experiment since there were limitations as to the capacity of data points stored. For example, for a one day long test, the scan intervals were selected at every one second, and for the longer tests (i.e. five day tests) the 15 second scan intervals were utilized. The scan intervals and count were chosen in the following manner; if it is desired to scan every two seconds for a one hour test, then the Scan Interval is set at 2 seconds, and the Count is set to 1800. This ensures that the data is recorded for the duration of the one hour test since 1800 counts multiplied by 2 seconds per count yields 3600 seconds, which is equivalent to one hour (see Fig. 6).

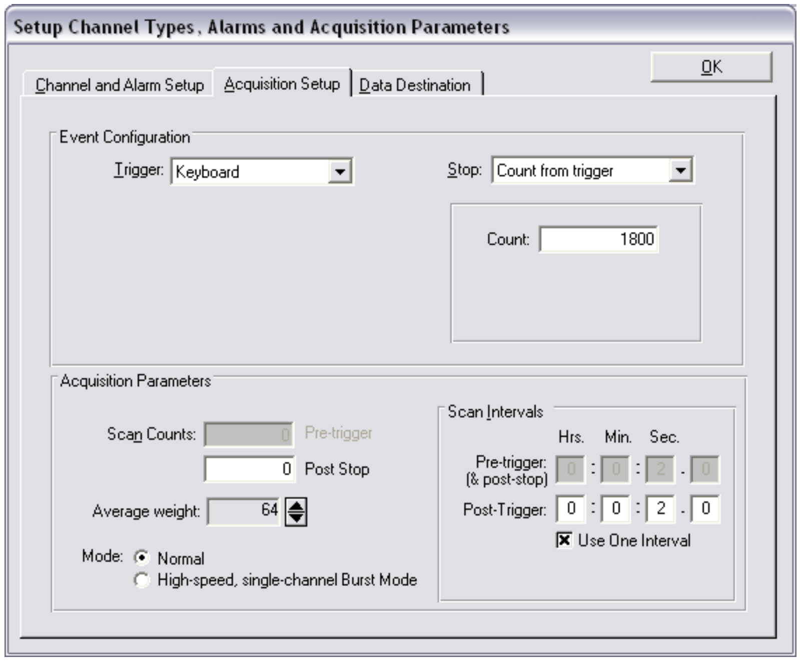


Figure 6: Omega ChartView Acquisition Setup

Under the Data Destination tab, the files were given a specific name following a certain naming convention. For example, for a 5 Day charging/discharging experiment with the 250 W solar panels, the wind generator, and the 225 A·h batteries taken on June 15th, 2008, the following name was given jun1508_CD_250W_WIND_225Ahr_5day. The naming convention was as follows; it starts with the start date of the experiment, followed by the C for charging, a D for discharging, or CD for both charging and discharging, then the power source (150 W, 250 W, or 650 W solar panels and WIND if included), batteries (74 or 225 A·h), and finally the duration of the experiment as shown in Fig. 7. The "Enable Auto Re-Arm" button was checked while the file incrementing was kept at 1 for the First and Last. The last couple of boxes that were checked were the

"Time/Date stamp" and "Alarm Stamp". Every experiment was performed using all of the steps described in this section.

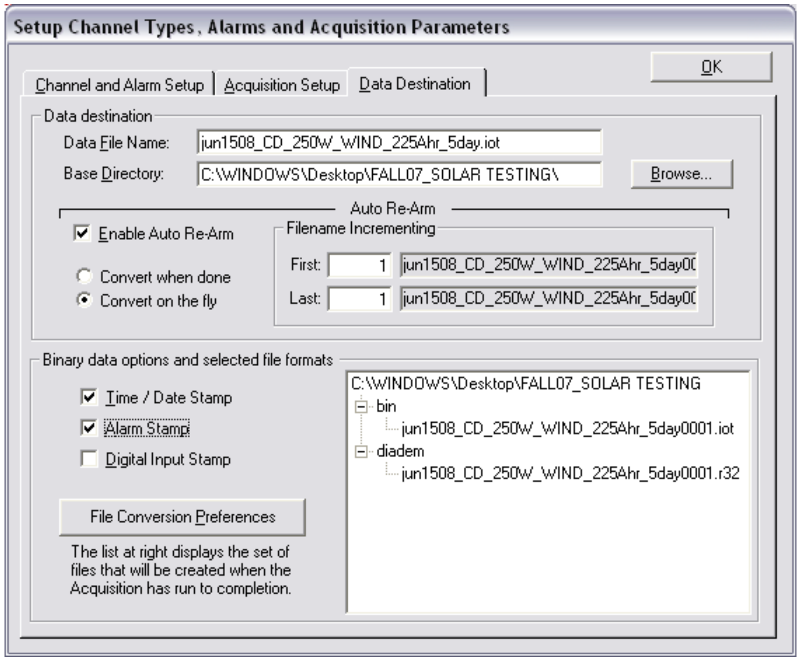


Figure 7: Omega ChartView Data File Name and Destination

3.3 Energy computation

In this section, the method of energy computation used for each experiment is shown for use in efficiency calculations and energy balance analysis. We must first understand how to calculate the amount of energy that can be stored in the batteries using the specifications given by the manufacturer. The smaller set of batteries supply 12 V and are rated at 74 A·h, and when they are connected in series the system becomes a 24 V battery bank with a 74 A·h capacity. Multiplying the 24 V by the 74 A·h yields a value of 1776 W·h of energy. A W·h is a measure of energy, and by multiplying by 3600 one can acquire the energy in Joules which is shown below.

$$1776\, W \cdot h = 1776\left(\frac{J}{s} * h\right) \cdot 3600\, \frac{s}{h} = 6393.6\, KJ \tag{7}$$

Assuming the batteries were at 100% charge capacity, then theoretically the small set of batteries would be able to supply a total of 1776 W·h. This would never be the case since it is recommended by the battery manufacturer to never discharge the batteries beyond 70% of their rated capacity. Following this recommendation, the amount of energy left in the batteries should not go below 532.8 W·h. This allows a value of 1243.2 W·h of energy that can be utilized while maintaining the suggested life span of the batteries. Using this same procedure, the 225 A·h batteries are able to provide 5400 W·h. To protect the batteries, the charge controller and inverter have a load disconnect safety feature that engages once it senses that the battery energy value has dropped below the 75% mark.

To calculate the performance of the system, voltages and currents were measured after every component. The data acquired was filtered using the "smooth" function provided in MATLAB. This was performed to remove noise that was present in the data. Several methods were used to quantify the energy within the system and to verify the values that were obtained. One method was to plot the power obtained by multiplying the voltage and current data and using the "trapz" function within MATLAB to calculate the area under the curve. The total area under the power curve, with respect to time, is equal to the amount of energy within the system in Joules and is given by

$$Total\ Energy = \int_{t1}^{t2} P(t)\, dt \tag{8}$$

The values acquired were then verified by utilizing the analysis button located in "cftool" and integrating about a specific range. The "cftool" function in MATLAB is a curve fitting tool that will create plots and curve fits from data that is input into the workspace. It also allows the user to evaluate derivatives and bounded integrals. By dividing these values, calculated via MATLAB, by 3600, we were able to convert from Joules to W·h, since it is just the opposite of what was done in Eq. (7). The energy calculations are essential in understanding the overall system and component performance.

3.4 System capability calculations

A hybrid power system must be sized according to the loads that are to be powered with the system. It would be undesirable to over design a system that will only power one light bulb, so there are some basic calculations that are required to select the appropriate components. In this study, the system configurations had already been selected, therefore the loads were designed to maximize the utilization of the hybrid power system. In either case, the same calculations are performed. The difference is that in the case where an existing system is known, the calculations show whether loads can be added or need to be removed. On the other hand, if the system configuration is being designed, then the calculations support the selection of the components based on the required energy. These calculations are important to ensure that the system theoretically is able to sustain its designed load with little or no interaction with the components. For example, if a scenario requires the design of a system to power four 20 W light bulbs for five hours, one 45 W laptop computer for three hours, and two 55 W fans for twelve hours in a single day, then the following equation shows the necessary process.

$$4\cdot(20\,W*5\,h)+1\cdot(45\,W*3\,h)+2\cdot(55\,W*12\,h)=1855\,W\cdot h \qquad (9)$$

Equation (9) shows that the required energy for the given example scenario of loads is 1855 W·h per day. This would have to be taken into account when selecting the PV solar panels to ensure that they are able to provide the necessary power. To continue with the example, let's say that a 500 W solar panel was purchased. The PV panel will not provide a constant power of 500 W throughout the day, so assuming that the day has six hours of sunlight and the solar panel outputs 50% of its rated power, then the solar panel will only provide 1500 W·h per day. The 50% rated power was chosen based on the experimental data from this study. The experiments show that during the best six hours of solar charging, the average power from the PV panels is around 67% of the rated capacity. In order to have a conservative assumption, the 50% of rated power was selected for this example and hence this solar panel would not be able to sustain the desired load. There are two options to follow from this point. Either extra PV solar panels are purchased for the system or the loads are altered in a way that lowers the required energy. If one fan were removed, the total energy required from the system would decrease to 1195 W·h, and therefore the 500 W solar panel can theoretically power the loads. It is important to remember that these calculations were based on several simplifying assumptions and that the actual results can vary. These calculations help size a hybrid power system, but will not provide very precise capability calculations. In this study, these calculations were validated against experimental results.

CHAPTER IV

EXPERIMENTAL APPARATUS AND PROCEDURE

Several experiments were performed to provide an in depth understanding of the feasibility of hybrid power systems for use in various residential and commercial applications. A number of different system configurations were implemented, but in all the cases the general arrangement of the components remained constant. This section provides a detailed description of the experimental apparatus and procedure utilized for the experiments required for the study.

4.1 Photovoltaic solar panels

A total of five photovoltaic (PV) solar panels were obtained for the purpose of this study (one 150 W panel, two 200 W panels and two 50 W panels). All of the solar panels were connected in such a manner that they were capable of providing between 12 to 24 V DC. The 150 W PV solar panel is a PHOTOWATT Model M-PW1650 12 V - 24 V and is shown in Fig. 8.

Figure 8: PHOTOWATT 150 W PV Solar Panel

The next two 200 W PV solar panels utilized were the BP Solar Model SX3195B. These solar panels are noticeably larger than the PHOTOWATT solar panel which is expected because of the higher power output. The last two solar panels were a couple of 50 W General Electric Model GE-PV-50-M. The BP and General Electric PV solar panels are shown in Figs. 9 and 10.

Figure 9: BP 200 W PV Solar Panels

Figure 10: General Electric 50 W PV Solar Panels (Qty. 2)

Unlike the 150 W panel, both sets of BP and GE solar panels were connected in series to provide the required 24 V to the hybrid power system. The solar panels were connected in a way that the system capability could be controlled by simply connecting or disconnecting a set of solar panels. For example, in the study, a 250 W solar panel system was utilized for several of the experiments. The later system consisted of the 150 W PHOTOWATT panel connected in parallel with the two GE 50 W solar panels in order to provide the necessary power. The larger 650 W system required all of the discussed solar panels to be connected in parallel. Through some previous experimental testing, it was determined that the ideal angle of inclination (angle facing the sun, with respect to the roof) was 26°, and therefore all of the solar panels were fitted with custom fabricated aluminum frames that provided that angle [19]. Figure 11 shows an angle indicator on the solar panels at the optimal angle of inclination for Edinburg, TX.

Figure 11: Angle Indicator at 26° Inclination

One drawback of the hybrid power system at UTPA was the distance between the solar panels and the remaining system components. In order to connect a data acquisition system, most of the hybrid power system components were kept in a laboratory indoors while the only items that remained on the roof of the building were the PV solar panels and the wind turbine. The large distance between these items meant that the selection of the wire utilized to connect the system components was critical since the longer the distance, the higher the power losses within the wire. A larger diameter wire helps mitigate that effect. The total length of wire that was required for the system was roughly 175 feet therefore, gauge 6 and 8 wires were selected to minimize the losses from such a large distance. At first, the gauge 8 wire was utilized for the smaller 250 W system, but once the larger BP solar panels were installed, gauge 6 wire was installed in addition to the gauge 8 wires for the larger 650 W configuration. It was very important that all of the wire connections were robust and that the solar panels were grounded to the roof. All of the wires that led back to the remaining components were carefully placed inside an electrical conduit from the roof of the building to the laboratory where the components were kept. The wires were connected to a large cut-off switch so that when necessary, the circuit from the solar panels can be opened, thus, de-energizing all voltage and current sources for maintenance and safety purposes. Figure 12 shows the cut-off switch utilized for the system.

Figure 12: Safety Cut-off Switch

4.2 Charge controllers

One very important component of a hybrid power system is the charge controller. A charge controller (also known as a battery regulator) protects the batteries from overcharging and also keeps the batteries from discharging to critical levels. Overcharging and over discharging will drastically reduce the life of the batteries; therefore, the use of a charge controller is essential for such systems. A charge controller also limits the supply voltage of the batteries to further protect them. There are many different types of charge controllers, from the basic to more expensive programmable controllers. For the purpose of this thesis, there were two charge controllers that were utilized in the experiments. For the initial experiments, a Morningstar SunSaver SS-10L-24V charge controller was used. This controller was rated for an overall system voltage of 24 V and solar current of 10 A. For the initial experiments using the smaller 250 W configuration, the SunSaver SS-10L-24V shown in Fig. 13 was sufficient.

Figure 13: SunSaver SS-10L-24V Charge Controller

For larger systems, the solar panel current would exceed the rated current of 10 A for the SunSaver, therefore another charge controller was utilized. A Morningstar TRISTAR with a digital display was used for the remaining experiments that included all of the PV solar panels plus the wind turbine providing power to the batteries. The TRISTAR is capable of working with an overall system voltage between 12 to 48 V. It was also rated to handle currents of up to 45 A, which is well beyond what is necessary for the system configurations utilized for this study. Figure 14 shows the TRISTAR charge controller equipped with the optional TRISTAR Digital Meter that displays real-time information of the system and it allows the user to program the controller to the desired settings.

Figure 14: TRISTAR Charge Controller

For the smaller system that utilized the SunSaver controller, the only connections used were the solar panel and battery terminals (see connections 1, 2, 3, and 4 on Fig. 13). The SunSaver controller also includes connections for a DC load that is powered with the batteries and is disconnected once it senses a critical low level voltage. Even though this is a sought-after feature, this was not utilized since the inverter that was included in the system had a similar cut-off mode that would protect the batteries from over discharging.

4.3 Batteries

The controller is connected between the PV solar panels and another important system component, the batteries. It was crucial to select batteries that are able to cycle (charge and discharge) many times without getting damaged in order to obtain good utilization of the hybrid power system. A drawback of the batteries is that there is a limit to the total amount of energy that can be discharged from them. Car batteries can be severely damaged if they are deeply discharged, therefore it was justified to obtain deep-cycle batteries for the setup since they can be discharged to a lower state of charge (SOC) than other batteries. For the purpose of this study, the batteries consisted of two DEKA GEL 12 V 225 A·h. All of the hybrid power system configurations were in 24 V DC mode, therefore the batteries connected in series to provide and acquire 24 V as well. Previous experiments that are not included in this study utilized four smaller MK Powered GEL 12 V 74 A·h batteries. Placing the 12 V batteries in series provides the required 24 V and for the previous experiments using the four 74 A·h batteries, the sets that were in series were connected in parallel to provide larger storage capacity. Batteries connected in series add their voltage and share the same current, whereas batteries connected in parallel add currents but maintain voltage. Figure 15 displays the two sets of smaller batteries that were utilized in a previous study for reference.

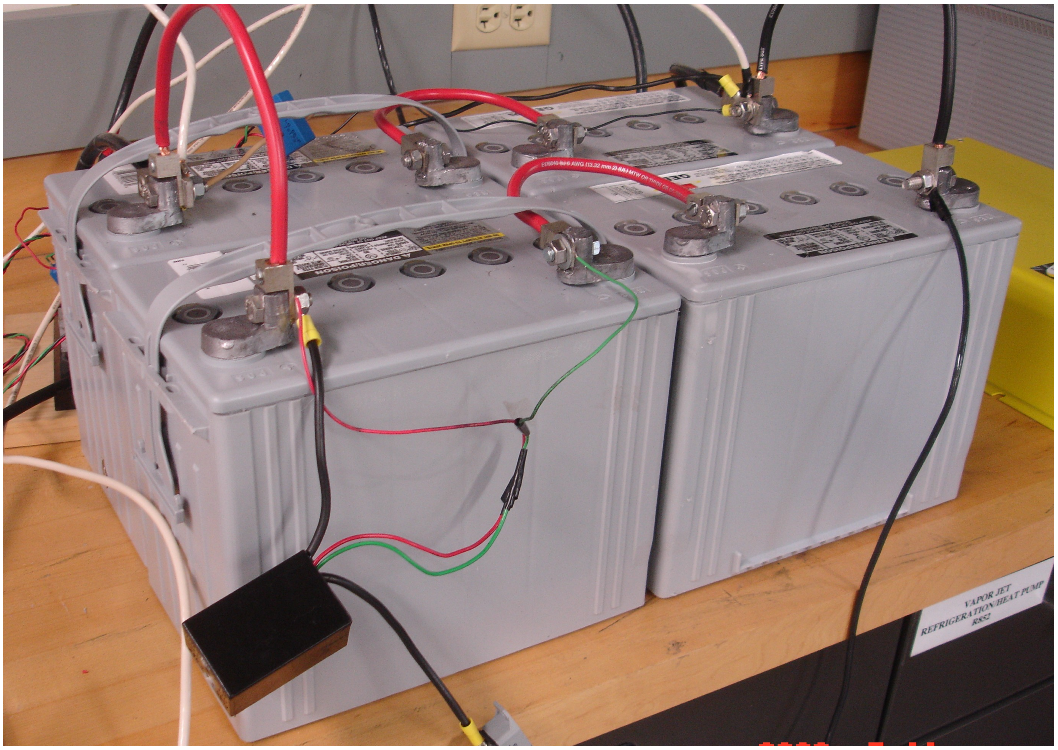


Figure 15: MK GEL 12 V 74 A·h Batteries (Qty. 4)

As can be seen from Fig. 15, the two batteries within each set are connected in series and then the two sets of batteries are connected in parallel. The batteries for any hybrid power system can be connected in various configurations to increase storage capacity but the system voltage must be maintained. Figure 16 shows the high capacity 225 A·h batteries that were utilized in the experiments for this study.

Figure 16: DEKA GEL 12 V 225 A·h Batteries (Qty. 2)

From Fig. 16, it can be noted that the batteries are connected in series at the inner terminals to provide the overall 24 V required voltage for the hybrid power system study.

4.4 Inverter

The loads for the system required AC power, therefore it was necessary to utilize an inverter that takes the DC power from the battery bank and inverts it to usable AC power. The inverter selected for the system configurations had a built in voltage cut-off that protects the batteries by continuously monitoring their voltage. Once the batteries reach critical discharge levels, the inverter cuts off the power to the electric loads to prevent over discharging. Consideration of the loads was required to select the appropriate inverter for the system configurations. The inverter that was used for this study is a Go Power! Sine-Wave 1500 W Inverter. This constrains the loads to be less than or equal to 1500 W which affects the selection of the loads in such small scale hybrid power systems. Figure 17 is a picture of the Go Power! Inverter used in this study.

Figure 17: Go Power! Sine-Wave 1500 W Inverter

The inverter was equipped with LED indicators that displayed the load in Watts, the voltage, various alarms, and specific modes of operation. As per the manufacturer's installation manual, the inverter was connected to the positive and negative terminals of the battery bank and was grounded for safety purposes. If more than two loads were required, a surge protector was connected to the inverter to enable it to supply the necessary power to all the loads.

4.5 Wind generator setup

The sustainability tests for this study were performed while incorporating power supplied by a wind generator. Initial tests with a wind turbine on the roof of the University's Engineering Building indicated that the power supplied was sporadic and inconsistent. The feasibility of wind power depends on geographic location and unfortunately the randomness of the wind power at this location and the distance from the laboratory to the wind turbine called for an alternate incorporation technique. For the sustainability experiments, a wind generator schedule was created where 100 W of wind power was generated three times a day for one hour durations. A setup was fabricated with the wind generator powered by a 3 phase 1.0 hp Marathon Electric microMAX Y364 electric motor through a 1:1 ratio belt pulley system. The motor was maintained at a constant velocity (associated with ~100 W of power) via an Automation Direct GS2-11P0 1 HP AC drive. This motor setup drove the Wind Blue DC-520 wind generator. The complete wind generator setup can be seen in Fig. 18.

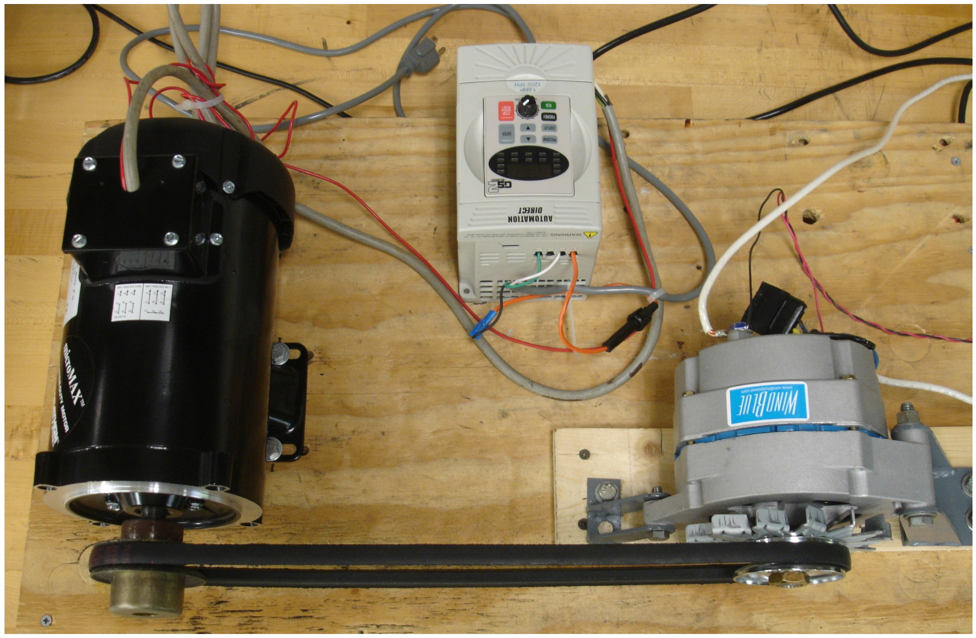


Figure 18: Simulated Wind Generator Setup

4.6 Loads

Several experiments were conducted with different combinations of loads on the system. As previously mentioned, one constraint on the load selection was to maintain the total power under 1500 W, which was the rated output of the inverter. Another constraint was that a small scale hybrid power system would not have the sustainable capability to power large loads such as air conditioners or heaters which have high power demands. The purpose of a small scale hybrid power system is to supplement the electricity usage within a home so the loads were selected by considering realistic scenarios. For the charging/discharging experiments, a 1080 W load was utilized to discharge the batteries. Even though it is unrealistic to use the small system to power a 1080 W load, for the purpose of these experiments, the large load is beneficial to accommodate many experiments in a short period of time. The charging/discharging experiments were selected to generate a basic understanding of the capabilities of a small scale hybrid power system by verifying the outputs versus inputs into the configuration. The remaining sustainability experiments were meant to depict a real life application. The loads selected for the sustainability tests were items that do not have high power demands but would be very beneficial to households and small businesses. These tests were aimed at verifying the feasibility of the hybrid power system to power these loads for a reasonable amount of time with little interaction. Table 1 provides a summary of the loads selected for the experiments in this study.

Table 1: Loads Chosen for the Charging/Discharging and Sustainability Tests

Item	Load Power [W]	Charging/Discharging Tests [Qty.]	Sustainability Tests [Qty.]
Light	18	None	2
Fan	110	None	1
Clock Radio	4	None	1
Refrigerator	100	None	1
Inverter	4	1	1
ShopVac	1080	1	None
Heating Coil	480	None	1

As can be noted from Table 1, the inverter was also included as a load since it does have some effect on the system and is comparable to the clock radio as far as power consumption. Table 1 further shows the difference between the purpose of the two types of experiments conducted. The charging/discharging experiments only utilized the inverter and the ShopVac load, while the sustainability tests consisted of the real life applicable loads for a small scale hybrid power system. It is important to note that the heating coil was used only as a safety feature for the experiments utilizing the wind generator. No voltage or current transducers were placed to monitor the heating coil, shown in Fig. 19, therefore the heating coil load was not used in any of the energy consumption calculations. It was only active when the batteries reached critical charge levels and the excess energy, that would otherwise damage the batteries, was utilized to heat water.

Figure 19: Water Heater With Heating Coil

Figures 20 and 21 show the various loads used on the system for this study.

Figure 20: Loads Utilized for the Sustainability Experiments

Figure 21: ShopVac Utilized for the Charging/Discharging Experiments (1080 W)

4.7 Data acquisition system

The performance of the hybrid power system was quantified by continuously monitoring and recording the voltage and current at key locations (see Fig. 22) using a series of voltage and current transducers and a portable data acquisition system.

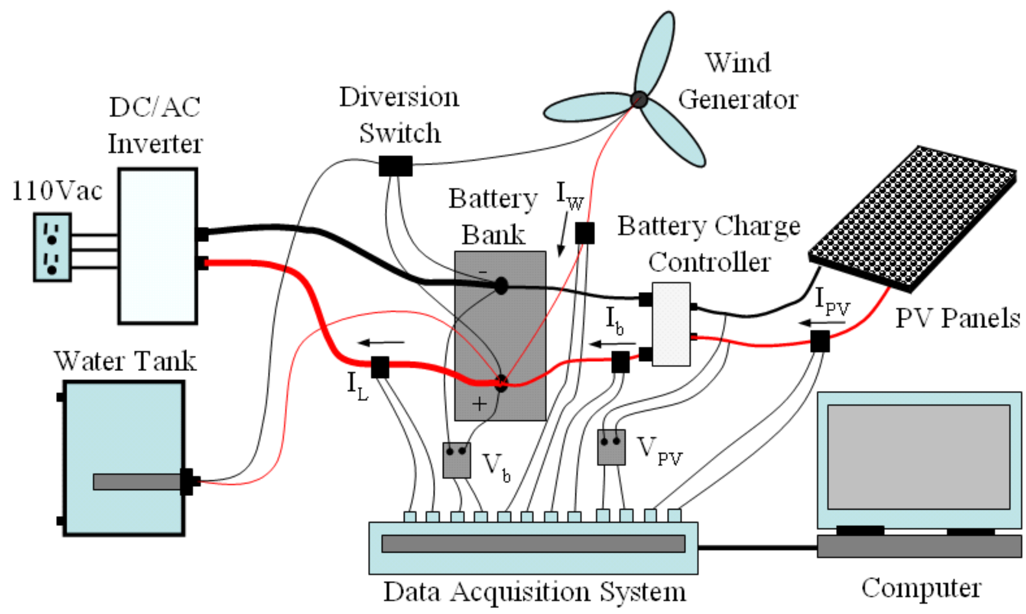


Figure 22: Schematic of the Hybrid Power System with Instrumentation

Two voltage transducers were utilized; one to measure the voltage across the PV panels, V_{PV}, and another to measure the battery bank voltage, V_b. The current in the system was monitored and recorded using three current transducers; one to measure the current flowing between the battery charge controller and the battery bank, I_b, another to measure the current drawn by the electric loads, I_L and the last one to measure the current from the wind generator, I_W. There was some redundancy within the system regarding the voltage and current transducers. The latter was done to verify that the measurements were accurate, and to provide a quick fix in case a transducer were to fail. Figures 23 and 24 are pictures of a current and voltage transducer, respectively.

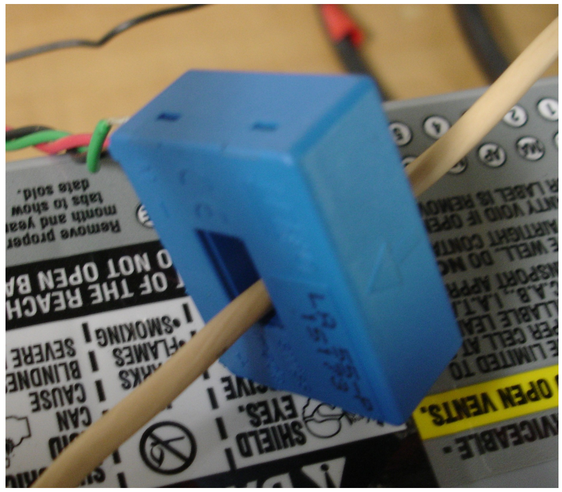


Figure 23: Current Transducer between the Charge Controller and Batteries, I_b

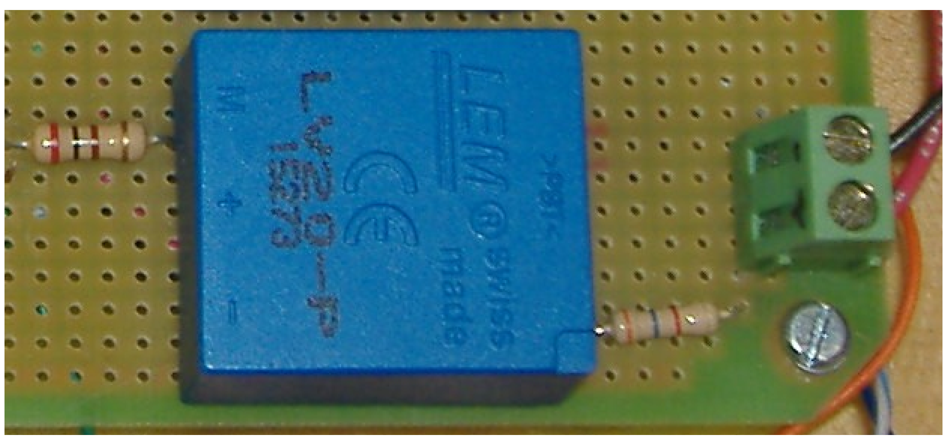


Figure 24: Voltage Transducer between the PV Panels and Charge Controller, V_{PV}

As mentioned previously, the voltage and current transducers were used in order to convert the actual voltages and currents within the system to measurable signals (0 – 5 V DC maximum) by the data acquisition system. The latter was accomplished by selecting appropriate resistors using the transducer's data sheets (see Fig. 24). The resistors and voltage transducers were carefully placed on a breadboard, and soldered in specific positions. The board was designed to provide the ±15 V input required by the transducers as well as provide a proper ground. The board was fitted with terminal posts and breadboard screw terminals in order to connect the appropriate wires out to the specific components that were going to be monitored.

An Omega Engineering OMB - ChartScan - 1400 data acquisition system (DAQ) equipped with a 16-channel analog input card was used to acquire all data. The DAQ system was connected to a PC computer via a RS-232 cable. The DAQ system software, Omega ChartView, which was installed on the PC computer, allows the user to control all aspects of the data acquisition process as well as display the real-time data on-screen. In addition, the software was used to set specific conversion factors to every input channel to perform the required calibration. To calibrate the system, a multimeter and a clamp meter were used to verify the readings displayed on the computer, which allowed for the determination of proper conversion factors that were used to display the correct voltages and currents measured from the system. Figure 25 shows the clamp meter being used to calibrate the current transducers.

Figure 25: Calibration of the Current Transducer I_L with a Clamp Meter

4.8 Hybrid power system configurations

Several hybrid power system configurations were utilized in this study. The basic blueprint of the solar power system starts with solar panels, connected to a charge controller, then wired to some batteries, the inverter and the loads (see Fig. 22). The Morningstar SunSaver charge controller was utilized with the smaller 250 W system. For the larger 650 W system with higher currents, the TRISTAR controller was used due to its higher current rating. The hybrid power system was consisted of the solar power system layout but with the addition of the wind generator connected directly to the battery bank with the diversion load relay.

4.8.1 Charging/discharging experimental setup

For the charging/discharging tests, the 250 W setup consisted of the 150 W PHOTOWATT solar panel,the two GE 50 W panels, the SunSaver charge controller, and all the other items that formed the solar panel system layout including the DAQ transducers. These three solar panels were connected in parallel to maintain the 24 V voltage drop across the batteries. The larger 650 W system consisted of all of the PV panels (i.e. one 150 W, two 50 W, and two 200 W panels), and the TRISTAR charge controller in addition to the other basic configuration of the solar panel system. In this system, the 150 W and 50 W solar panels were connected with the smaller gauge 8 wire, and the two 200 W solar panels were connected with the thicker gauge 6 wire. These two sets of wires were installed to the laboratory where the charge controller was located and connected per the manufacturer's instructions. The positive and negative wires of both sets were connected in parallel to the appropriate terminals in the charge controller to deliver up to 650 W at 24 V DC. Since the 650 W system consisted of the gauge 6 and 8 wire, it was necessary to install both wires into the current transducer (I_{PV}) to obtain the overall solar panel current input into the system .

The charging/discharging tests were performed with the previously mentioned configurations and the ShopVac as the load for the experiments. The ShopVac was chosen as the load for the system because it would discharge the batteries quickly and the discharge rate is not a factor in the results. The DAQ system was utilized to compute a power curve over the period of discharge time and therefore, the area under the power-time curve yields the total energy that was depleted from the battery bank. If a load such as the mini-fridge were used, the system would take a relatively long amount of time to discharge. For the purpose of this thesis, both the charging/discharging experiments were performed while only using the high capacity 225 A·h batteries. These batteries were selected for these experiments because of their large energy capacity and would be recommended in the design of small scale hybrid power systems for the same reason. All systems utilized the 1500 W inverter.

4.8.2 Sustainability experimental setup

The sustainability experiments differed from the rest in that the simulated wind generator was used and the loads consisted of common useful loads that can be utilized in a home or business environment. As previously mentioned, the wind generator was connected directly to the battery bank with gauge 8 wire bypassing the controller providing the batteries with direct charging capability. The batteries were protected from overcharging by the diversion load relay (see Fig. 26) that diverted any excess energy to the water heating element.

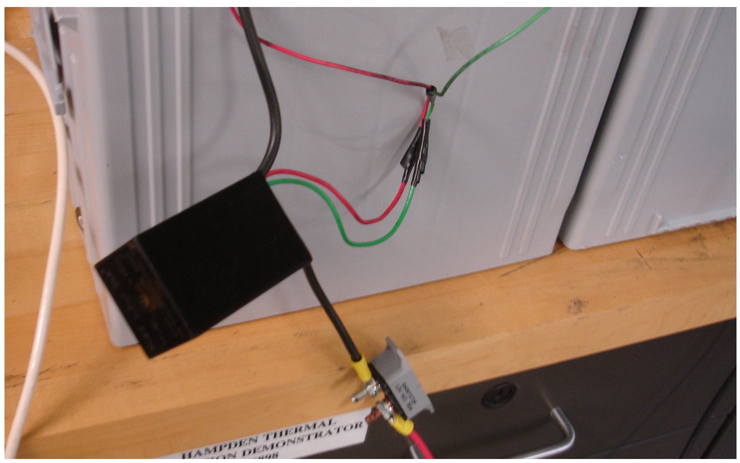


Figure 26: Diversion Load Relay (Sustainability Tests)

This diversion load connection was not monitored and was only installed to protect the batteries from harmful overcharging. It is important to note that during operation, the current was monitored with a multimeter on several occasions to verify whether the diversion load was engaged or not. If this diversion relay was actively diverting power to the water heater, this would signify that the system was performing at a desirable level when the batteries are either fully charged or close to their upper charge limit. It was discovered that the diversion relay did engage to protect the batteries, therefore for future experiments it would be beneficial to monitor the energy utilized by the diversion load to develop a complete energy balance of the system. The focus of the sustainability experiments was to verify whether the designed hybrid power system could sustain itself indefinitely with little or no human interaction. The wind generator was also fitted with current and voltage transducers to monitor the power input into the battery bank. Simulated wind power was used in parallel with the small 250 W solar panels configuration, and the large 650 W panel system.

4.9 Experimental procedure

Numerous experiments were performed in which the selected battery bank was charged, discharged, or simultaneously charged and discharged using different configurations of the solar panels and electric loads. The procedure followed for each of the three different types of tests is provided here.

4.9.1 Charging test procedure

The charging experiments were geared towards identifying the timeline required for charging the deep-cycle batteries under different weather conditions, i.e., clear sunny, partly cloudy, and cloudy. The batteries were first inspected to ensure that they were discharged (down to about 30% capacity for the 74 A·h batteries, and down to 25% capacity for the 225 A·h batteries) before starting the test. The data acquisition system was then turned on, and the ChartView software was initiated and set to acquire data at an appropriate sampling rate depending on the length of the test. A sampling frequency between 0.5 to 1 Hz was chosen for all of the charging/discharging tests and one and two day sustainability tests. The longer sustainability experiments had a smaller sampling frequency of 1 sample every 10 to 15 seconds due to the large amount of data that was being stored. To maximize daylight utilization, all charging experiments were started before sunrise. Once the DAQ system was triggered, the cut-off switch would be set to the on position closing the circuit and allowing the solar power to charge the battery bank. Charging was complete when the voltage across the deep-cycle batteries became saturated at 28 V, at which point the battery charge controller stopped current from flowing into the batteries to protect the batteries from damage caused by overcharging. Once the batteries were fully charged, the cut-off switch was disconnected, and the system was prepared to discharge the batteries with the 1080 W ShopVac load.

4.9.2 Discharging test procedure

The purpose of the discharge experiments was to verify the discharging times under different electrical load conditions. The discharging of the batteries was always performed immediately following the complete charging of the batteries to eliminate any discharging while the system is idle. To begin the discharging test, the batteries were first inspected to ensure that they were fully charged. The desired electric load was connected to the inverter with the inverter turned off. At this point, the inverter was turned on allowing power to flow from the batteries to the electric loads. As was previously mentioned, the inverter has a built in safety feature that protects the batteries from excessive discharge. Therefore, data collection continued until the inverter cut off power to the load. Once the inverter safety load disconnect feature was engaged, the data acquisition system was switched off, and the data file was saved for future analysis. After the battery bank had discharged, the solar panel cut-off switch was connected to provide power to the batteries so that they could recover. The latter is necessary to avoid a low state of charge, which could permanently damage the batteries.

4.9.3 Sustainability test procedure

Different combinations of the following devices provided the various electrical loads used in the sustainability experiments; a 100 W small refrigerator, two 18 W CFLs (compact fluorescent light bulbs), a 110 W floor fan, and a 4 W alarm clock radio. Note that some of these loads were used continuously and others intermittently in an attempt to recreate the conditions of a house environment; i.e. the lights were turned on during the night and not during the day, the fans were turned on during the warmest time of the day, and the refrigerator was filled with food and was opened frequently in order to simulate normal operation. The sustainability experiments represent the feasibility study conducted on the typical home energy consumption scenario. Therefore, a schedule was generated to follow during the experiments. Table 2 shows the load schedule followed during a typical day in the sustainability experiments.

Table 2: House Load Schedule Used for Sustainability Tests

Item	Load Power [W]	Time On	Time Off	Duration [hrs.]
Fan	110	8:30 a.m.	12:30 p.m.	4
Clock Radio	4	8:30 a.m.	12:30 p.m.	4
Two Lights (18 W each)	36	8:30 a.m.	12:30 p.m.	4
Refrigerator	100	8:30 a.m.	8:30 p.m.	12

These loads are directed towards remote homes with no power grid where they would provide great benefit. One important point to take into account is that the house loads given in Table 2 can be substituted for equivalent loads depending on the application. In other words, if you have a small business and would rather power a printer and a laptop computer, then you could substitute two items from Table 2 that add up to the same power load for blackout situations to maintain productivity. Table 3 provides several other equivalent loads that may be beneficial for homes and small businesses.

Table 3: Equivalent Loads for Use with Hybrid Power System

Item	Load Power [W]
Laptop	45
Printer	15
Copy Machine	32
Fax Machine	15
Television	55
Telephone	6

For the sustainability tests, the experimental setup shown in Fig. 22 was utilized with the 250 W and 650 W solar panel configurations with the addition of the wind generator in both. Initial tests used the four 74 A·h batteries in a previous study while the experiments presented in this work utilized the larger high capacity 225 A·h batteries. The solar panels provided power as long as there was sufficient sunlight. The experiments showed that the available charging sunlight in Edinburg, TX is about eight to ten hours. However, as mentioned earlier, wind is very intermittent in the Rio Grande Valley region, therefore the hybrid power system utilized a wind generator propelled with a motor to simulate wind power. The latter was done in order investigate the added value of wind energy on our system. Since the wind energy was simulated, some calculations were performed using typical meteorological year (TMY) data and the power curve of the 400 W AIR-X wind turbine (the initial wind turbine utilized before opting for the simulated setup) and will be discussed in Chapter 5. For the simulated wind power, it is not realistic to provide power into the system all day with the wind generator so it was assumed that the wind generator would only provide power for a small amount of time because this will more closely follow an actual wind turbine being driven by variable wind. It was decided by persons involved with this thesis to simulate the wind as providing power at three intervals throughout the day, early morning, the middle of the day and in the evening. These three intervals were selected to identify the supplemental characteristics of the wind generator power when there is early morning sunlight, peak sunlight power that occurs at around 12 and 2 p.m., and in the evening when there is no sunlight. The wind generator was capable of providing 100 W of power generation during the aforementioned intervals. Table 4 shows the schedule utilized for the simulated wind generator used in the hybrid power system.

Table 4: Wind Generator Schedule Used for Sustainability Tests

Item	Load Power [W]	First Time On [1 h]	Second Time On [1 h]	Third Time On [1 h]	Estimated Energy [W·h]
Wind Generator	100	8:30 a.m.	12:30 p.m.	8:30 p.m.	300 per day

The sustainability experiments started with the battery bank fully charged. The data acquisition system was turned on, and the ChartView software was programmed to collect data at a sampling rate of 0.1 Hz. The electrical loads listed in Table 1 for the sustainability tests were then connected to the inverter and were activated throughout the day at scheduled times to simulate actual operating conditions. The periods of operation listed in Table 2 were followed as closely as possible. The wind generator schedule given in Table 4 was also utilized for these experiments, but it is important to note that the time intervals did vary in the actual tests because of several limitations attributed to accessing the laboratory and other unrelated scheduling conflicts. All tests were initiated before sunrise in order to maximize daylight utilization. The targeted duration for the 250 W setup was five days of continuous operation without fully discharging the battery bank, and the larger 650 W was aimed for eight days. Hence, a successful test is one for which the energy stored within the battery bank at the end of the last day is more than sufficient to power the selected electrical loads the following day without getting fully discharged. The following chapter presents the experimental results.

CHAPTER V

EXPERIMENTAL RESULTS AND DISCUSSION

As previously mentioned, several experiments were conducted to verify the charging of the battery bank utilizing various sizes of PV solar panels and charge time, investigate the discharging characteristics of the batteries, and develop an understanding of the sustainability of a small-scale hybrid power system. In this chapter, the experimental results and discussion is presented.

5.1 Charging/discharging experiments

The charging/discharging experiments consisted of testing a 250 W and a 650 W solar panel configuration for various days. For example, the 250 W solar panel setup was tested for one day to compute the solar panel energy and battery energy supplied, then discharged immediately after to quantify the total load energy acquired for that day. For the 250 W setup, the five day test was necessary since it takes roughly five days to completely charge the large 225 A·h batteries. The 650 W setup was tested for one, two, and three day tests since it is understood that it can provide more energy than the 250 W panels and charge the batteries at a faster rate.

5.1.1 Results for 250 W setup

In these experiments, the system performance was verified through charging the batteries for the specified amount of time and then calculating the energy used by the ShopVac load. The 250 W charging tests were performed for one, two, three, four, and five days since it was important to generate a complete understanding of how the system performs under various days of charging and different weather conditions. The results are summarized in Table 5.

Table 5: Results for 250 W Setup Charging/Discharging Tests

Experiment	Solar Panel Energy [W·h]	Battery Energy [W·h]	Load Energy [W·h]
One Day Test	1229.9	1166.4	1265.2
Two Day Test	2786.9	2675.0	2321.1
Three Day Test	3563.9	3359.1	2625.9
Four Day Test	5175.9	4867.1	3539.8
Five Day Test – 1st	5572.2	5360.4	3843.0
Five Day Test – 2nd	4838.2	4837.0	3756.7

As can be seen from Table 5, the one day test had a higher load energy than what the solar panel provided. The explanation for this is that the batteries already had some residual energy. As for the other tests, the load energy is consistently lower than the input energy from the solar panels. This was expected since the batteries are not capable of storing all of the energy that flows into the system. As previously mentioned, once the batteries reach a certain charge capacity, the controller dissipates some energy in the form of heat to protect the batteries from overcharging and only allows a small percentage of energy through to continue to charge the batteries. This feature prevents any accidental overcharge of the battery bank and explains the extra power input into the system. The column that shows the battery energy is the total energy that goes directly into the batteries immediately after the controller. This is important to note because this shows that the energy is being dissipated by another additional method other than the charge controller. Even though the inverter is not on during the charging tests, it is suspected that it is consuming energy to run internal electrical components and this accounts for the excess energy. A small 10 to 20 W load for the duration of each test can account for the difference between the battery and load energy. Another item of interest is that the load energy does not exceed the critical 75% power capability from the large 225 A·h batteries (i.e. 5400 W·h total, 4050 W·h at 75% capacity). This shows that the inverter was engaging the load disconnect feature to protect the batteries from being discharged below their critical level. For the four and five day tests, the load energy is consistently around 3700 W·h and this is basically the amount of usable energy within the batteries. This is slightly below the expected 4050 W·h of energy, but as previously mentioned, during charging the controller regulates the amount of electrical energy flowing into the batteries when they are near full capacity and this can explain the lower value of load energy. The weather conditions were recorded for the experiments to correlate with the data. Table 6 shows the date and weather information pertaining to their respective tests.

Table 6: Weather Conditions for 250 W Setup Charging/Discharging Tests

Experiment	Weather Conditions	Date
One Day Test	1st – Sunny	12/20/07
Two Day Test	1st – Sunny, 2nd – Sunny	03/04/08
Three Day Test	1st – Partly Cloudy, 2nd – Partly Cloudy, 3rd – Partly Cloudy	01/31/08
Four Day Test	1st – Sunny, 2nd – Sunny, 3rd – Sunny, 4th – Partly Cloudy	02/25/08
Five Day Test – 1st	1st – Sunny, 2nd – Sunny, 3rd – Sunny, 4th – Sunny, 5th – Partly Cloudy	03/18/08
Five Day Test – 2nd	1st – Partly Cloudy, 2nd – Partly Cloudy, 3rd – Cloudy, 4th – Sunny, 5th – Sunny	05/18/08

The plots generated for the 250 W experiments show the input solar panel voltage and current, as well as the battery voltage and ShopVac load current. The remaining plots that were generated are given in Appendix B. It is important to note that the ShopVac was inadvertently changed after the 250 W four day test, therefore the five day test utilized a newer slightly more powerful ShopVac. This does not change the results since the total load energy was considered, not the power or time during discharge (see Appendix B for the difference in ShopVac discharge plots).

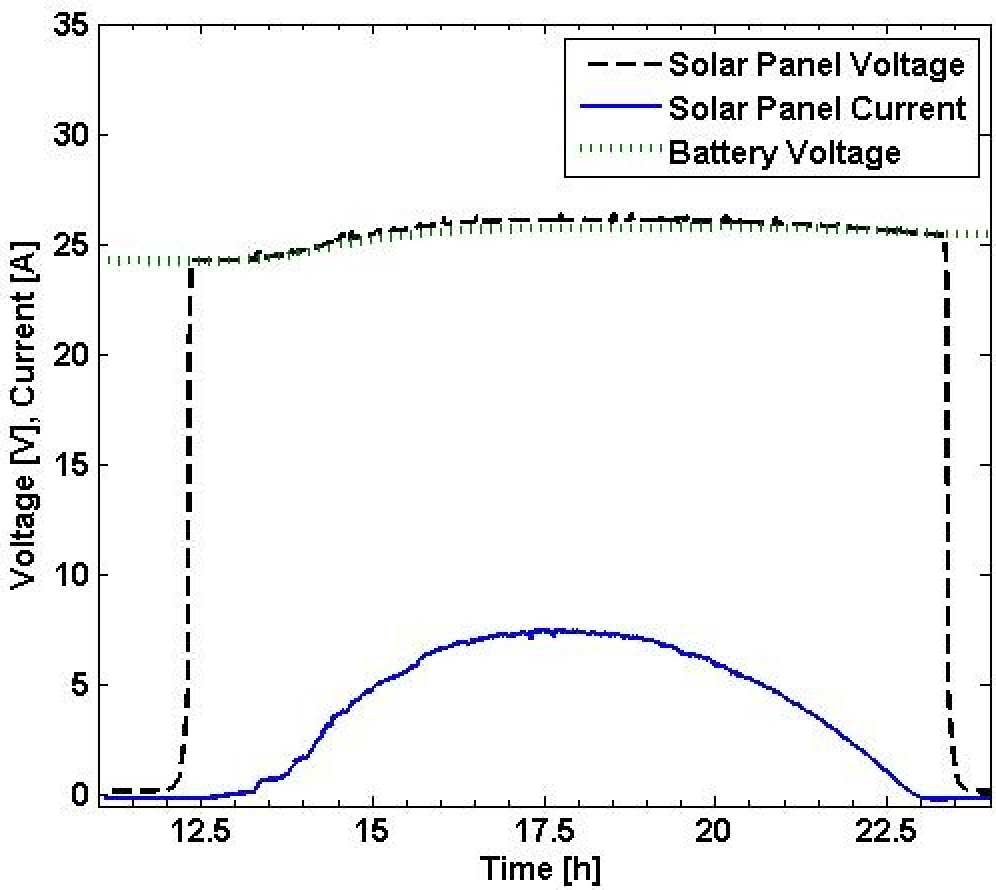


Figure 27: 250 W One Day Test: Solar Panel Voltage and Current

Figure 27 shows the voltage and current from the PV solar panels and the battery voltage on a typical sunny day. As can be seen from the plot, the voltage and current do not vary much throughout the day which implies that there was very little cloud activity and this is supported by the weather data shown in Table 6. The figure also shows that the PV solar panels are able to produce voltage for about 12 hours a day with the max occurring between 12 and 2 p.m., but the usable power is only about eight to ten hours which can be seen from the current curve. Figure 28 shows the discharge plot of the 250 W one day test.

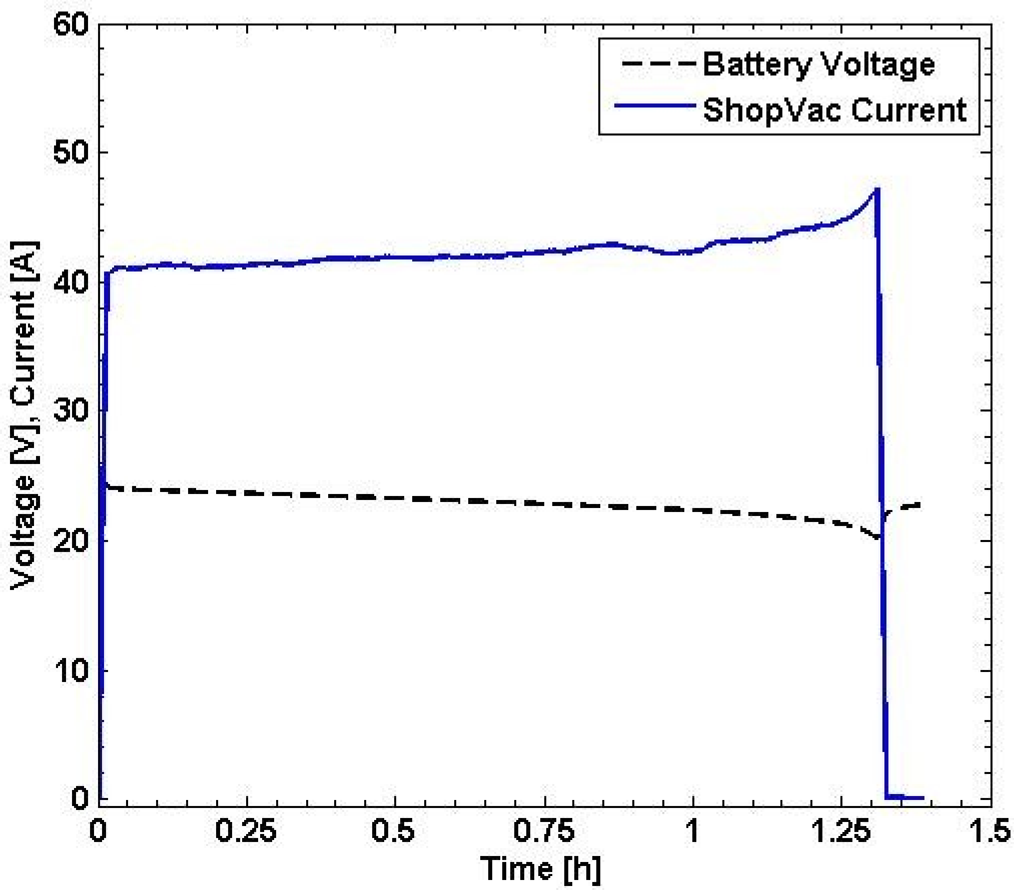


Figure 28: 250 W One Day Test: ShopVac Voltage and Current

This is a typical discharging plot of the battery bank utilizing the ShopVac load. For the 250 W one day test, the total discharge time took roughly 1.3 hours. This time was dependent on the amount of energy in the system, and therefore for these experiments, the total amount of time spent charging the batteries. Figure 28 shows that the current increases as the voltage decreases in the batteries. This is what was expected since the power required by the load remains relatively constant throughout the discharge. Once the voltage goes below roughly 23 V, the load disconnect feature of the inverter engages and shuts off any power to the load. To verify the effects of weather conditions on the system, the difference between a very sunny day and a cloudy day can be seen in Figs. 27 and 29.

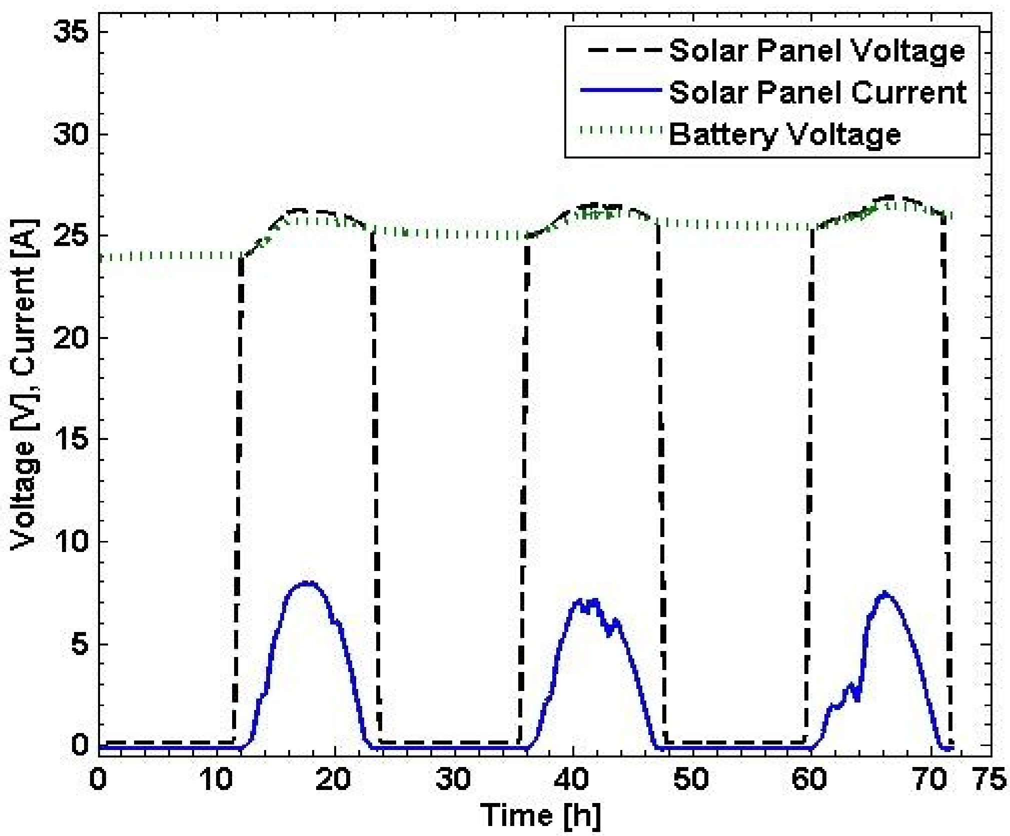


Figure 29: 250 W Three Day Test: Solar Panel Voltage and Current

From Figs. 27 and 29, one can see that the second and third day is different when compared to the first days of both tests. In these cloudy days, the current varies greatly, and this greatly affects the power input into the system. The power plot for the three day test is shown in Fig. 30, which is the product of the voltage and current curves shown in Fig. 29.

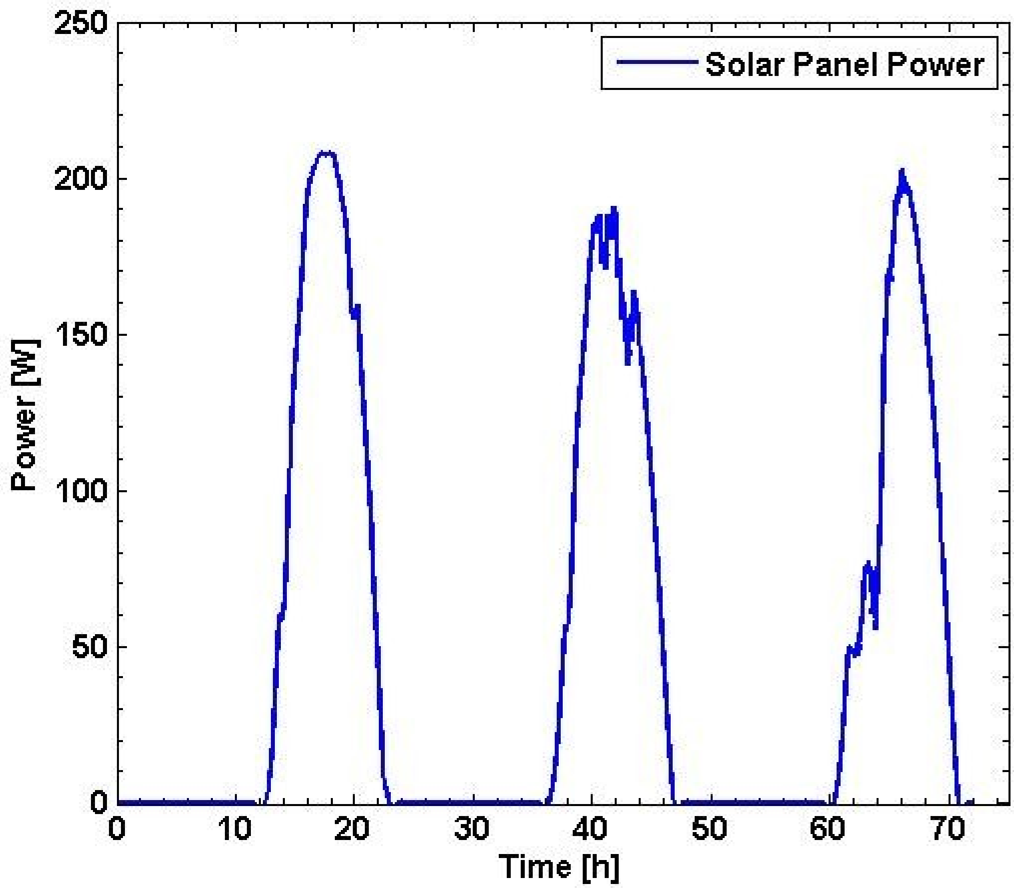


Figure 30: 250 W Three Day Test: Solar Panel Power

Figure 30 also shows that the clouds affect the power from the solar panels on the second and third day. Another important item of interest is that the maximum power at any moment in the experiment never reaches the maximum rated power of the 250 W solar panels. The highest power obtained from the solar panels was about 220 W, which is only 88% of the rated power from the 250 W panels. The latter must be considered when sizing a solar power system. Figure 31 shows the results of the first five day charging test in March 2008.

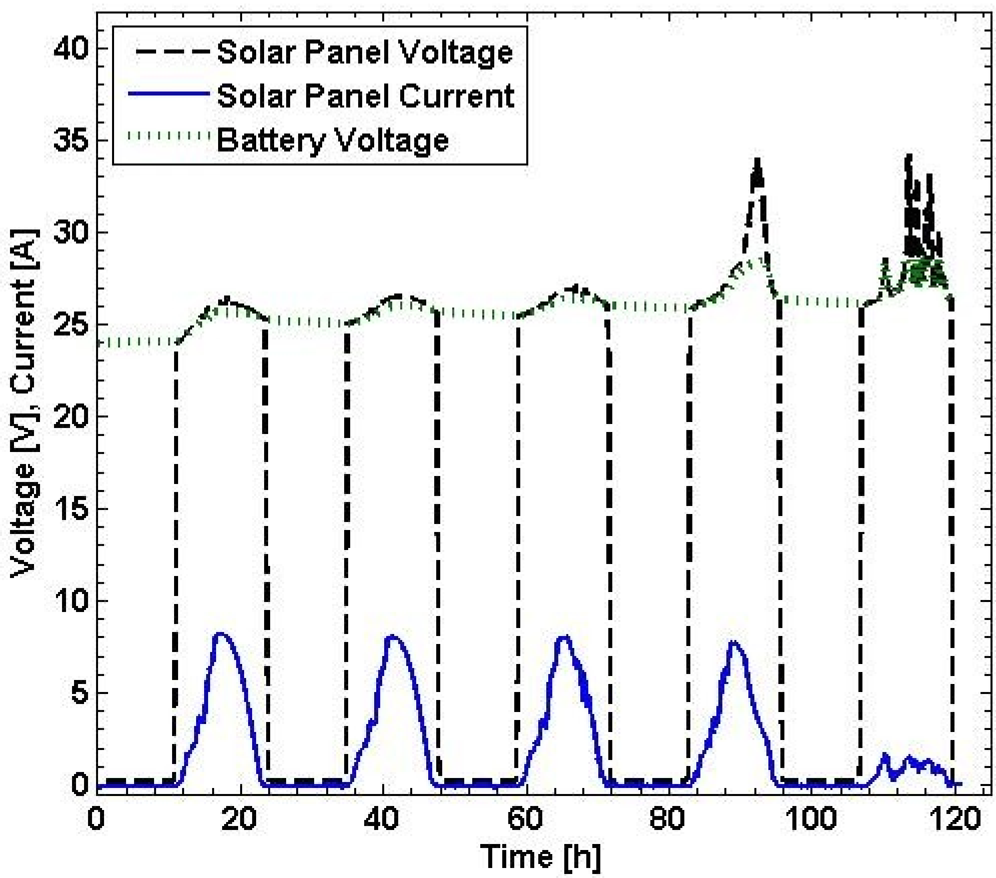


Figure 31: 250 W Five Day Test (March): Solar Panel Voltage and Current

Since the experiments utilizing the 250 W solar panels required at least four days of charging for the large batteries to be completely charged, a five day test was performed. From Fig. 31, the solar panel voltage spikes while the current drops on the fourth and fifth days and this is important to remember since this voltage is of the solar panels, and this suggests that the battery bank is near its full charged capacity. On the fifth day, the current decreases when compared to the other days, and this visually displays that the charge controller is disconnecting the power input into the battery bank to keep them from overcharging. When the controller disconnects the solar panels, the spike in the panel supply voltage is expected since the open circuit panel voltage is higher than the closed rated voltage. Table 5 shows that the first five day test provided the batteries with about 5500 W·h of energy. The discharge test also shows that the load utilized around 3800 W·h of energy which is what was expected. Figure 32 provides the second five day test (May 2008) for comparison with the five day test conducted in March 2008.

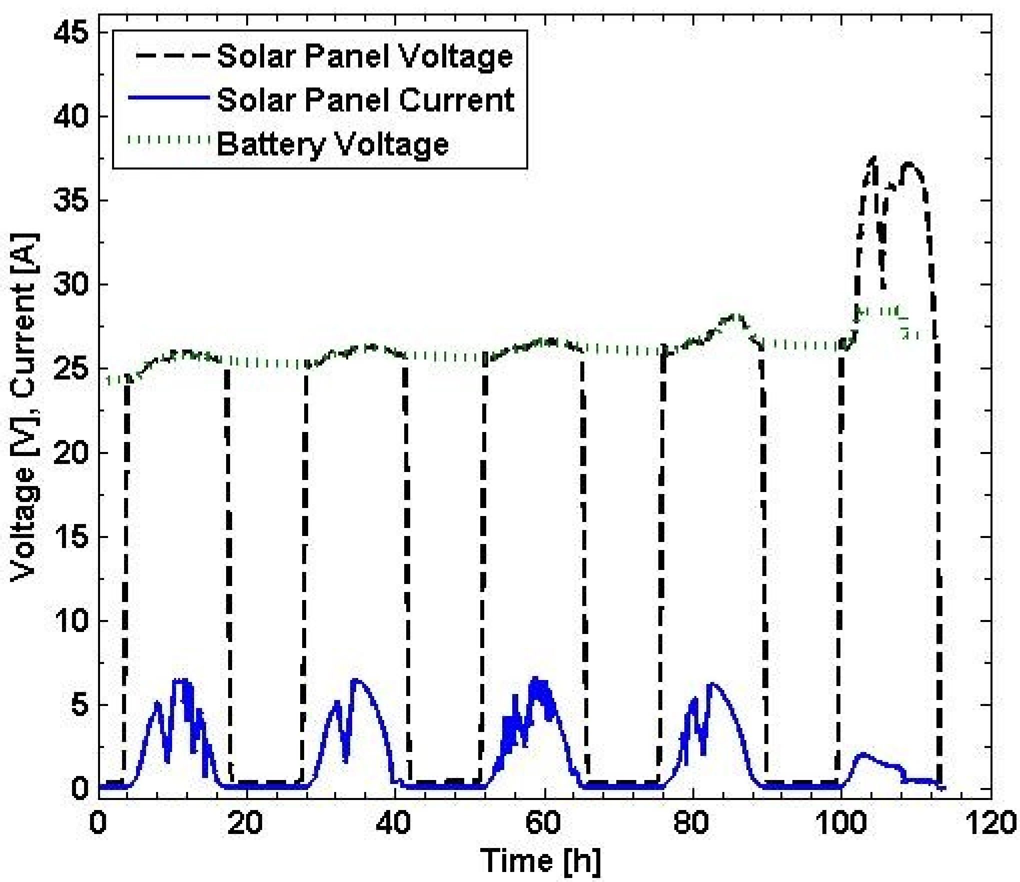


Figure 32: 250 W Five Day Test (May): Solar Panel Voltage and Current

Figures 31 and 32 are very similar but show the effect of having cloudy days. In either test, the solar panels were still able to bring the batteries to near full capacity. The fifth day from Fig. 32 shows the characteristic voltage spike and current decrease that occur when the batteries are near fully charged. Table 5 shows that the solar power input energy from the second test in May is about 700 W·h less than that from the first test and at the same time, the load energy is about the same in both tests. This comparison shows the difference in performance due to the weather conditions.

5.1.2 Results for 650 W setup

Unlike the 250 W experiments, the 650 W charging tests were only performed for one, two, and three days since it would take less time to fully charge the battery bank because of the higher power rating. These tests were also discharged with the different ShopVac load, but as previously mentioned, the energy supplied from the batteries would remain the same since an increase in load power, causes a decrease in the time to discharge the batteries. Even with the slightly higher load, the discharging plots remained similar to the previous experiments and the results are presented in the following tables and plots.

Table 7: Results for 650 W Setup Charging/Discharging Tests

Experiment	**Solar Panel Energy [W·h]**	**Battery Energy [W·h]**	**Load Energy [W·h]**
One Day Test	2675.8	2638.7	2044.8
Two Day Test	4517.2	4415.9	3402.9
Three Day Test	4511.6	4387.5	3643.3

Table 7 shows that the 650 W setup charged the battery bank in less time than the 250 W system as expected. Once again, the input battery energy is higher than the total load energy extracted from the batteries which is attributed to that unforeseen load from the inverter. In Table 8, the summary of the weather conditions for the experiments is provided.

Table 8: Weather Conditions for 650 W Setup Charging/Discharging Tests

Experiment	Weather Conditions	Date
One Day Test	1st – Partly Cloudy	04/29/08
Two Day Test	1st – Partly Cloudy, 2nd – Partly Cloudy	04/30/08
Three Day Test	1st – Partly Cloudy, 2nd – Cloudy, 3rd – Partly Cloudy	05/05/08

These experiments show that the 650 W system was capable of charging the batteries even with cloudy day weather conditions which is shown in Table 8. The partly cloudy weather conditions also explains the relatively low load energy for each test in Table 7 since it did not allow the batteries to absorb more electrical power. It is reasonable to expect about 2.6 times more power per day from the 650 W system when compared to the 250 W system (i.e. 650/250 = 2.6), but for these sets of experiments, the clouds greatly affected the energy being stored into the system. Tables 6 and 8 show the difference in weather conditions between the 250 W and 650 W experiments. All of the power plots from the 650 W tests show a maximum power output of about 400 W, which is about 61.5% of the possible 650 W of power. This is significant since it is lower than the 88% of the rated power from the 250 W system. If the clouds did not limit the 650 W system, it is safe to say that the performance would have been much better than what was obtained in these tests. Figure 33 shows the solar panel power plot generated for the 650 W one day test.

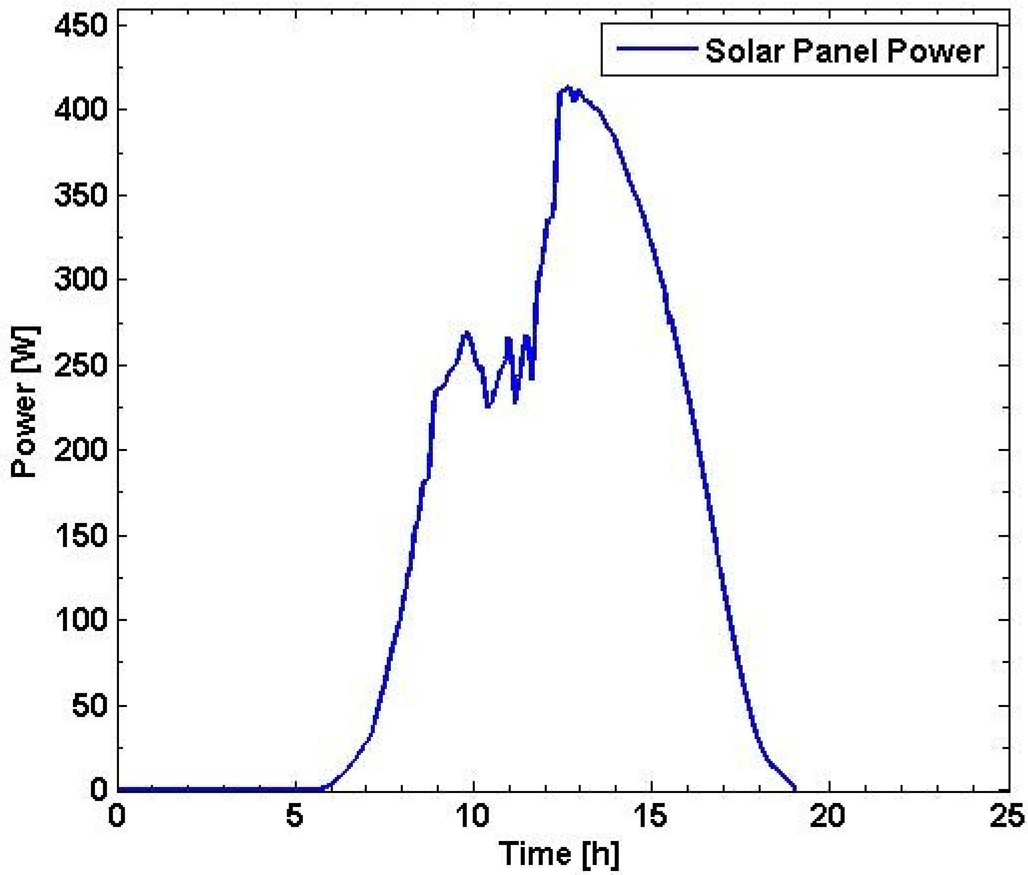


Figure 33: 650 W One Day Test: Solar Panel Power

From this plot, it can be seen that the power has a maximum of about 400 W, and there is also a large section where the clouds limited the system in the early part of the day.

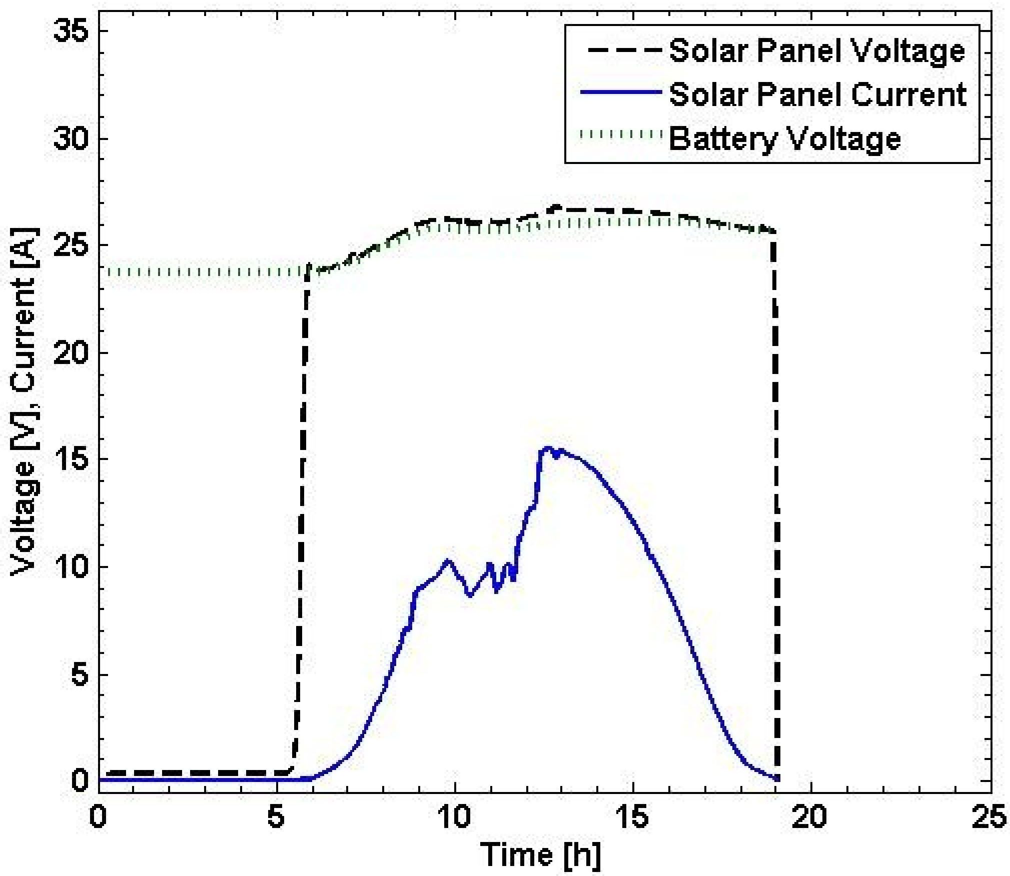


Figure 34: 650 W One Day Test: Solar Panel Voltage and Current

Figure 34 basically shows the input voltage and current to the batteries from the solar panels and resembles a typical charging day for the solar power system. The effect of the clouds is more evident from the electric current line, but the voltage line does show a slight drop during that time interval as well. The three day test utilizing the 650 W solar panel setup produced similar results to the 250 W tests in that the voltage sharply increases and current decreases once the batteries reach their full capacity.

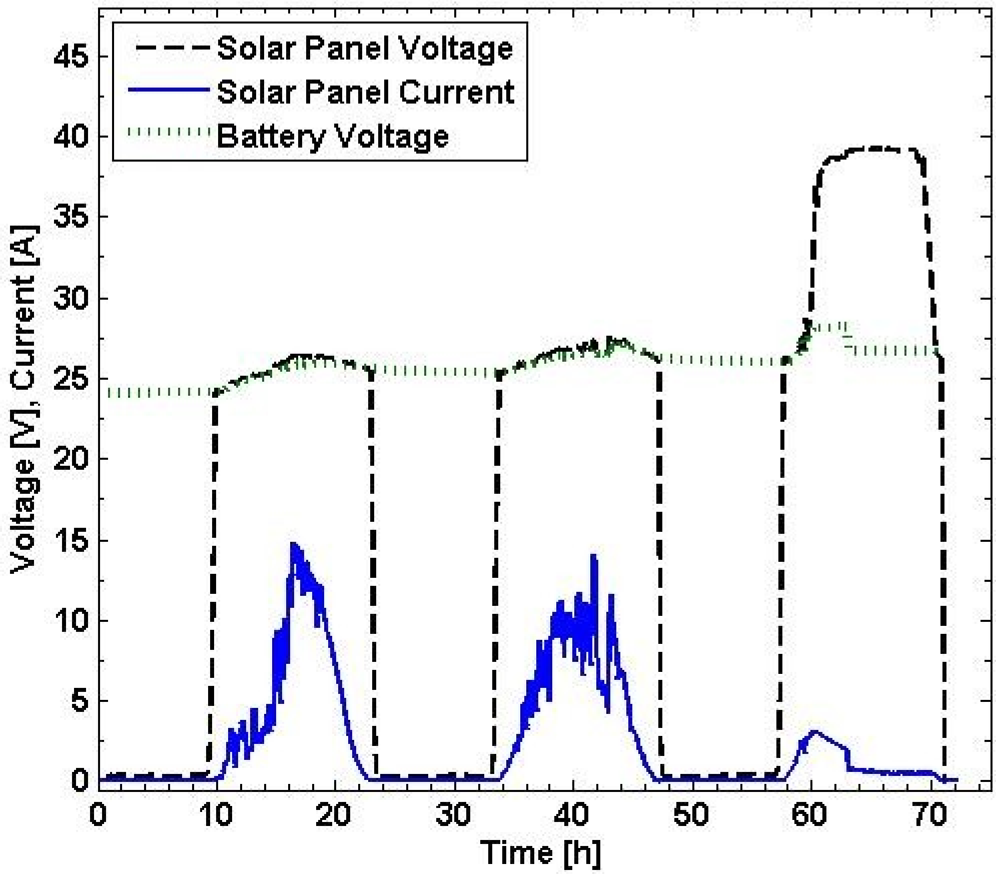


Figure 35: 650 W Three Day Test: Solar Panel Voltage and Current

Even with the first two days being partly cloudy, the 650 W system was able to charge the battery bank near full capacity in a little over two full days. The third day from Fig. 35 shows the large spike in voltage and drop in current as the batteries become full. As previously mentioned, the discharge plot remained similar but slight difference is due to the updated ShopVac model that operated at a slightly higher power. Figure 36 shows the discharge plot with a different load current towards the end of the test attributed to the new ShopVac.

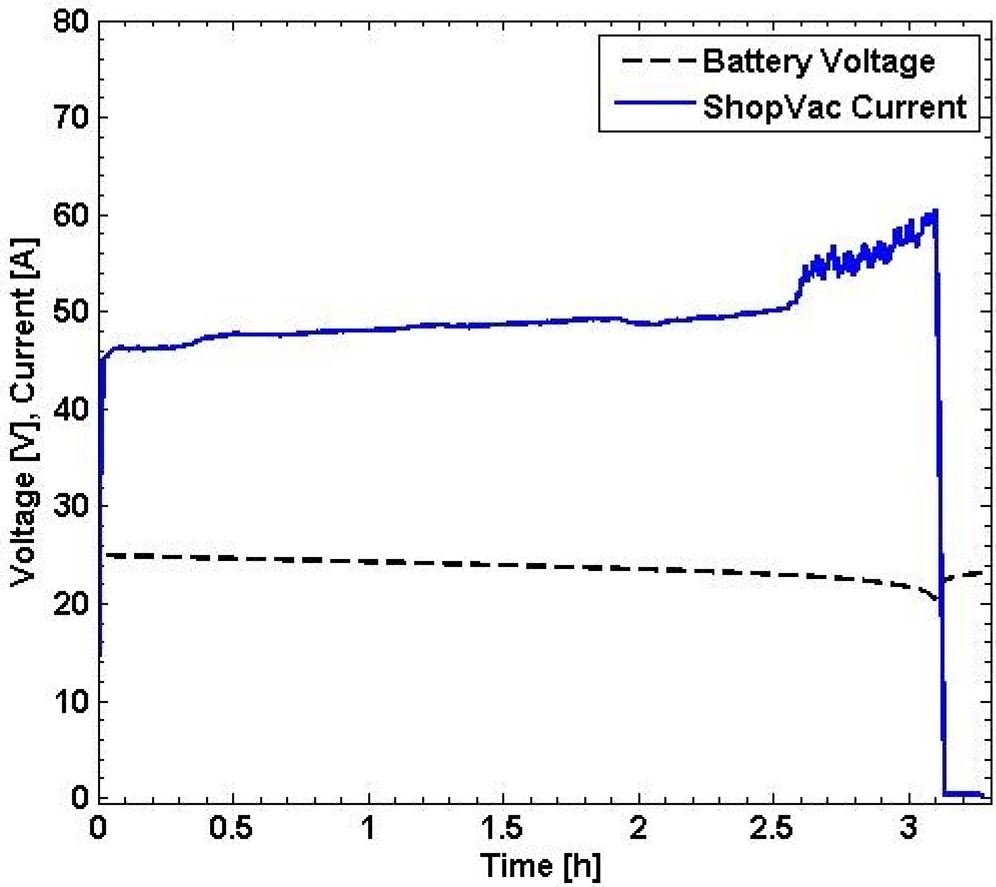


Figure 36: 650 W Three Day Test: ShopVac Voltage and Current

This plot was consistent with the other experiments that used the upgraded ShopVac load and can be seen in the remaining discharge plots (see Appendix B).

<u>5.1.3 Battery energy plot</u>

The results of the the charging/discharging experiments were also utilized to generate the plot in Fig. 37.

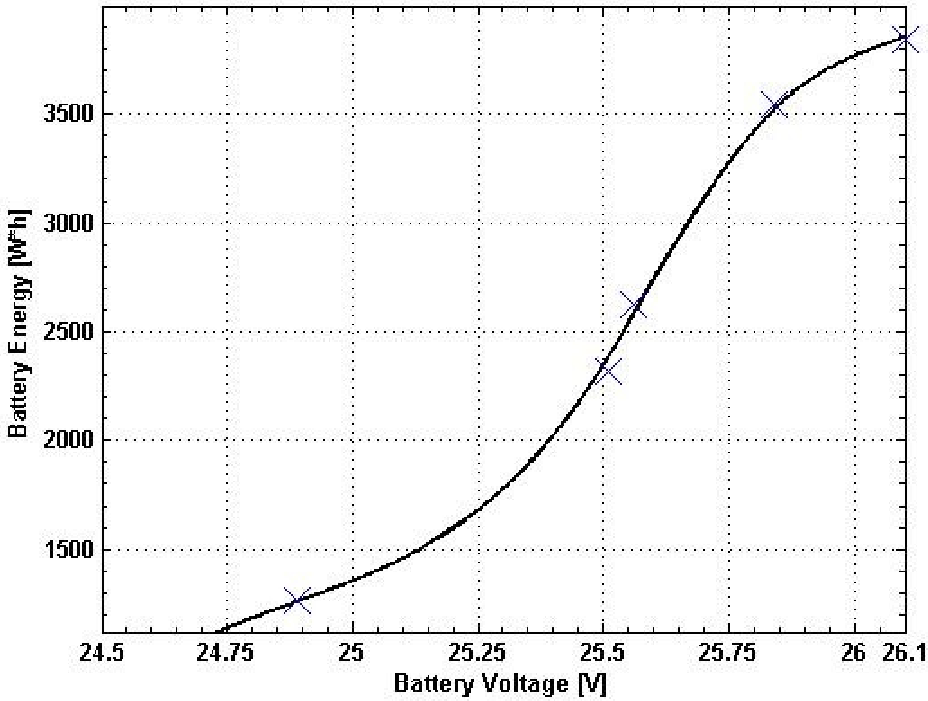


Figure 37: Usable Energy in 225 A·h Batteries Depending on Battery Voltage

Figure 37 provides a graphical reference to estimate the usable amount of energy within the 225 A·h battery bank (two sets of batteries). This amount of energy takes into account the 75% discharge capacity of the batteries. For example, if the batteries have a voltage of 25 V, then the estimated amount of usable energy is roughly 1350 W·h. This plot was generated using the charging/discharging experiments and should only be utilized as a reference since there are several factors that can affect the performance of the deep cycle batteries which include efficiency, type, and age.

5.2 Sustainability experiments

The following tests were performed to verify the sustainability of a hybrid power system. Along with the solar panels, the wind generator propelled with a motor was included to complement the input power and sustain the output required from the load. The loads were presented earlier in Table 2, and the wind generator schedule utilized was given in Table 4. The sustainability tests were performed with the 250 W and 650 W systems, and as expected, the 650 W system was able to fully sustain the loads with relative ease. It is important to remember that initial testing with an actual wind turbine mounted on the engineering building roof produced unfavorable results. The wind in the Rio Grande Valley proved to be too inconsistent to study using the system, and there were various problems with the 400 W Air-X wind turbine that was installed for the study. The people involved in this study decided to simulate the wind inside the laboratory to provide a general understanding of a working hybrid power system.

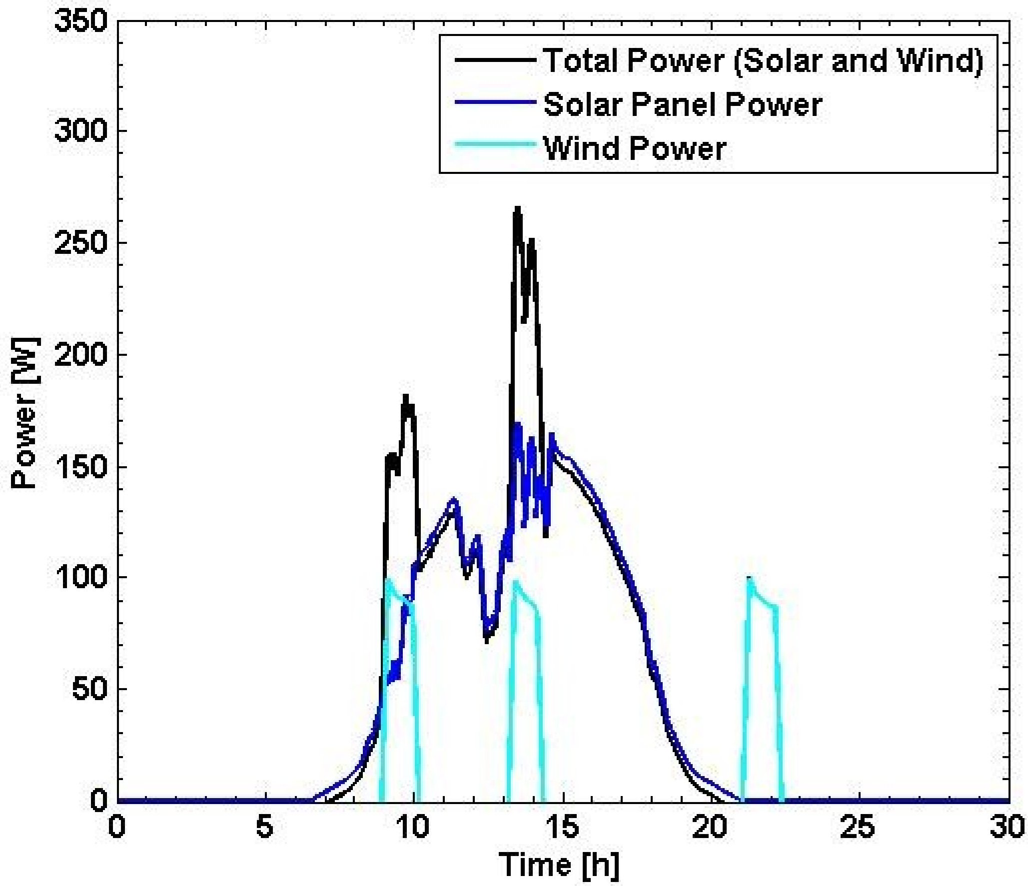


Figure 38: 250 W Sustainability Test: Solar and Wind Power

Figure 38 shows the solar panel and wind generator power from a typical day. Notice that the wind generator was only supplying power during the schedule that was previously mentioned. The solar panel power also shows evidence of clouds in the earlier part of the day which affects the total power input into the system.

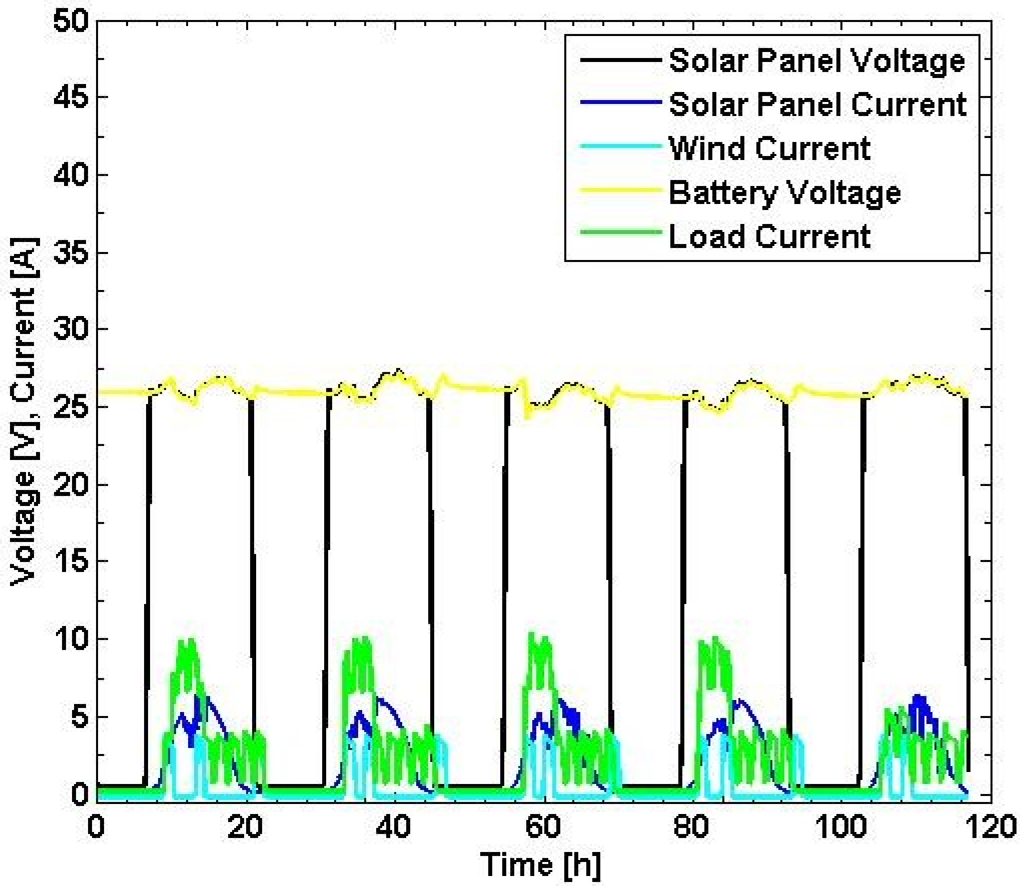


Figure 39: 250 W Sustainability Test: Solar, Wind, and Load Voltage and Current

From the Fig. 39, the interaction between the supply power and the load power is provided. The plot shows the supplied voltage and current from the solar panels and wind generator and also the battery voltage and load current for the duration of the experiment. Figure 39 also displays the periodic current from the refrigerator and the increase in current due to the addition of the other loads (fan, clock radio, and lights) in the earlier part of each day according to schedule in Table 2. The input wind power was considered to be the product of the wind current and the battery voltage for the length of time of the experiment. The battery voltage was utilized for this calculation because the batteries control the input voltage of the wind generator. Figure 40 shows the plot of the energy input into the system minus the energy utilized by the load for the 250 W hybrid power system.

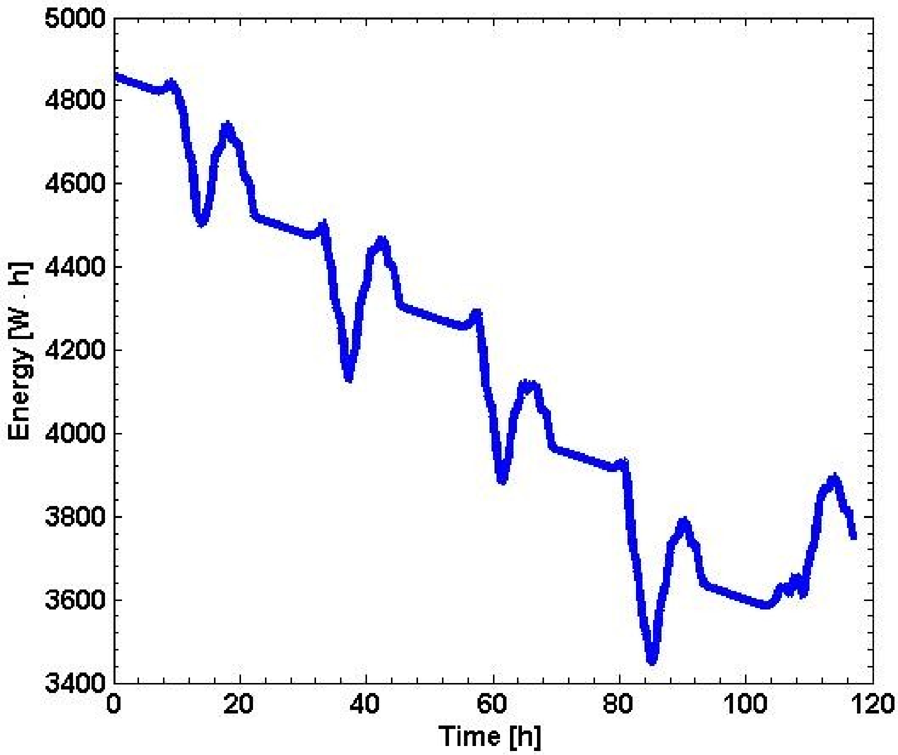


Figure 40: Estimated Energy Difference Between Input and Loads (250 W Hybrid Power System)

From Fig. 40 it can be seen that the batteries start at almost full capacity and then the energy starts to drop throughout the test. The fluctuations in energy correspond to the input and output energy that occurs during the experiment. The downward trend from Fig. 40 shows that the 250 W hybrid power system will not provide enough to meet the demands of the loads. The system was able to sustain itself for the duration of the five day test, but it is unlikely to be adequate for longer periods of time especially if it is not allowed to recover or if the weather conditions are unfavorable. Hence, this size of hybrid power system does not have any safety margin in case the conditions are not ideal for power generation. It is important to note that the initial value of energy within the batteries was assumed to be roughly 90% of the total energy capacity of the deep cycle batteries. This was done because of the feature that protects the batteries by not allowing an overshoot of energy when they are near full energy capacity.

The following results of the 650 W sustainability tests show the difference in performance when compared to the 250 W hybrid power system.

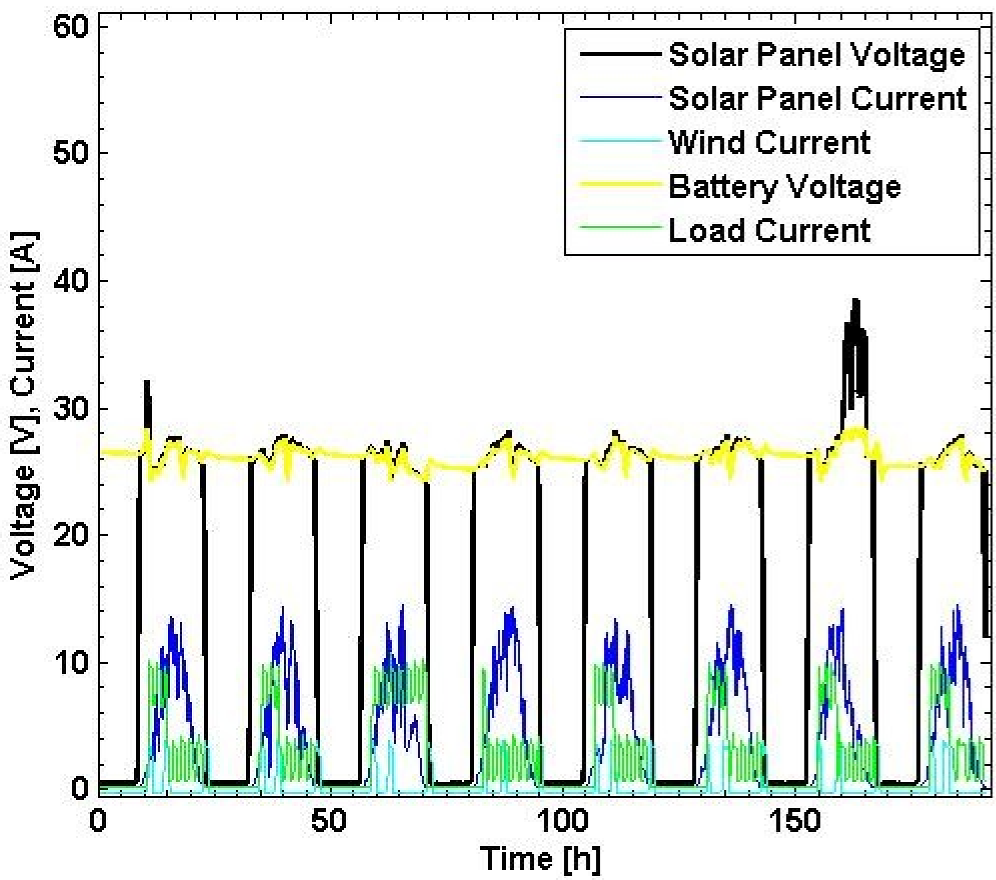


Figure 41: 650 W Sustainability Test: Solar, Wind, and Load Voltage and Current

Figure 41 displays the 650 W sustainability relationship between the input power (solar and wind) and the load power. This test was able to sustain itself for a total of eight days and it is capable of sustaining itself indefinitely as long as the weather conditions permit and there are no prolonged periods of time with no solar power. On the seventh day, the 650 W sustainability test shows that the system actually fully recovers and brings the batteries to almost a fully charged state. During the third day, all of the loads were left on during the day to help understand how the system would perform if the loads were unexpectedly being powered for a longer period of time. This was performed to simulate a condition where the loads are not being utilized as recommended. On the fourth day of the experiment, the fan, clock radio, and lights were only powered on for one hour, and then the system was allowed to recover from the previous day while still providing power to the refrigerator. This scenario actually had little effect on the sustainability of the system since it was able to fully recover and almost charge the batteries completely.

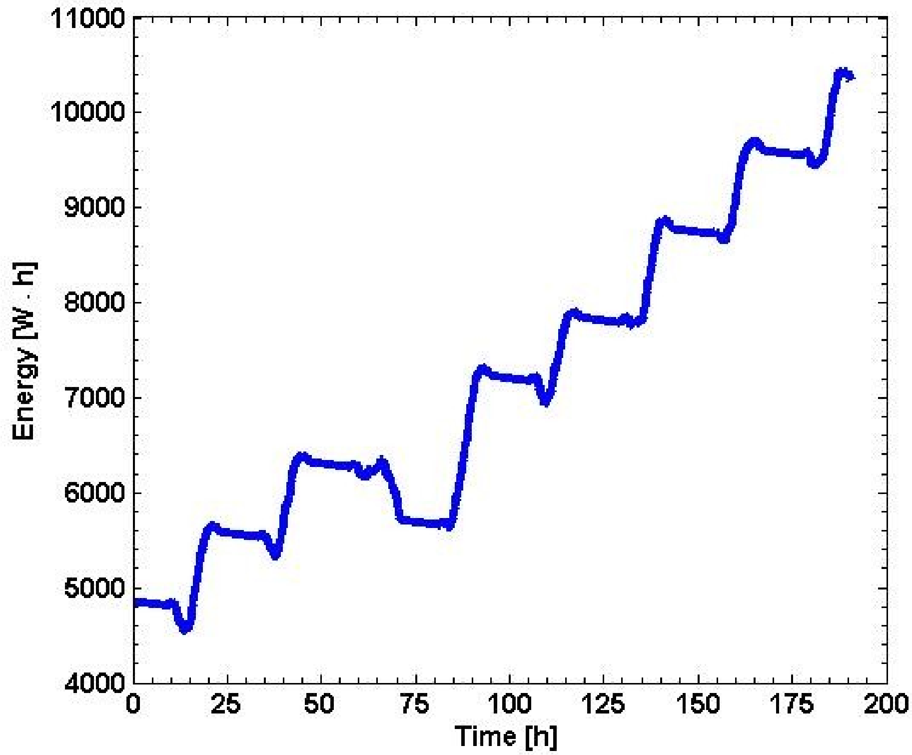


Figure 42: Estimated Energy Difference Between Input and Loads (650 W Hybrid Power System)

Figure 42 shows an increasing trend of the energy difference between the input and output of the 650 W hybrid power system. In this experiment, the batteries start once again at an almost fully charged capacity and the input energy continues to overcome the output energy. One important note from the plot is that the energy throughout the duration of the experiment is a combination of the energy stored in the battery as well as any excess energy that is being utilized by the diversion load. Since the diversion load was not monitored for these experiments, it is difficult to compute the actual energy that remains in the batteries. Though, as previously mentioned, if the system has to activate the diversion relay, this signifies that it is operating in an ideal condition since there is enough energy to maintain the batteries and heat water with the excess. The diversion load was not monitored using voltage and current transducers since it was initially placed as a safety device to protect the batteries, but the results of these experiments clearly show that this must be included for energy balance purposes in the future.

Table 9: Sustainability Experimental Results

Experiment	Total Battery Energy [W·h]	Total Wind Energy [W·h]	Total Load Energy [W·h]	Difference [W·h]
250 W + Wind (Five Day Test)	5685.6	1352.1	6667.0	370.7
650 W + Wind (Eight Day Test)	17416.0	2069.0	11986.0	7499.0

Table 9 further shows that the 650 W hybrid power system supplies enough energy to power the load and was able to sustain itself. The 250 W setup was also able to provide enough energy to the loads for the duration of the test, but would not be able to sustain the loads for much longer which is supported by the trend from Fig. 40. From these experiments, there seemed to be very little advantage to having a wind generator supplementing power for this system. In reality, the wind generator was powered by a motor, and it is unknown what actual effect it would have on the system. This greatly depends on the geographic location of the hybrid power system. This study shows that the wind generator would have to be capable of providing more power for longer periods of time to be able to supplement the system in a advantageous manner. Table 10 compares the first days of all the experiments (charging/discharging and sustainability tests).

Table 10: Experiments First Day Comparison

Experiment	Total Battery Energy [W·h]	Total Wind Energy [W·h]	Total [W·h]
250 W One Day Test	1166.4	0.0	1166.4
650 W One Day Test	2638.7	0.0	2638.7
250 W + Wind Test (First Day)	1186.2	277.9	1464.1
650 W + Wind Test (First Day)	2158.2	274.3	2432.5

Table 10 also shows that the simulated wind energy does not play as significant a role compared to the energy from the solar panels.

The original wind turbine that was purchased for this study was a 400 W Air-X model and the power plot of the wind turbine is given in Fig. 43.

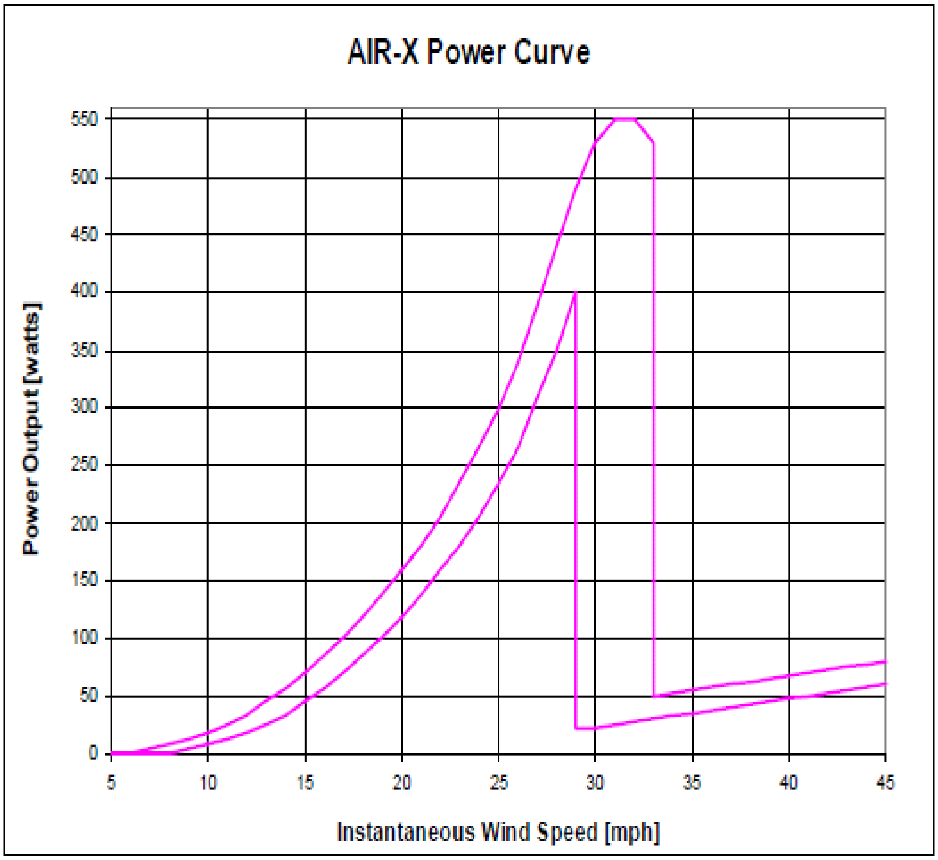


Figure 43: 400 W Air-X Power Curve

The upper plot in the Fig. 43 is the estimated power during smooth wind conditions, while the lower plot is the power produced during turbulent wind conditions both as a function of wind speed. This is another feature that was built into the wind generator to reduce the variability of the power input into the battery bank. This wind turbine was equipped with several additional features that did not perform well with the hybrid power system. This and the negative effect of the long distance between the batteries and the wind turbine hindered the addition of the Air-X wind turbine and led to the decision of including a simulated wind generator setup. Simulating the wind energy into the system does not show the actual wind energy capability from the Rio Grande Valley, therefore it was necessary to estimate it using hourly wind speed data and the Air-X datasheet. Utilizing typical meteorological year (TMY) data for Brownsville, Texas provided by the National Solar Radiation Data Base, energy data was computed to estimate the amount of wind energy that could have been generated in the Rio Grande Valley region with the 400 W Air-X wind turbine. Table 11 provides the overall results from these computations.

Table 11: Air-X TMY Data Results

	Energy [W·h]	**Average Energy per Day [W·h]**
Average Energy for TMY per Month	24330.7	798.8
Lowest Month (January 1981)	12642.8	407.8
Highest Month (March 2002)	40431.4	1304.2

From Table 11, the month with the highest estimated wind energy was in March of 2002 with a total value of 40431.4 W·h. The roughly 300 W·h per day that was produced with the wind generator setup is only about 74% of the average energy per day of the lowest month (January 1981). Figures 44 and 45 show the estimated Air-X wind energy for the lowest and highest TMY months.

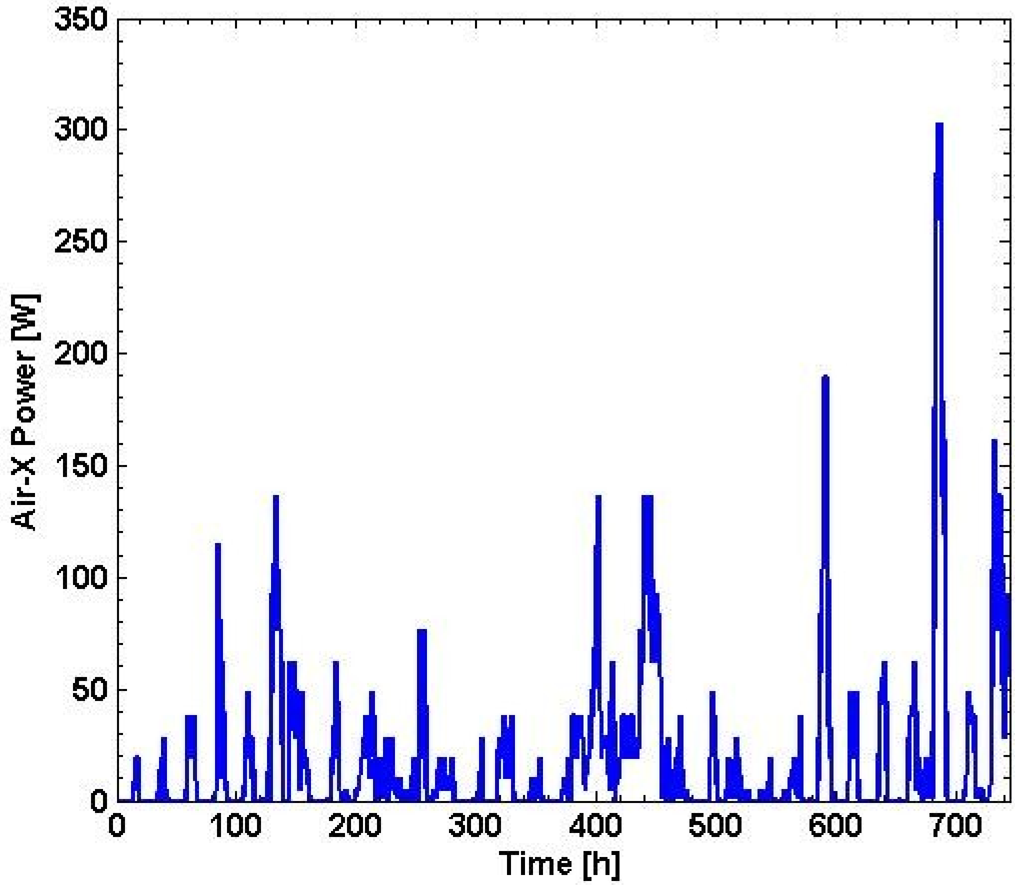


Figure 44: Air-X TMY Power January 1981

Figure 44 shows that the maximum power produced by the 400 W Air-X during the month of January 1981 was about 300 W.

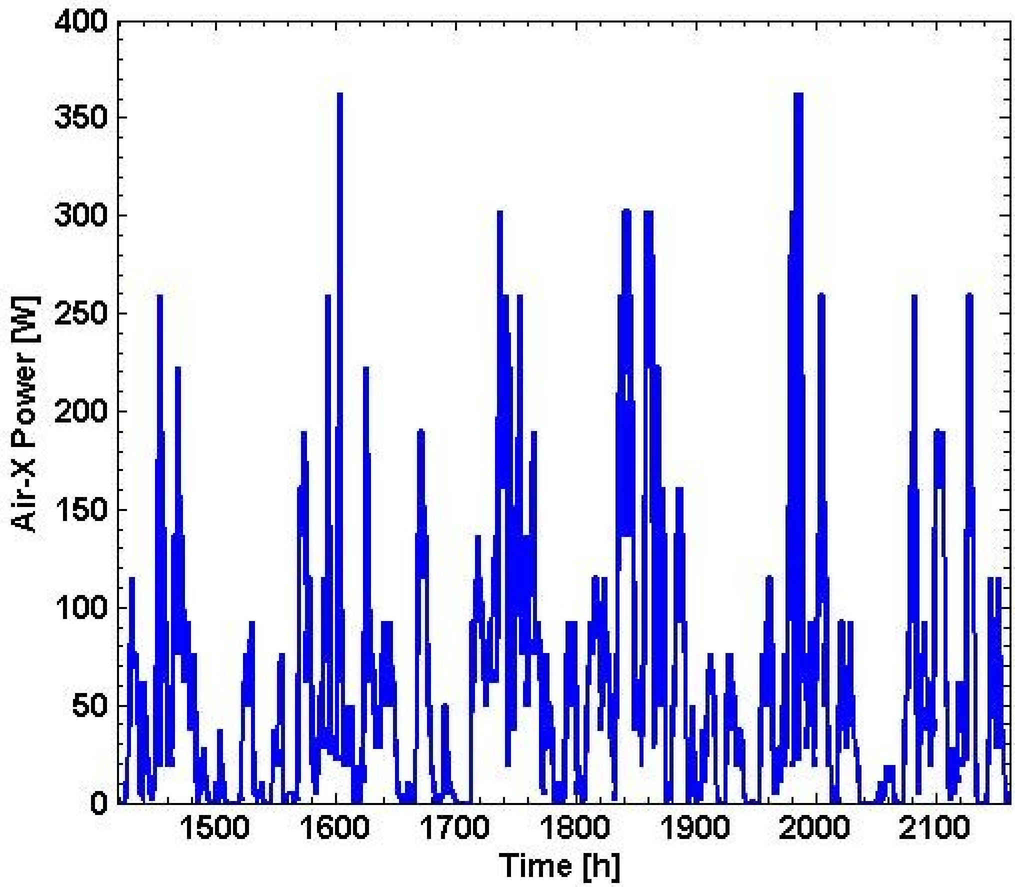


Figure 45: Air-X TMY Power March 2002

The difference in the power curves between the lowest and highest energy producing months is visible since the peaks for the TMY month of January 1981 are lower than in March 2002. Another important point that is visualized from Figs. 44 and 45 is the variability of the wind in the Rio Grande Valley region. The energy for every month was computed by utilizing the power plot with respect to time and computing the area under the curve which was discussed and provided in Eq. (8). Table 12 displays the total amount of estimated energy produced for each month of the TMY data.

Table 12: Air-X TMY Monthly Data

Month	W·h
January 1981	12642.8
February 1980	25243.2
March 2002	40431.4
April 1990	39836.4
May 1981	25186.2
June 1999	26541.8
July 2002	27668.3
August 1978	26663
September 2001	14051.6
October 2001	16105.3
November 1986	20458.1
December 1985	17139.8
Year Total	291967.9

The estimated year total energy that would be produced from the Air-X wind turbine in the Rio Grande Valley would be roughly 292 kW·h. This data shows that the benefit of having a wind turbine in the Rio Grande Valley region is minimal. According to the current prices of electricity per kW·h, including this wind turbine within the system would take a long time to pay for the initial investment because of the low energy produced.

5.3 Feasibility for isolated communities

This research in conjunction with another study verified the feasibility of related solar power systems for use in the rural region of the Municipality of Ciudad Valles in the state of San Luis Potosi, Mexico [20]. Three specific sizes of systems were investigated which include a 250 W House/Mobile Clinic system, a 450 W School system, and a larger 650 W Community Center system. The systems were created based on loads that would be required to provide some basic utility needs. Tables 13, 14, 15, and 16 display the loads associated with the different scenarios that were investigated.

Table 13: Mobile Clinic Energy Consumption Requirements (24 hour basis)

Mobile Clinic					
Item	**Quantity**	**Power Per Item [W]**	**Total Power [W]**	**Period of Operation [h/day]**	**Energy Consumption [W·h]**
Light	1	18	18	4	72
Satellite Phone	1	14	14	3	42
Laptop	1	45	45	4	180
Refrigerator	1	50	50	12	600
Inverter	1	4	4	24	96
Total Power Requirements for the System					990

Table 14: House Energy Consumption Requirements (24 hour basis)

House (Two-Room Home)					
Item	**Quantity**	**Power Per Item [W]**	**Total Power [W]**	**Period of Operation [h/day]**	**Energy Consumption [W·h]**
Light	2	18	36	4	144
Fan	1	55	55	4	220
Radio	1	4	4	1	4
Refrigerator	1	50	50	12	600
Inverter	1	4	4	24	96
Total Power Requirements for the System					1064

Table 15: School Energy Consumption Requirements (24 hour basis)

School (Two Classrooms + One Office)					
Item	**Quantity**	**Power Per Item [W]**	**Total Power [W]**	**Period of Operation [h/day]**	**Energy Consumption [W·h]**
Light	5	18	90	4	360
Laptop	3	45	135	2	270
Fan	3	55	165	4	660
Radio	1	4	4	2	8
Printer	1	15	15	2	30
Inverter	1	4	4	24	96
Total Power Requirements for the System					1424

Table 16: Community Center Energy Consumption Requirements (24 hour basis)

Community Center (Two Large Rooms + One Bathroom)					
Item	**Quantity**	**Power Per Item [W]**	**Total Power [W]**	**Period of Operation [h/day]**	**Energy Consumption [W·h]**
Light	5	18	90	6	540
Satellite Phone	1	14	14	3	42
Laptop	1	45	45	3	135
Fan	2	55	110	6	660
Radio	1	4	4	6	24
Television	2	90	180	3	540
Inverter	2	4	8	24	192
Total Power Requirements for the System					2133

It is important to mention that only the house energy consumption scenario was validated; however, by verifying the house configuration, the mobile clinic was validated as well considering that the loads for both scenarios are very similar. Performance predictions for the school and community center system configurations based on the results obtained from the house scheme and the charging tests conducted utilizing the 650 W solar panels were also computed. Table 17 provides a breakdown of the total energy supplied by the 250 W solar panels to the two sets of 74 A·h batteries and the energy consumed by the electric loads for each of the eight days in the week long feasibility test.

Table 17: House Scenario (250 W panels, and two sets of 74 A·h Batteries)

Day	Energy Supplied by Solar System [W·h]	Actual Energy Consumed by Electric Loads [W·h]	Actual Energy Remaining in Batteries [W·h]	Theoretical Energy Consumed by Electric Loads [W·h]	Theoretical Energy Remaining in Batteries [W·h]
1	831	934	2383	1064	2253
2	1111	977	2486	1064	2300
3	1102	972	2486	1064	2338
4	758	734	2486	1064	2032
5	527	526	2486	1064	1495
6	761	514	2486	1064	1192
7	505	518	2473	1064	633
8	1147	666	2486	1064	716

Examining the data shown in Table 17 reveals that five out of the eight days had inadequate (less than the needed 1064 W·h of energy) supply of energy to the battery bank. Ciudad Valles experiences approximately five days of rainfall per month, on average, indicating cloud cover during part or all of those days. Therefore, the week long experiment unintentionally simulated a worst case scenario week incorporating five days of limited sunlight. The highest value of energy supplied by the 250 W solar panels occurred on the eighth day and was equal to 1147 W·h of energy, which is approximately 76.5% of the maximum attainable theoretical value of 1500 W·h/day based on an insolation value of 4.0 kW·h/m^2/day in South Texas, and a solar panel area of 2.5 m^2 performing at an efficiency of 15%. The Ciudad Valles region has a higher insolation value of 4.7 kW·h/m^2/day, so the maximum possible energy collection in that area using the same solar panels would be about 1762 W·h/day. Hence, for a day similar to that of day eight where 76.5% of the maximum possible energy collection was attained, the energy collected in Ciudad Valles should measure about 1348 W·h, which is approximately 200 W·h of energy per day more than what was collected in this test. The latter discussion implies that the conditions in Ciudad Valles are even more favorable than in South Texas, so validation of the solar power system in South Texas signifies its feasibility in the Ciudad Valles region.

To compensate for the days of low charging power, the electric load was reduced in those days to ensure that the test would be completed successfully. Therefore, all appliances other than the refrigerator were in operation for half of their proposed time on the fourth day, and on the fifth, sixth, and seventh day, all appliances were turned off except for the refrigerator. On days one, two, three, and eight, the full electric load was used. Note that the actual energy consumed by the electric loads when operated as proposed in Table 14 differs from the theoretical energy consumption rate of 1064 W·h/day for two main reasons; first, the load from the refrigerator varies depending on usage, and second, the power requirements for each of the appliances has been rounded up, meaning that these appliances draw a little less power than what is stated. The actual energy remaining in the battery bank at the end of each day was calculated by subtracting

2486 W·h, which is the total energy available for usage in both 74 A·h battery sets which start off fully charged, from the actual energy consumed by the electric loads, and adding the energy supplied by the solar panels. For example, on the first day, more energy was consumed than supplied; hence, the remaining energy in the batteries dropped slightly. On the following day, the energy supplied by the solar panels was more than the energy consumed by the electric loads, so the battery bank was fully recharged back to 2486 W·h.

Looking at the fourth column in Table 17, it can be seen that by reducing the amount of energy consumption in the days with low energy collection, the battery bank was allowed to recover and the actual energy stored in the batteries remained very close to fully charged conditions. However, in real application mode, it is not possible to regulate how people will use appliances on a cloudy day; thus, theoretical calculations were performed to ensure that the system would run continuously had the 1064 W·h/day consumption rate been used consistently during the worst case scenario week. The latter calculations are shown in columns five and six of Table 17, and demonstrate that the solar power system would still be able to run continuously, even after five days of inadequate energy collection. Using the average value of the energy collection in days two, three, and eight, which is 1120 W·h of energy, as the basis to calculate the amount of time required for the batteries to fully recover their initial charge of 2486 W·h, it would take about 30 days if the 1064 W·h/day consumption rate were consistently utilized. On the other hand, the energy reserve in the battery bank could be depleted if bad weather persisted resulting in more days with low energy collection, assuming no efforts were made to reduce the amount of energy consumed per day. The aforementioned underscores the necessity of advance research to assess the expectations of the people that will use a renewable energy system, coupled with training designed to manage expectations when they take control of the system, with follow-up maintenance checks and continuing education to train users to understand, manage, and maintain their power system.

Based on the results of Table 17, theoretical predictions for the school and community center energy consumption scenarios were carried out and are presented in Tables 18 and 19, respectively. The energy supplied by the 450 W solar panels was calculated by multiplying the insolation of Ciudad Valles, 4.7 kW·h/m^2/day, times the total surface area of the solar panels that form the system which is 3.38 m^2, times the efficiency of the solar panels (15%), times the percentage of maximum possible energy collection discussed earlier (76.5%), which gives a total energy of 1823 W·h/day. The energy supplied by the 650 W solar panels was obtained in a similar fashion using a total solar panel surface area of 5.31 m^2, which gives an energy collection value of 2864 W·h/day. The theoretical energy consumed by the electric loads in Tables 18 and 19 was taken from Tables 15 and 16, respectively. To provide realistic predictions, four consecutive days were modeled as bad days, supplying only half the energy of a good day. The theoretical analysis demonstrates that both systems are capable of sustaining a continuous operation. Furthermore, it can be observed that it takes the system powering the school about five days to recover to fully charged battery bank condition, while the system powering the community center recovers in only four days.

Table 18: School Scenario (450 W panels, and two sets of 74 A·h Batteries)

Day	Theoretical Energy Supplied by Solar System [W·h]	Theoretical Energy Consumed by Electric Loads [W·h]	Theoretical Energy Remaining in Batteries [W·h]
1	1823	1424	2486
2	1823	1424	2486
3	912	1424	1974
4	912	1424	1461
5	912	1424	949
6	912	1424	436
7	1823	1424	835
8	1823	1424	1234
9	1823	1424	1633
10	1823	1424	2032
11	1823	1424	2431

Table 19: Community Center Scenario (650 W panels, and 225 A·h Batteries)

Day	Theoretical Energy Supplied by Solar System [W·h]	Theoretical Energy Consumed by Electric Loads [W·h]	Theoretical Energy Remaining in Batteries [W·h]
1	2864	2133	4100
2	2864	2133	4100
3	1432	2133	3399
4	1432	2133	2698
5	1432	2133	1997
6	1432	2133	1296
7	2864	2133	2027
8	2864	2133	2758
9	2864	2133	3489
10	2864	2133	4100
11	2864	2133	4100

Finally, a simple cost analysis was conducted to provide a basis of comparison for the three different size solar power systems devised at UTPA. The total cost, including all accessories and wiring, of the system developed for the house and mobile clinic, which consists of 250 W solar panels and two pairs of 74 A·h deep-cycle batteries, comes out to about $3,000 per household or mobile clinic. The cost of the system designed for the school, which consists of 450 W solar panels and two pairs of 74 A·h deep-cycle batteries, is approximately $4,500, and the cost of the system developed for the community center, which consists of 650 W solar panels and one set of 225 A·h deep-cycle batteries, is close to $8,000. It is important to note that these cost values were computed utilizing the current prices of the components that make up the solar power systems. The cost estimate information given here along with the experimental results presented can be used to assess the feasibility of implementing these solar power systems in South Texas, in Ciudad Valles, and in any region characterized with comparable weather conditions.

CHAPTER VI

CONCLUSIONS AND FUTURE WORK

This study shows the overall performance of a small-scale hybrid power system in the Rio Grande Valley region in Texas. In this work, a solar power system implemented and tested through some charging/discharging experiments, and the sustainability of a hybrid power system was confirmed. These experiments provide an initial understanding of the application of small hybrid power systems in areas similar to the Rio Grande Valley and helped investigate the feasibility of these systems for application in isolated communities that are not connected to a power grid.

Previous experiments from an earlier study determined that the system utilized for this study did not require a solar tracking system and provided the optimal inclination angle of 26°, therefore the experiments conducted for this study utilized the optimal inclination angle without solar tracking. Charging/discharging experiments from the previous study also gave a preliminary understanding of the battery bank capabilities as well as the difference of having various sizes of solar panels supplying power to the system which helped provide some initial insight for this work.

The results from this study shows the correlation between weather conditions and the power generated by such small-scale systems. As expected, experimental data proves that the actual power generated by the solar panels is lower than their rated power. The 250 W tests provided up to 220 W of power, which is about 88% of the rated solar panel output. The 650 W tests were even lower, at only about 400 W of power from the solar panels which is 61.5% of 650 W. The difference in performance between both systems can be attributed to different weather conditions. If the 650 W experiments were conducted during the same exact days of the other 250 W experiments, then it is possible that they would have provided more power. It is also safe to assume that the batteries would have charged in a shorter amount of time with more sunny days during the 650 W system experiments. However, this was very beneficial in understanding that the performance of a hybrid power system would vary due to many different variables. When such systems are utilized with homes or small businesses, it is important have a hybrid power system that was designed with these types of scenarios in mind to ensure that it performs desirably. Other items that can affect the performance of these systems is the wire utilized within the system (length and gauge), component efficiencies, type and age of components, and several other unforeseen factors. As previously mentioned, these experiments were conducted with an overall wire length between the solar panels and charge controller of 175 feet. This long distance causes more losses within the system because of the higher resistance in the wire. Ideally in homes and small businesses, the solar panels will not be placed at such distances and these losses within the connecting wire will be minimized. The large 225 A·h batteries were able to provide a maximum of 3843 W·h of energy which is about 71% capacity of the batteries. While the batteries are capable of providing around 75% or 4050 W·h, a couple of factors could have contributed to the lower values obtained during the experiments. These include, the battery age and length of charging time. As has been previously discussed, the charge controller has a limiting feature that engages while the batteries are charging at almost full capacity. This feature protects the batteries by controlling the amount of energy that goes into the batteries. If the experiments would have been conducted for a slightly longer period of time, then the batteries might have provided close to the full 4050 W·h of energy. The age of the batteries also limits the performance of the system and even though the 225 A·h batteries were utilized immediately after they were purchased, it is unknown how long they were in storage before we obtained them and this could have contributed to the lower amount of usable energy. To help visually show the amount of usable energy within the batteries Fig. 37 was created using the data that was obtained from the experiments. This plot shows the estimated usable energy within the battery bank as a function of the voltage of the batteries. It is important note that this voltage must be verified when the power source (solar panels, wind generator, etc.), and loads are disconnected from the battery bank since they can affect the measured voltage. Figure 37 can be utilized to estimate the usable energy by homes and small businesses.

The sustainability experiments helped provide valuable information regarding the feasibility of such systems with a supplemental wind generator. These experiments provided insight into whether the chosen configuration of the hybrid power system would be able to support typical loads found in a house. It was found that the 650 W solar panels, paired with the wind generator, would be able to fully sustain energy for use with the loads given in Table 2 by looking at the upward trend given in Fig. 42. Figure 40 shows that the 250 W solar panel setup with the wind generator would not be able to provide the necessary power for the loads indefinitely, especially when having to consider the factors that affect the performance of the system (i.e. weather conditions). As mentioned earlier, the wind energy was simulated for both 250 and 650 W solar panel setups because of the sporadic wind in the Rio Grande Valley, the effect of the long wires to the roof, and limitations to the 400 W Air-X wind turbine. In both sets of experiments, the wind energy did not produce a significant amount of energy into the battery bank when compared to the solar panels. Therefore, these experiments only provide insight into what effect a wind generator can have with a solar power system. Furthermore, the wind setup described in the study can also be utilized in renewable energy laboratories in universities that do not have sufficient wind or have specific limitations that does not allow the used of an actual working wind turbine. In this study, calculations were also performed with TMY data to predict what a working 400 W Air-X wind turbine can produce in the Rio Grande Valley region. The results of the calculations show that the possible wind energy in the region is comparable to the energy produced from a 250 W solar panel. The one day test of the 250 W solar panel system showed that the batteries obtained about 1230 W·h of energy during a sunny day. Assuming the system can produce the same amount of energy for every day of the year, then the yearly energy from the 250 W solar panels would be equal to about 449 kW·h while the Air-X wind turbine produced about 292 kW·h shown in Table 12. This assumption is not possible since it would mean that every day of the year would be sunny, so it is safe to assume that this yearly value for the 250 W solar panels will be much closer to the energy from the Air-X wind turbine. In either case, the results from this study shows that the energy from small-scale hybrid power systems will not produce significant savings if utilized in regular home and small business applications to supplement the electricity obtained from a power grid. However, it does provide benefit for homes in isolated communities and regular small businesses during a blackouts since it will be able to power important appliances like a small refrigerator or a laptop computer and printer. During blackouts, a small business can maintain productivity and possibly pay for the system relatively quickly. For isolated homes, a simple light or refrigerator can increase the quality of life and therefore, such systems are invaluable. Other more inexpensive options such as electric power generators can be utilized, but this would require that gasoline or diesel be readily available and this is where the real benefit of this study is seen.

This study further investigated the potential feasibility of such systems being utilized in isolated communities in Ciudad Valles and it was found that there is still much room for improvement. The Ciudad Valles approach begins with governmental (Ciudad Valles Municipal administration and Mexican Consulate) and institutional (UTPA) planning and research. The municipal government will lead the way in setting up an initial system for a rural community. However, by establishing an infrastructure to support local community education, training, and decision making meetings, it is laying a foundation from which the community will eventually be able to take full ownership of its own renewable energy infrastructure, with the know-how to grow it for economic development. Rural Ciudad Valles is plagued with the negative local side of emigration; a large portion of adult males are absent from the local labor market and working in the United States due to lack of local jobs. In the media there is much discussion of the need for Mexico to develop its economy, but in the United States there is little understanding of the challenges this poses for a country with large, isolated indigenous populations that have no experience in their own communities with the energy infrastructure required to participate competitively in more than the impoverished local labor economy. Achieving regional, national, and global knowledge economy development in indigenous regions of

Mexico will require multi-staged, long term planning to achieve success. Ciudad Valles and researchers at UTPA are approaching this project with that in mind. Consequently, future work will require building local technical and cultural support, which will include ongoing energy system and human factors data collection for improvement of the plan and its outcomes as it is implemented across the region. In the early stages, this will have to be managed by UTPA researchers and Ciudad Valles administrators, while local communities, educators, and entrepreneurs are identified and develop the skills to sustain and grow the plan.

Overall, this study gives a general understanding of the performance of a small-scale hybrid power system configurations in similar environments. The information provided can be utilized as a guide to anyone interested in obtaining a hybrid power system in regions similar to the Rio Grande Valley. The design of hybrid power systems should incorporate the items that were discussed in this thesis, including the selection of system components as well as the system loads. Through more studies and technological advances, component efficiencies should increase and overall cost should decrease making the application of these systems more enticing to reduce the rate of consumption of fossil fuels. One recommendation is to focus research on an overall smart controller for such systems that protects the batteries but also intelligently manages the energy usage and storage simultaneously. This type of smart controller can act as the overall brain of hybrid power systems and efficiently manage the energy within the system minimizing human interaction to ensure the system sustainability. This could prove very beneficial since it would allow consumers to install hybrid power systems and have little interaction with it since the controller is addressing any issue in a safe and effective manner. The method of storing energy is also another area of interest for such alternative energy systems. This system could be used to test several methods of storing energy such as fuel cells and newer types of batteries or supercapacitors.

In conclusion, research into hybrid solar/wind power systems and their possible residential and commercial applications is required to contribute generating renewable energy in an efficient environmentally friendly way to lead the world into a new generation of innovation and technology.

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APPENDIX A

APPENDIX A

SAMPLE MATLAB M-FILE

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%               One Day Charging/Discharging             %%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

load 'dec2007_C_250W_225Ahr_1day.dat'; %Loads charging data file
load 'dec2707_D_SHOPVAC_225Ahr_1day.dat'; %Loads discharging data file

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
CHARGING
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

tc = dec2007_C_250W_225Ahr_1day(:,1); %time during charging
Vc = dec2007_C_250W_225Ahr_1day(:,2); %unfiltered voltage from solar
panels during charging
Cc = dec2007_C_250W_225Ahr_1day(:,3); %unfiltered current from solar
panels during charging
Vsp = smooth(Vc,55); %filtered voltage from solar panel during charging
Csp = smooth(Cc,55); %filtered current from solar panel during charging
Psp = Vsp.*Csp; %charging power from solar panel during charging

figure(1)
plot(tc/3600,Psp) %solar panel power 250W
```

```
xlabel('Time [Hrs]')

ylabel('Power [Watts]')

legend('Solar Panel Power')

axis([10 25 -0.5 250])


figure(2)

plot(tc/3600,Vsp,'k--') %solar panel voltage

hold on

plot(tc/3600,Csp,'b') %solar panel current

xlabel('Time [Hrs]')

ylabel('Voltage [Volts], Current [Amps]')

legend('Solar Panel Voltage', 'Solar Panel Current')

axis([10 25 -0.5 35])


Esp = trapz(tc,Psp)/3600 %Energy in W*hr during charging using cftool


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

DISCHARGING

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%


td = dec2707_D_SHOPVAC_225Ahr_1day(:,1); %time during discharging

Vd = dec2707_D_SHOPVAC_225Ahr_1day(:,2); %unfiltered voltage from

batteries during discharging

Cd = dec2707_D_SHOPVAC_225Ahr_1day(:,3); %unfiltered current from

inverter during discharging

Vbat = smooth(Vd,55); %filtered voltage from batteries during

discharging

Ci   = smooth(Cd,55); %filtered current from inverter during discharging

Pload = Vbat.*Ci; %discharging power from load during discharging
```

```
figure(3)
plot(td/3600,Pload) %power shopvac
xlabel('Time [Hrs]')
ylabel('Power [Watts]')
legend('Shop Vac Power')
axis([0 1.5 -0.5 1200])

figure(4)
plot(td/3600,Vbat,'k--') %discharging voltage shopvac
hold on
plot(td/3600,Ci,'b') %discharging current shopvac
xlabel('Time [Hrs]')
ylabel('Voltage [Volts], Current [Amps]')
legend('Shop Vac Voltage', 'Shop Vac Current')
axis([0 1.5 -0.5 60])

Eload = trapz(td,Pload)/3600 % Energy in W*hr during discharging using
cftool
```

APPENDIX B

APPENDIX B

EXPERIMENTAL RESULTS

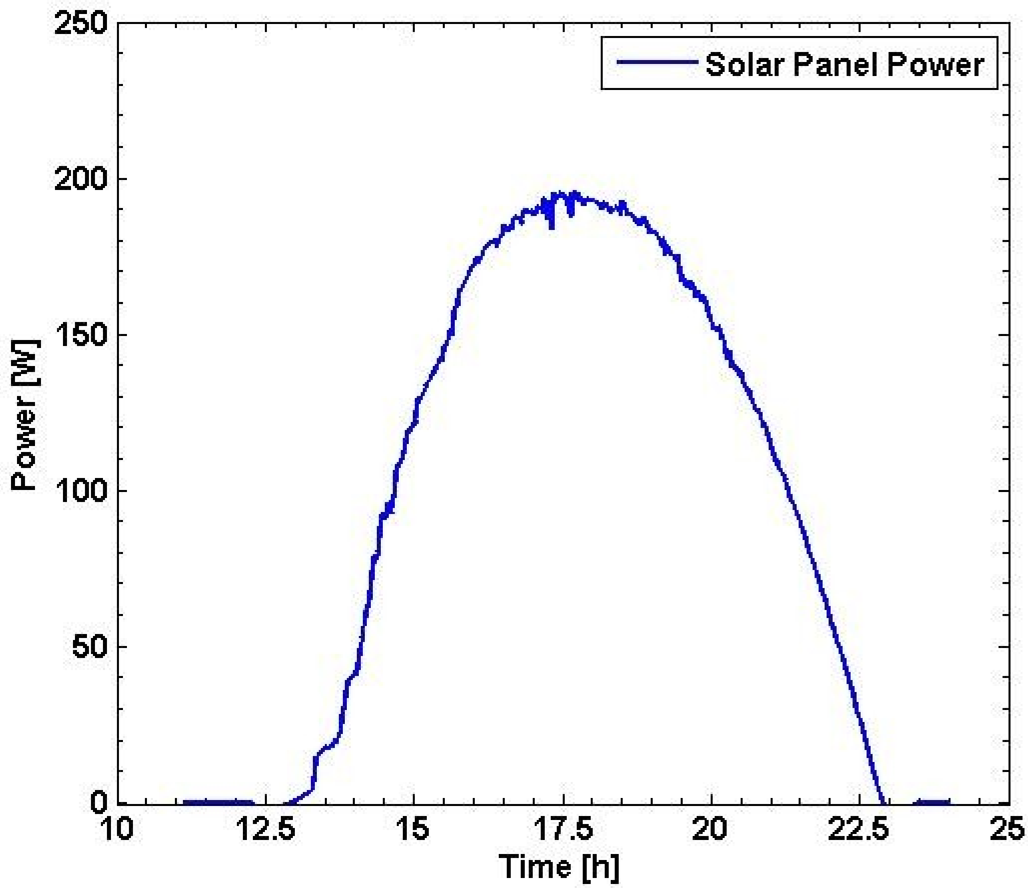

Figure 46: 250 W One Day Test: Solar Panel Power

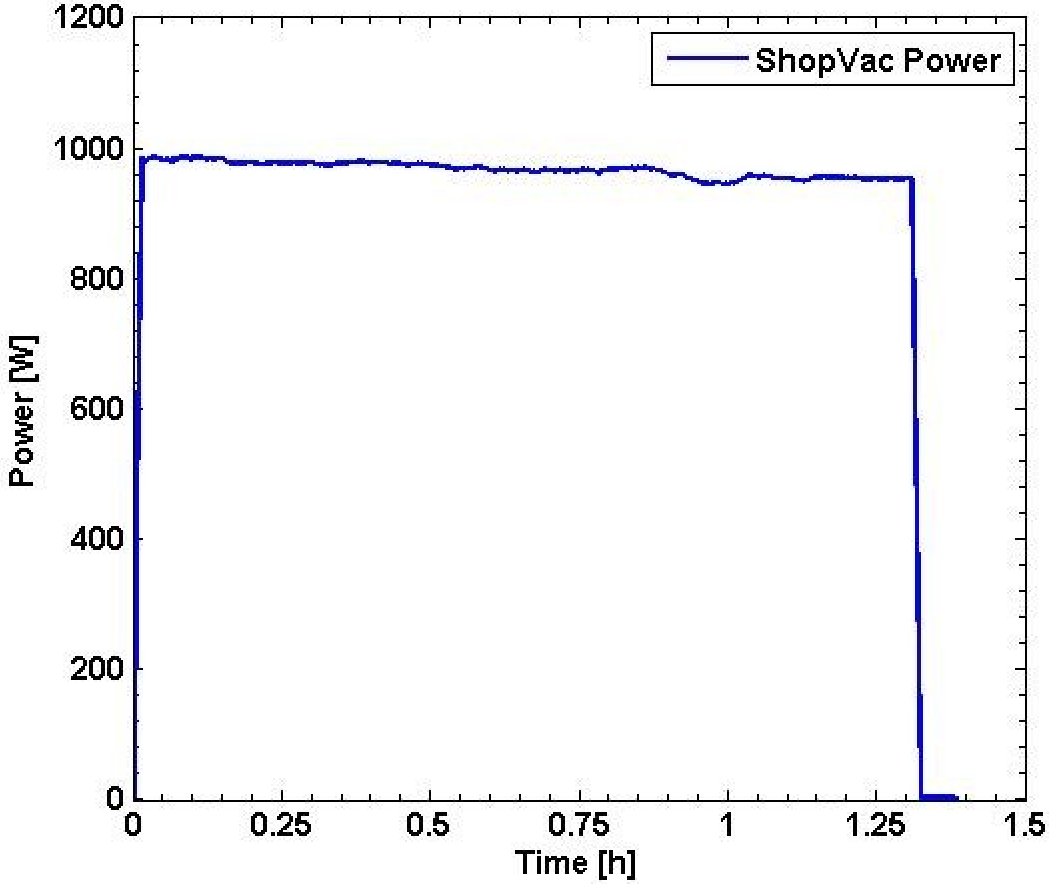

Figure 47: 250 W One Day Test: ShopVac Power

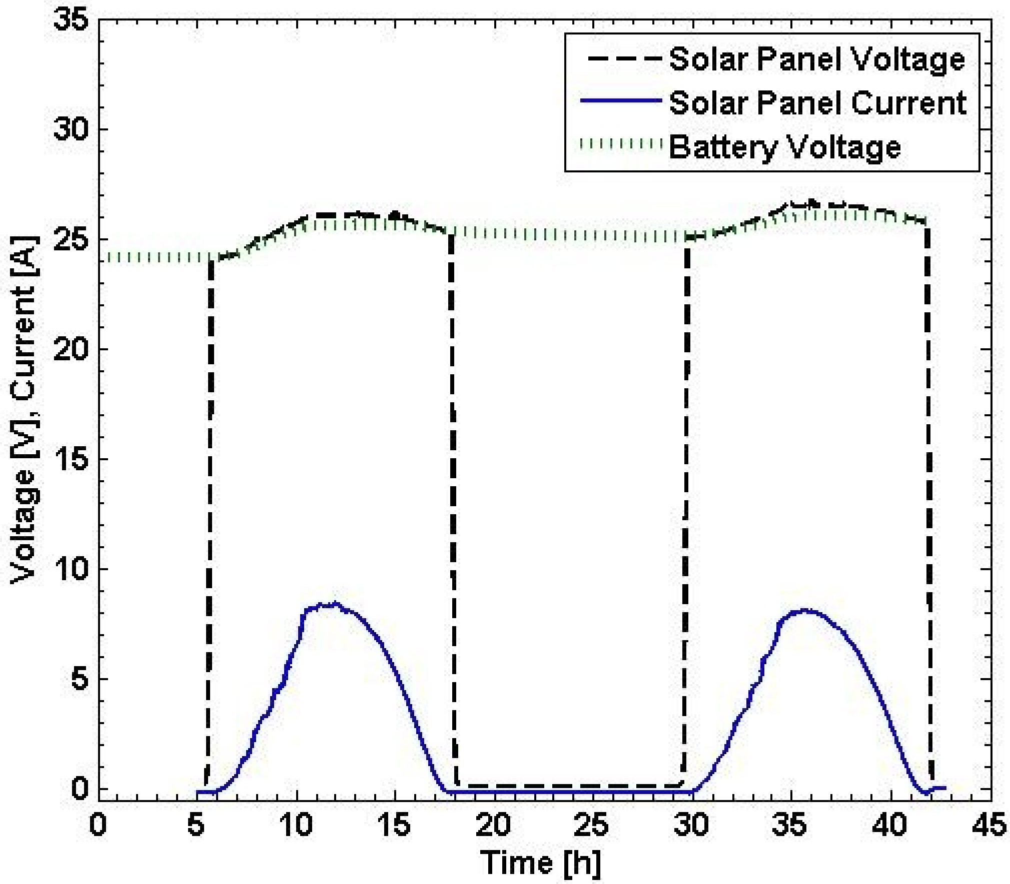

Figure 48: 250 W Two Day Test: Solar Panel Voltage and Current

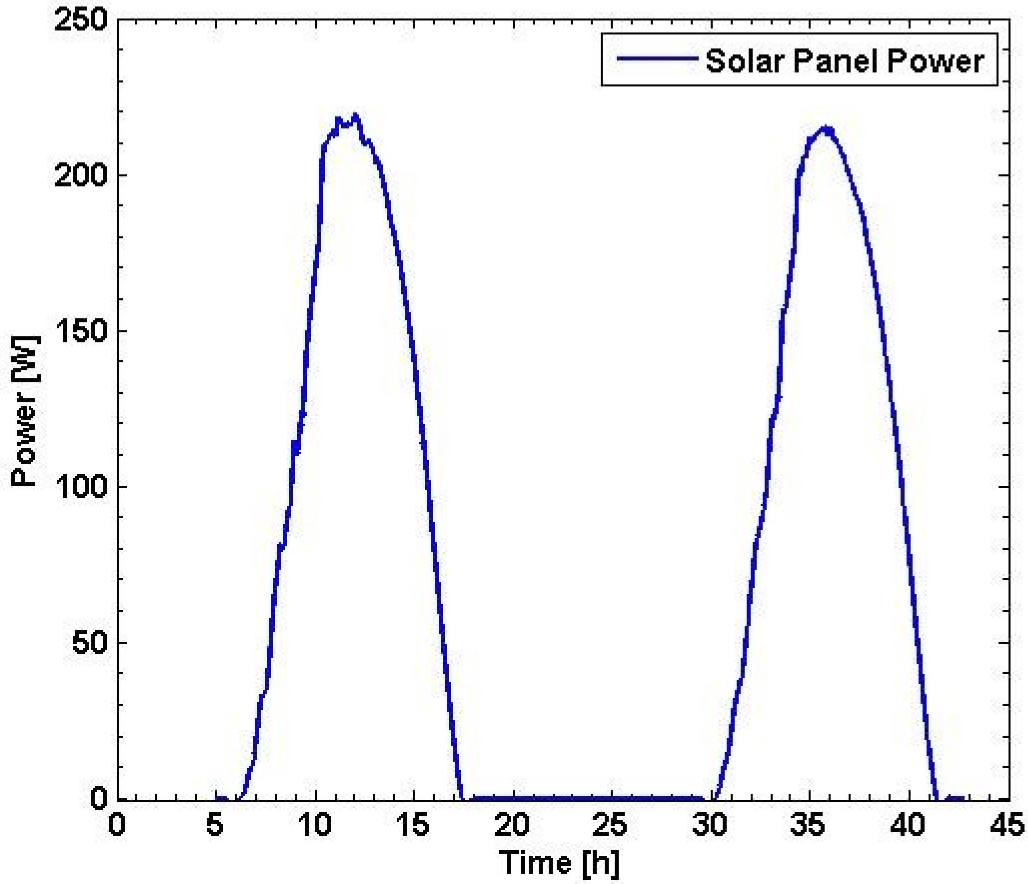

Figure 49: 250 W Two Day Test: Solar Panel Power

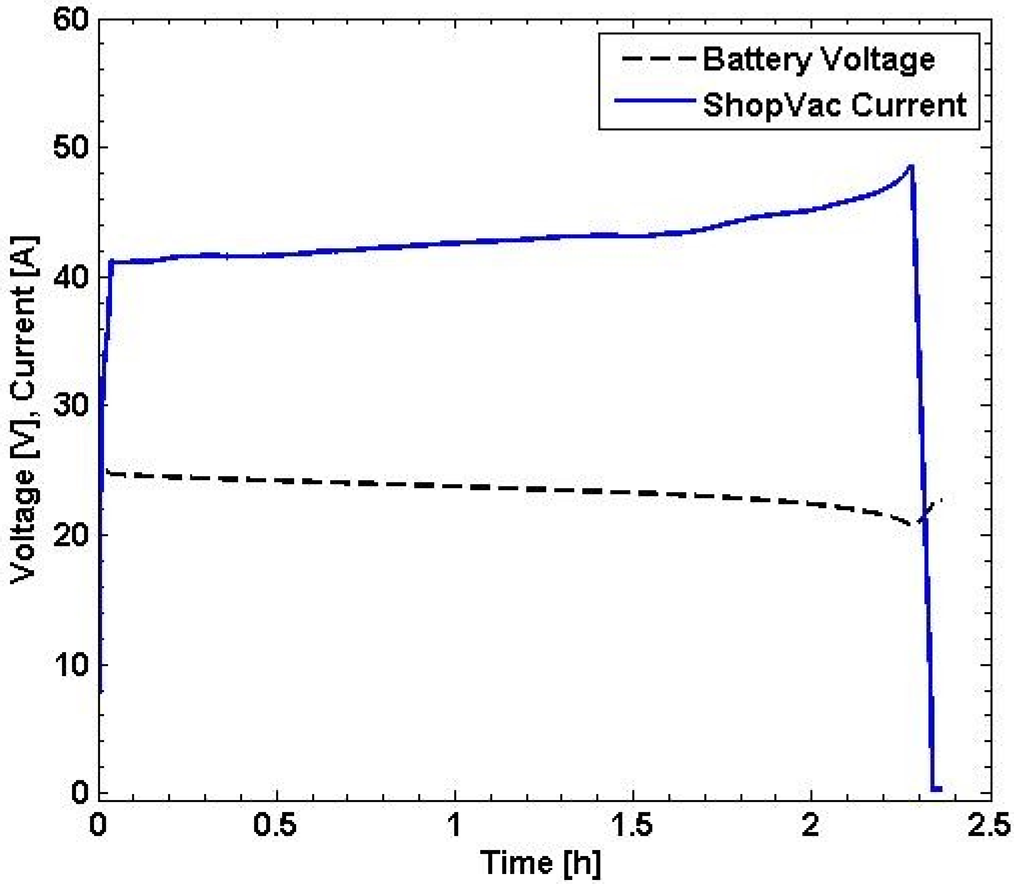

Figure 50: 250 W Two Day Test: ShopVac Voltage and Current

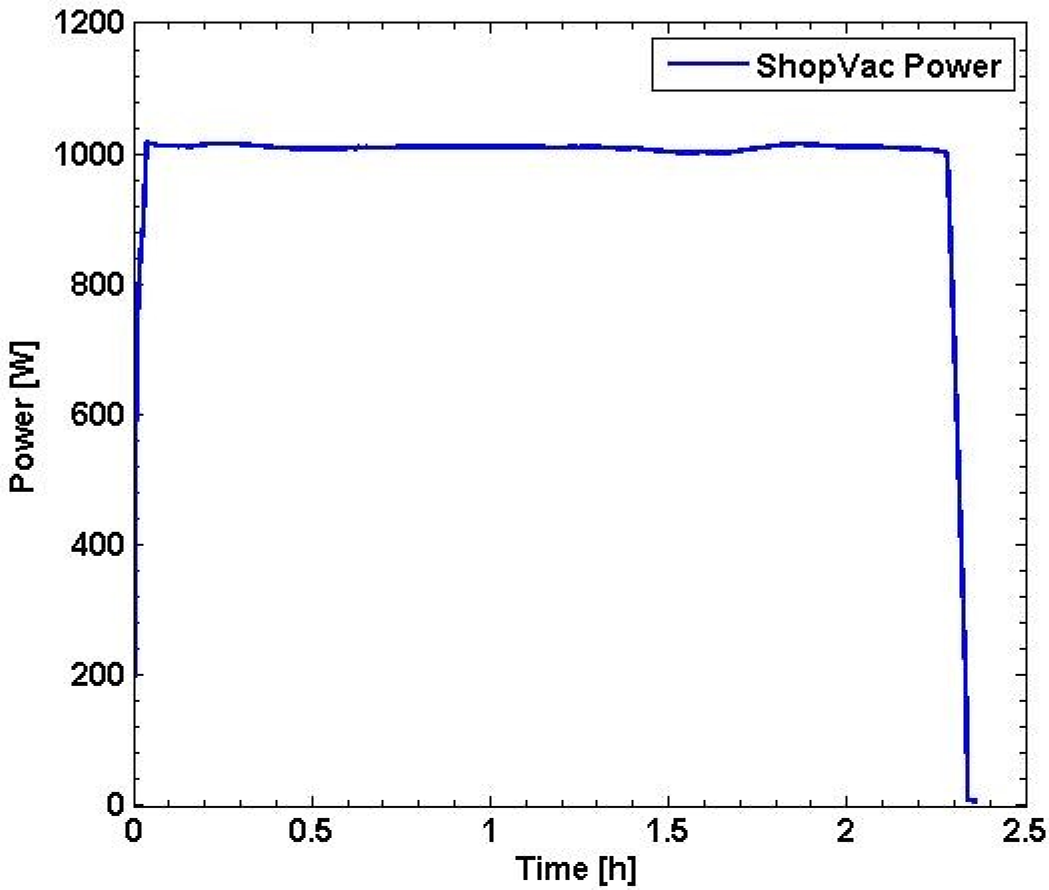

Figure 51: 250 W Two Day Test: ShopVac Power

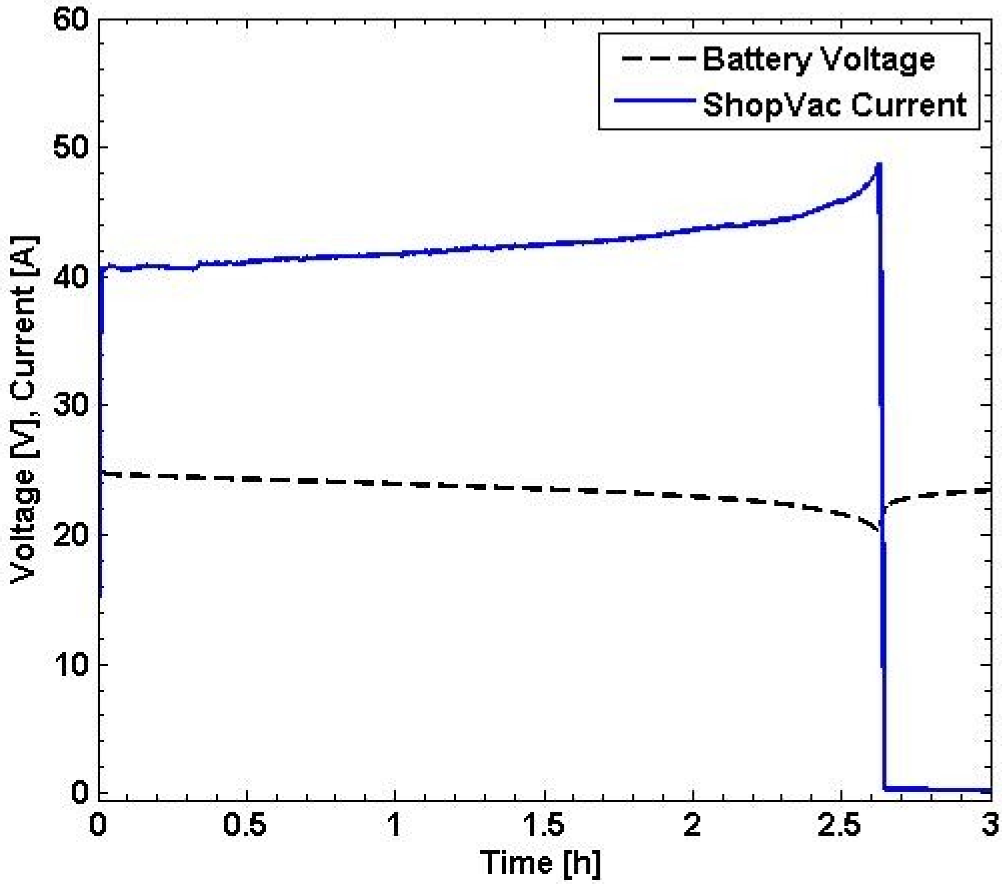

Figure 52: 250 W Three Day Test: ShopVac Voltage and Current

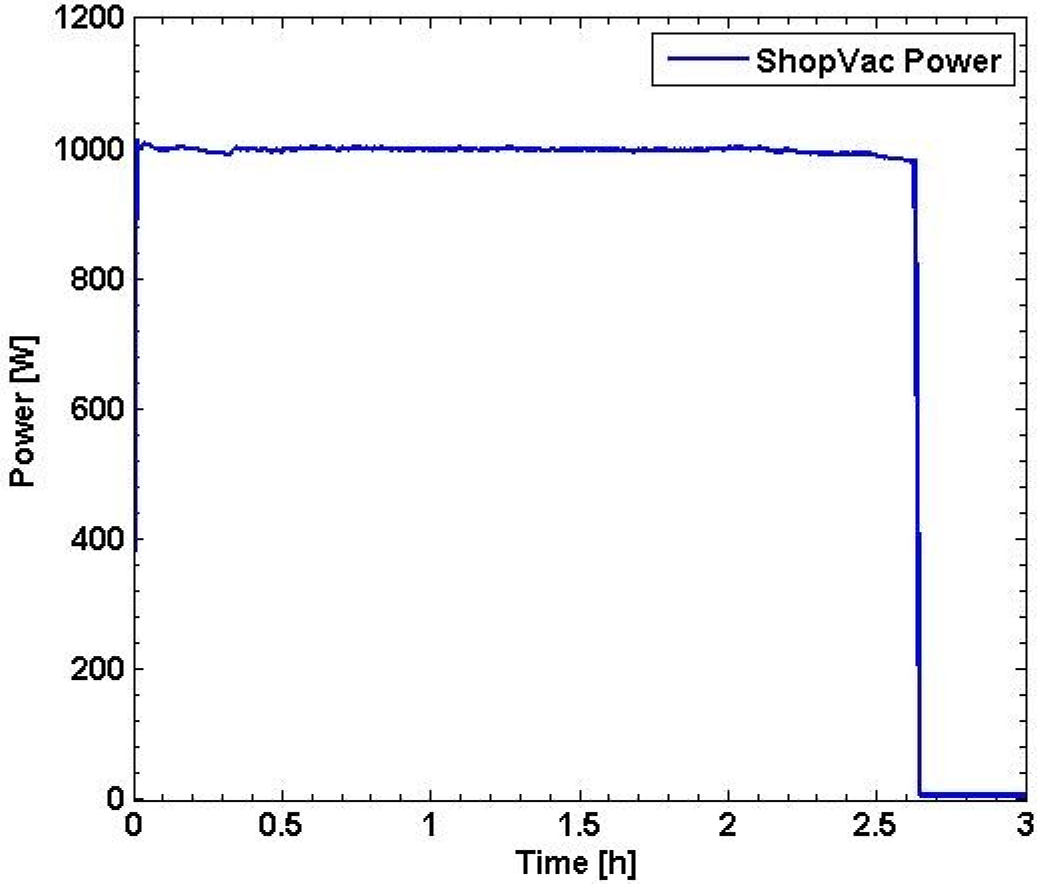

Figure 53: 250 W Three Day Test: ShopVac Power

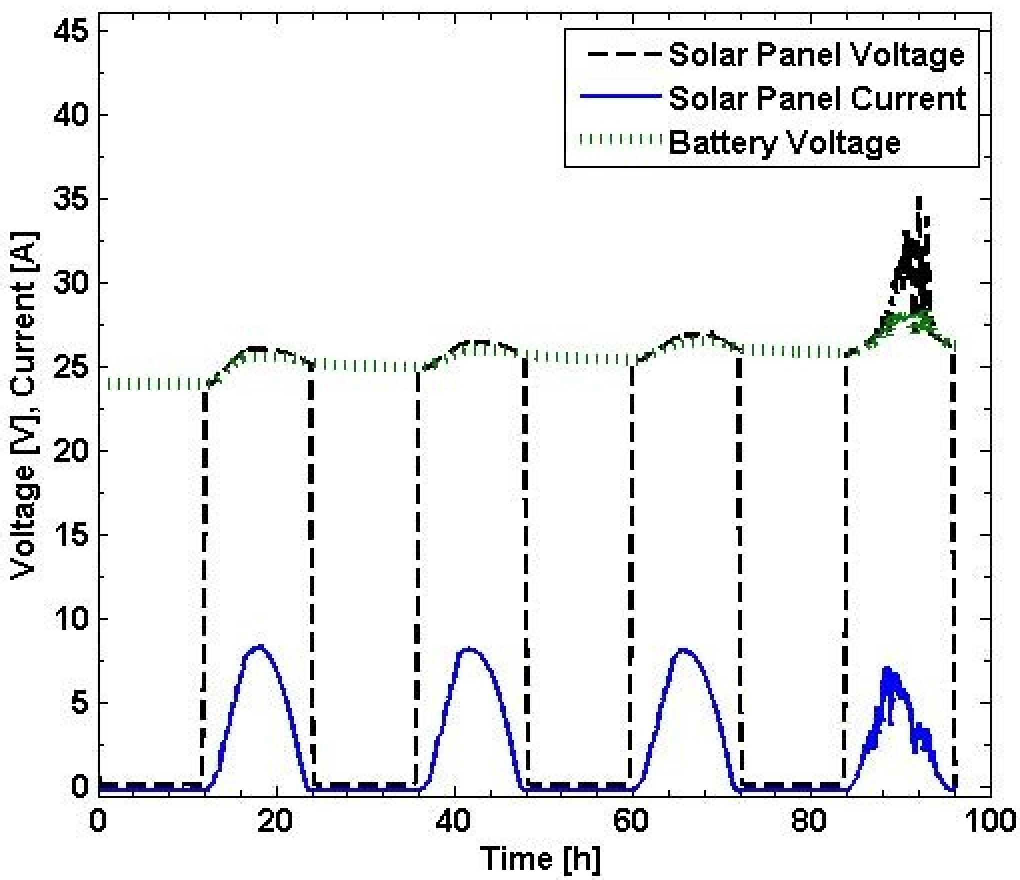

Figure 54: 250 W Four Day Test: Solar Panel Voltage and Current

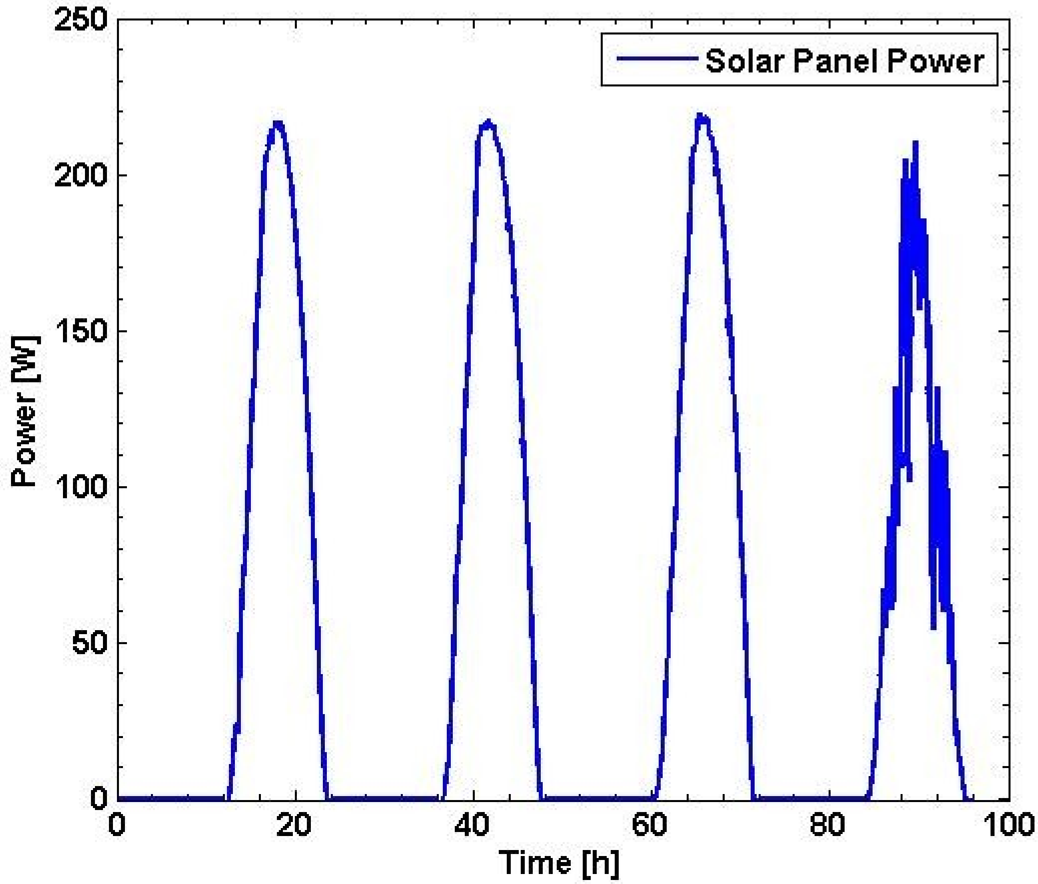

Figure 55: 250 W Four Day Test: Solar Panel Power

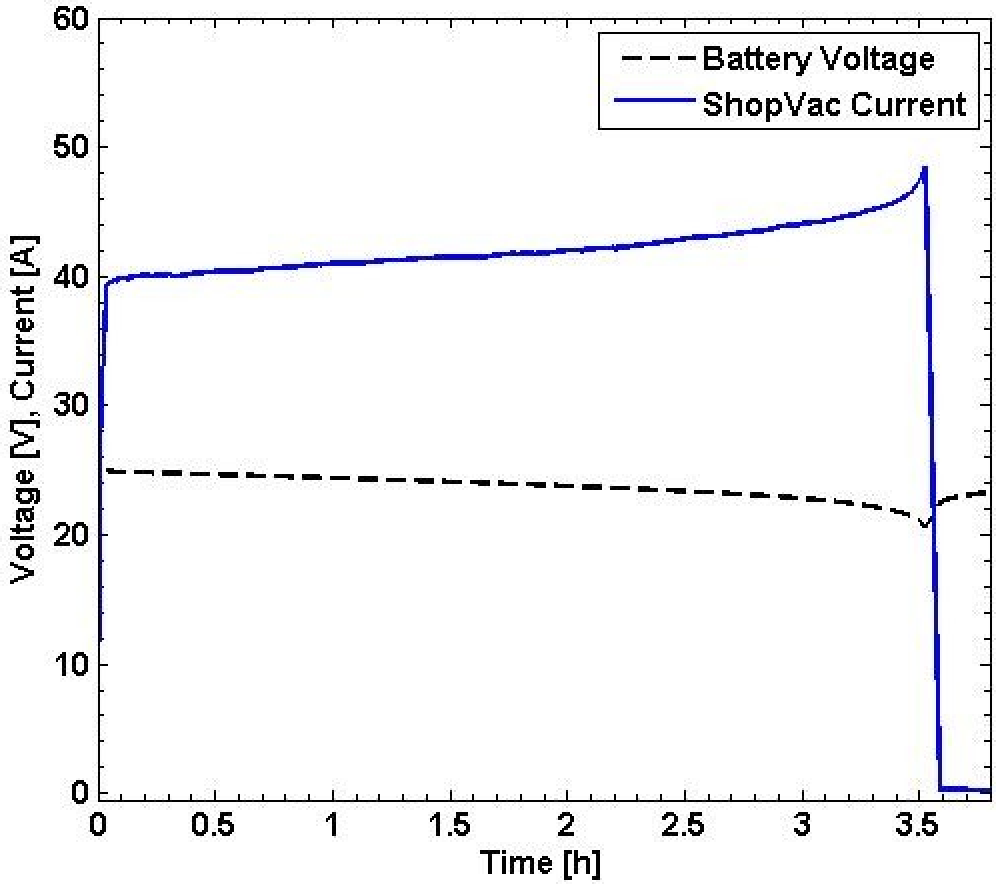

Figure 56: 250 W Four Day Test: ShopVac Voltage and Current

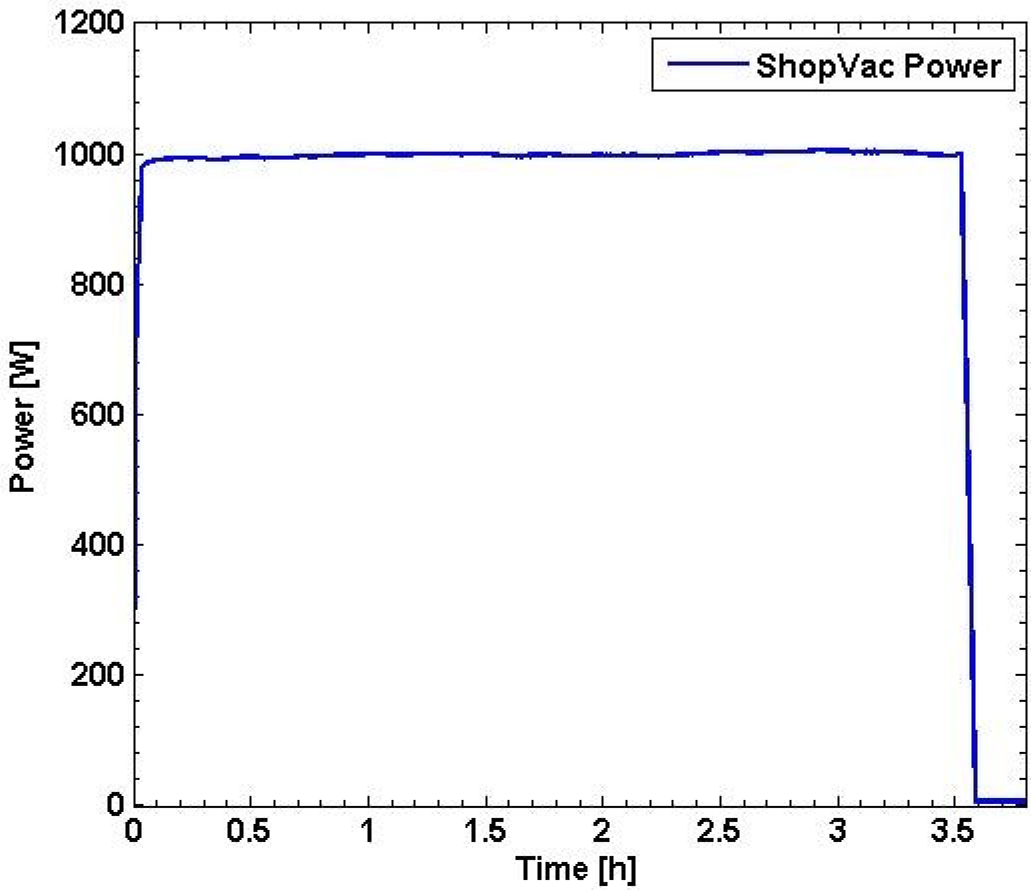

Figure 57: 250 W Four Day Test: ShopVac Power

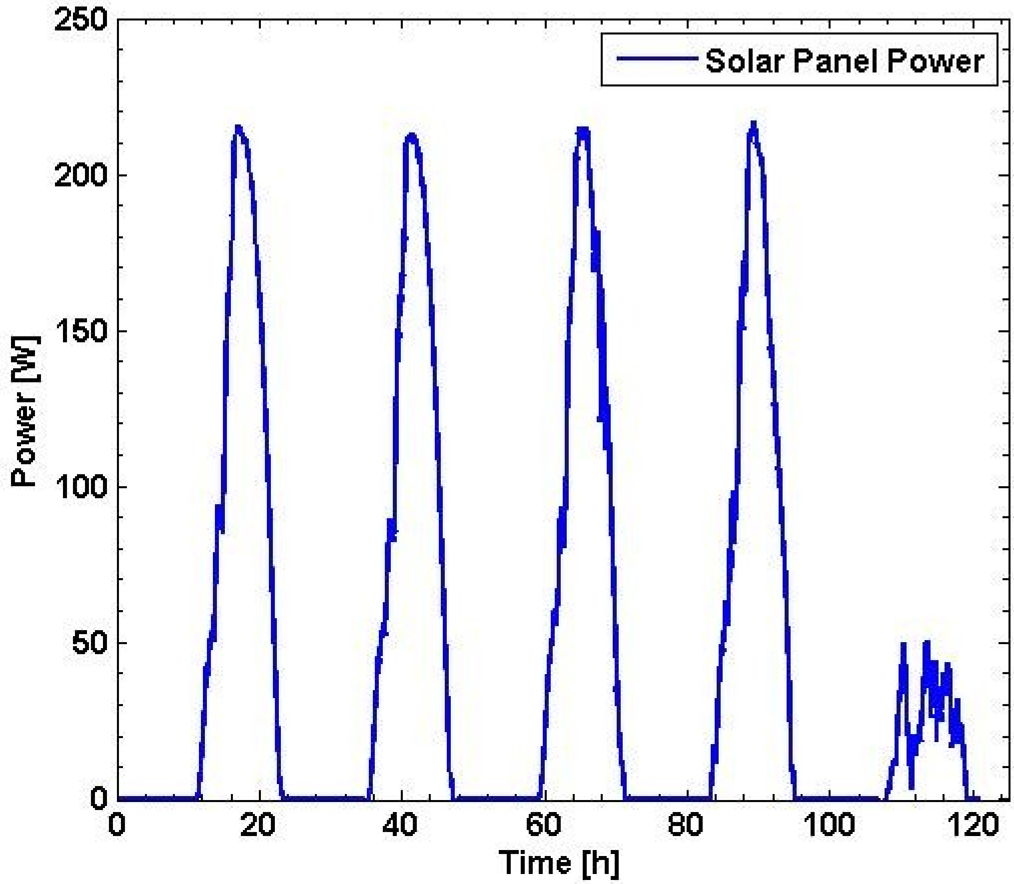

Figure 58: 250 W Five Day Test (March): Solar Panel Power

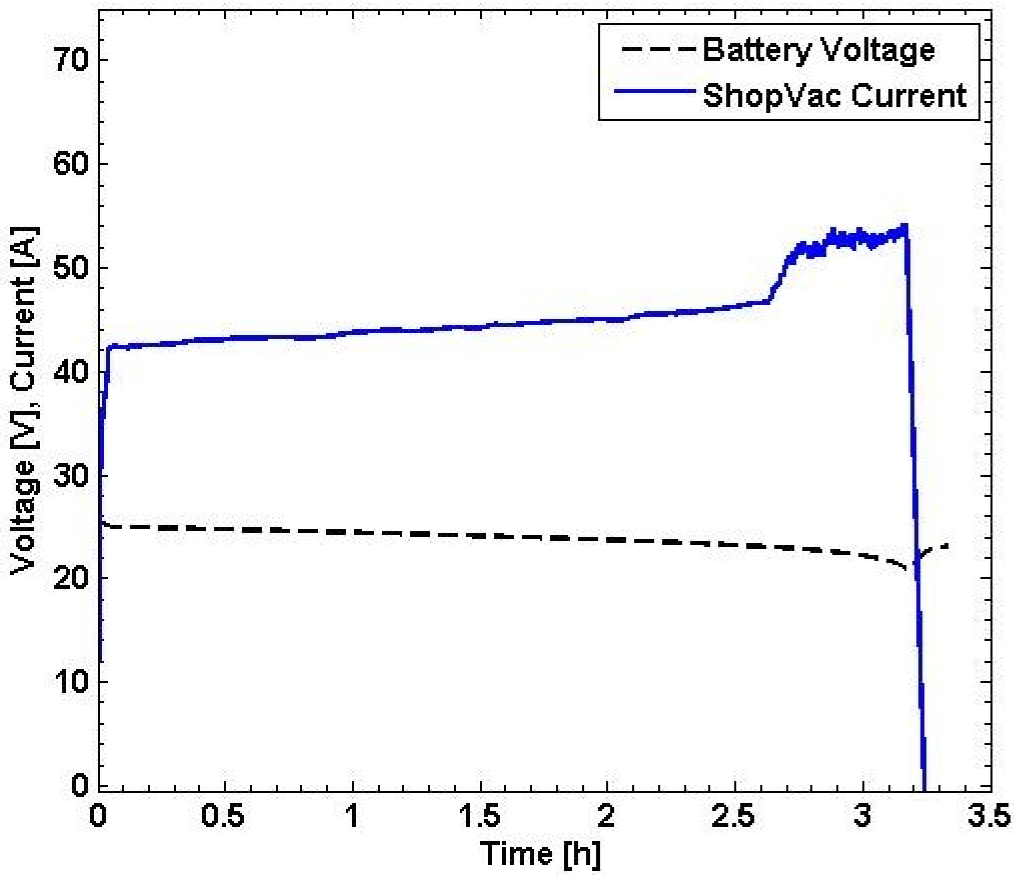

Figure 59: 250 W Five Day Test (March): ShopVac Voltage and Current

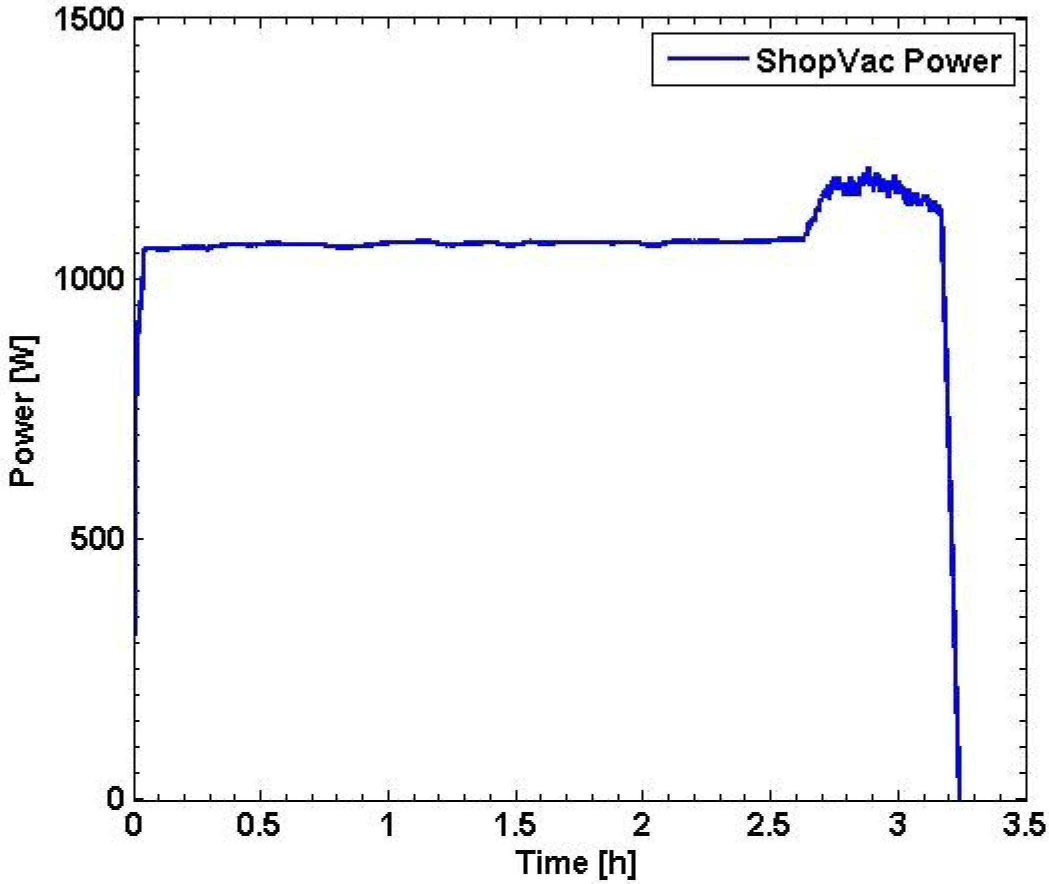

Figure 60: 250 W Five Day Test (March): ShopVac Power

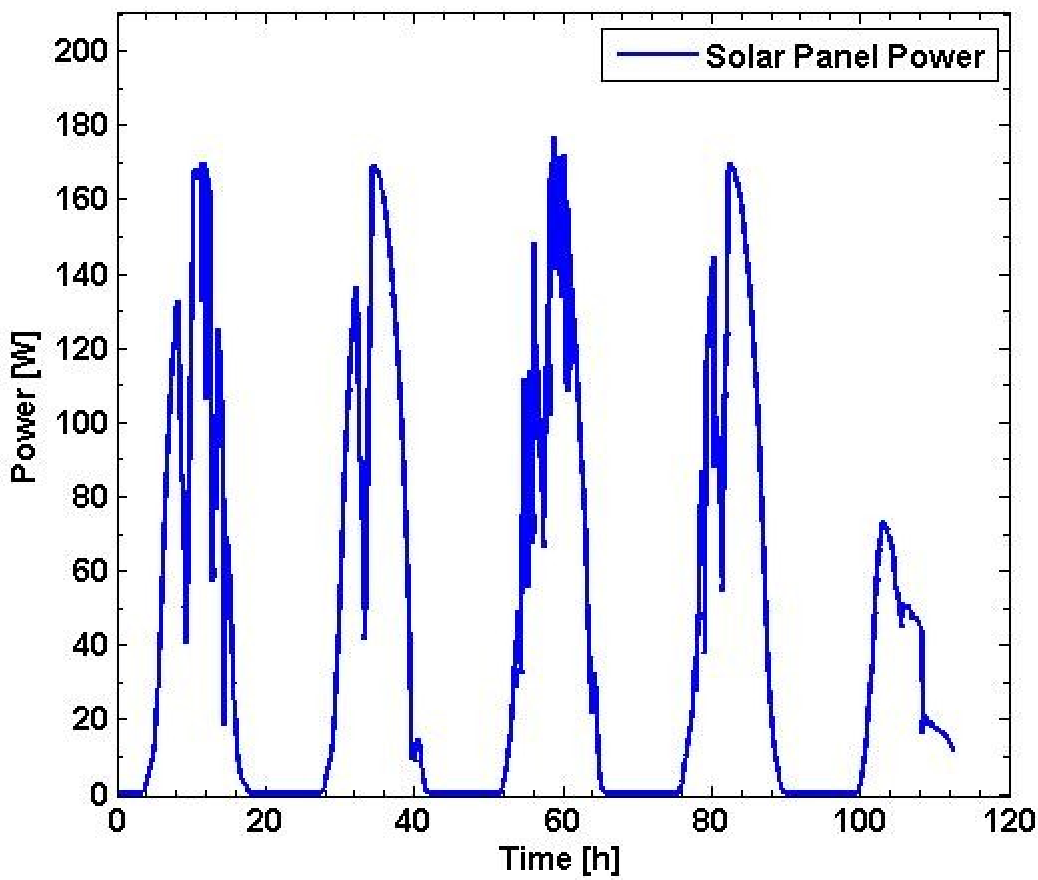

Figure 61: 250 W Five Day Test (May): Solar Panel Power

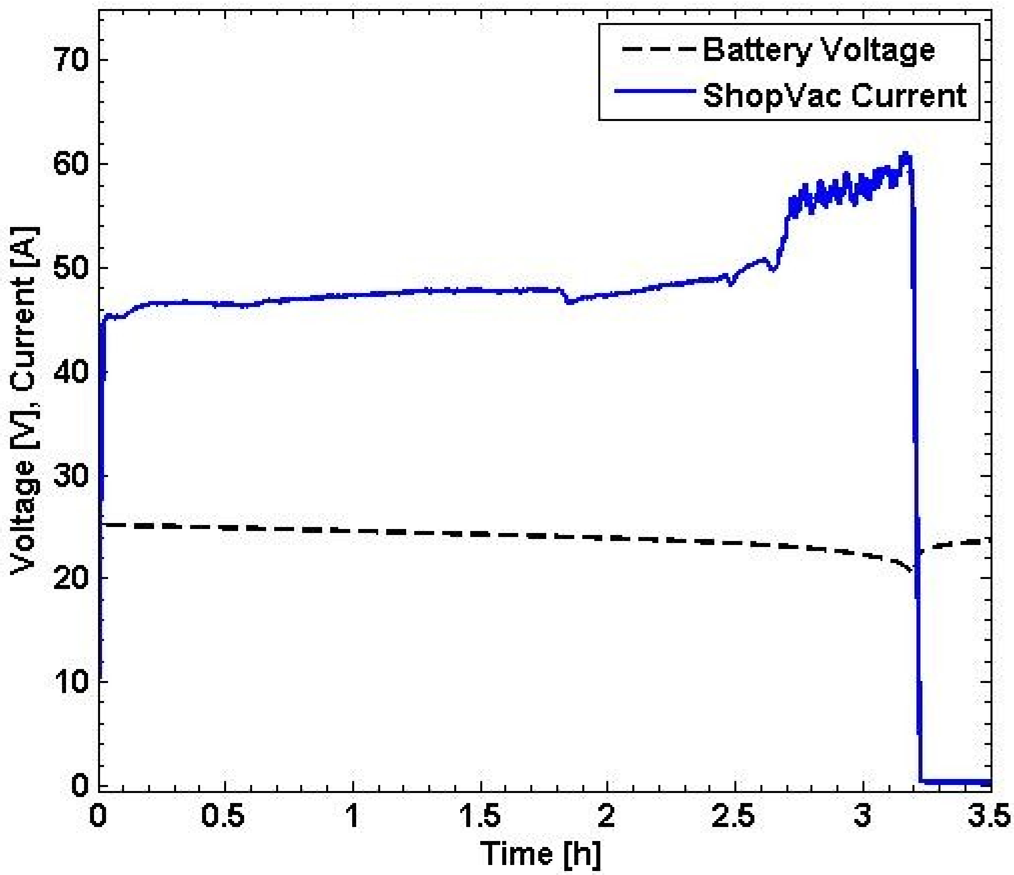

Figure 62: 250 W Five Day Test (May): ShopVac Voltage and Current

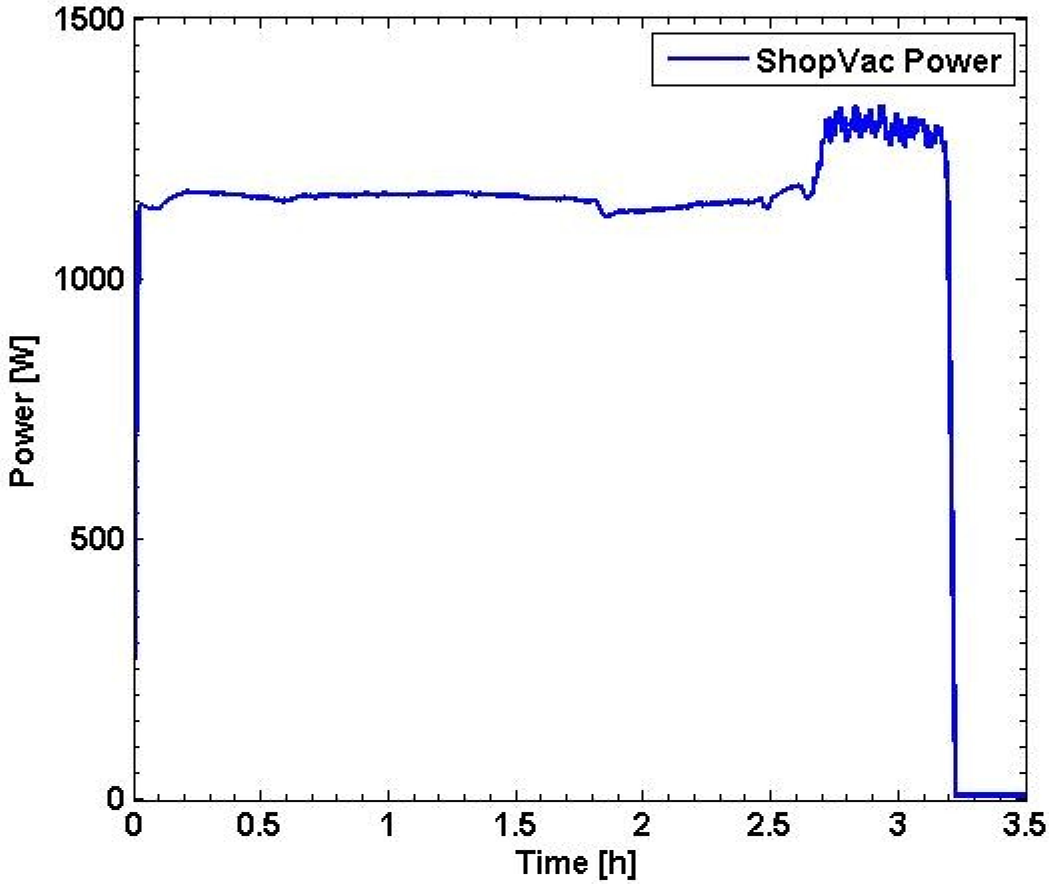

Figure 63: 250 W Five Day Test (May): ShopVac Power

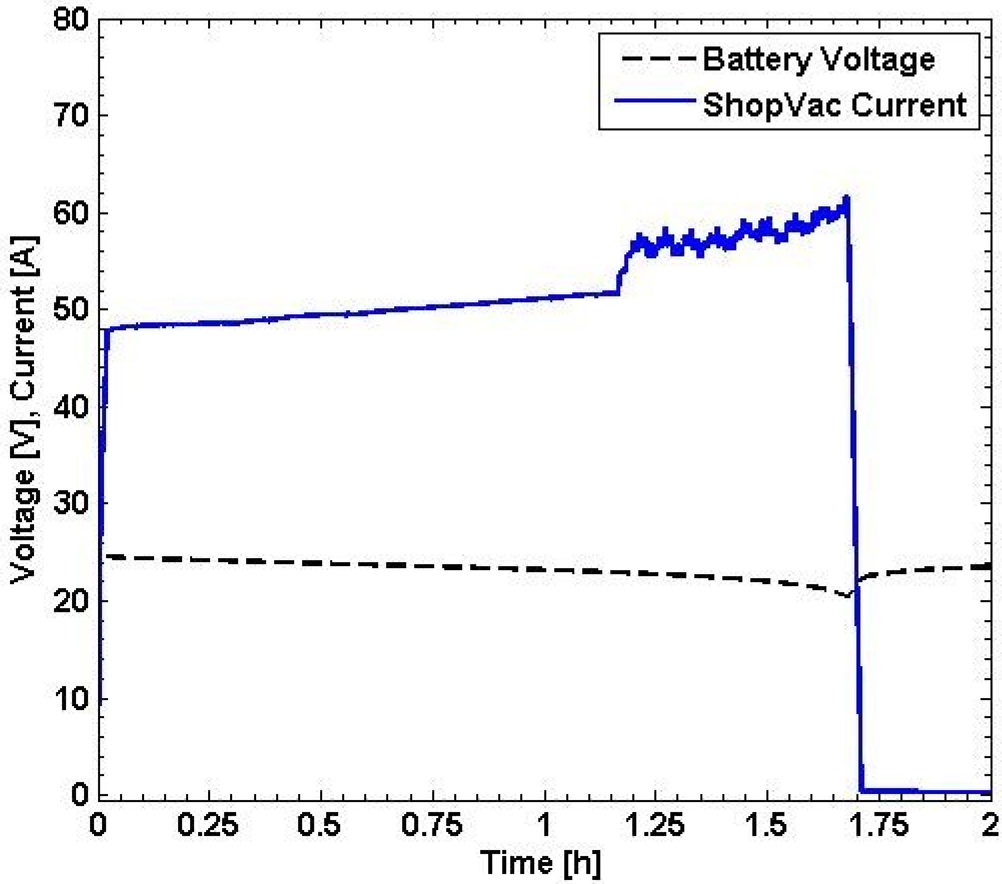

Figure 64: 650 W One Day Test: ShopVac Voltage and Current

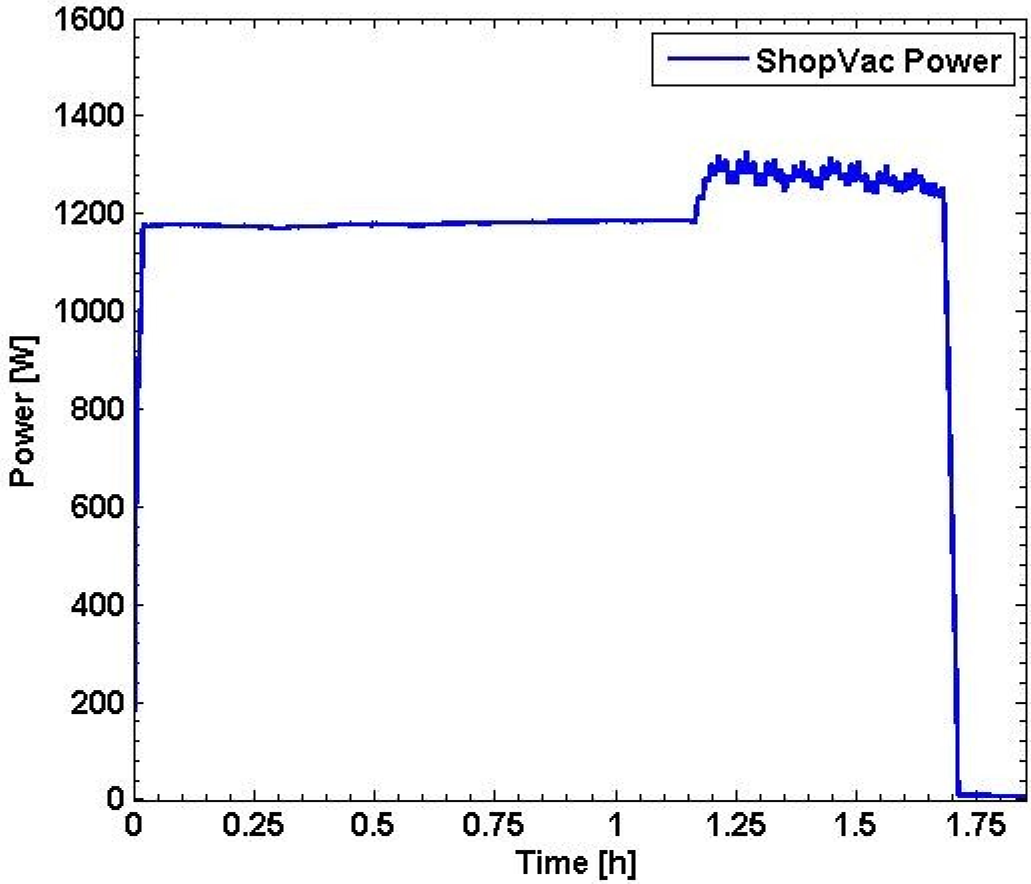

Figure 65: 650 W One Day Test: ShopVac Power

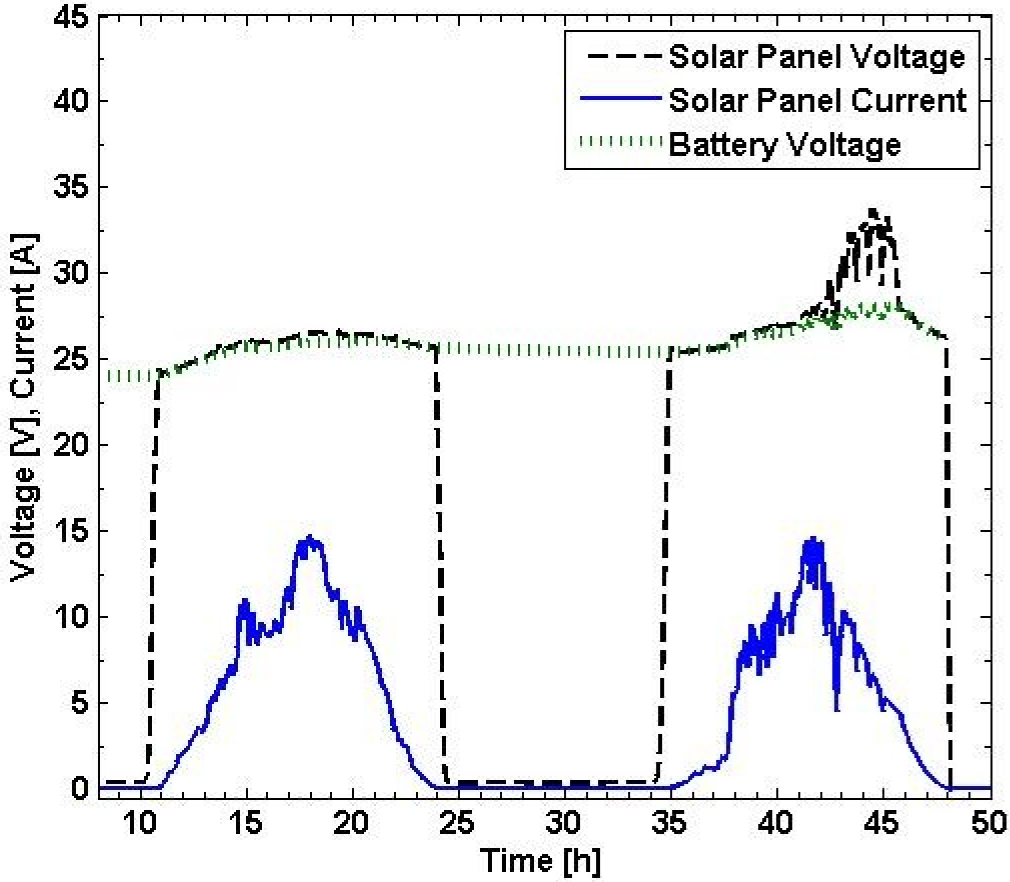

Figure 66: 650 W Two Day Test: Solar Panel Voltage and Current

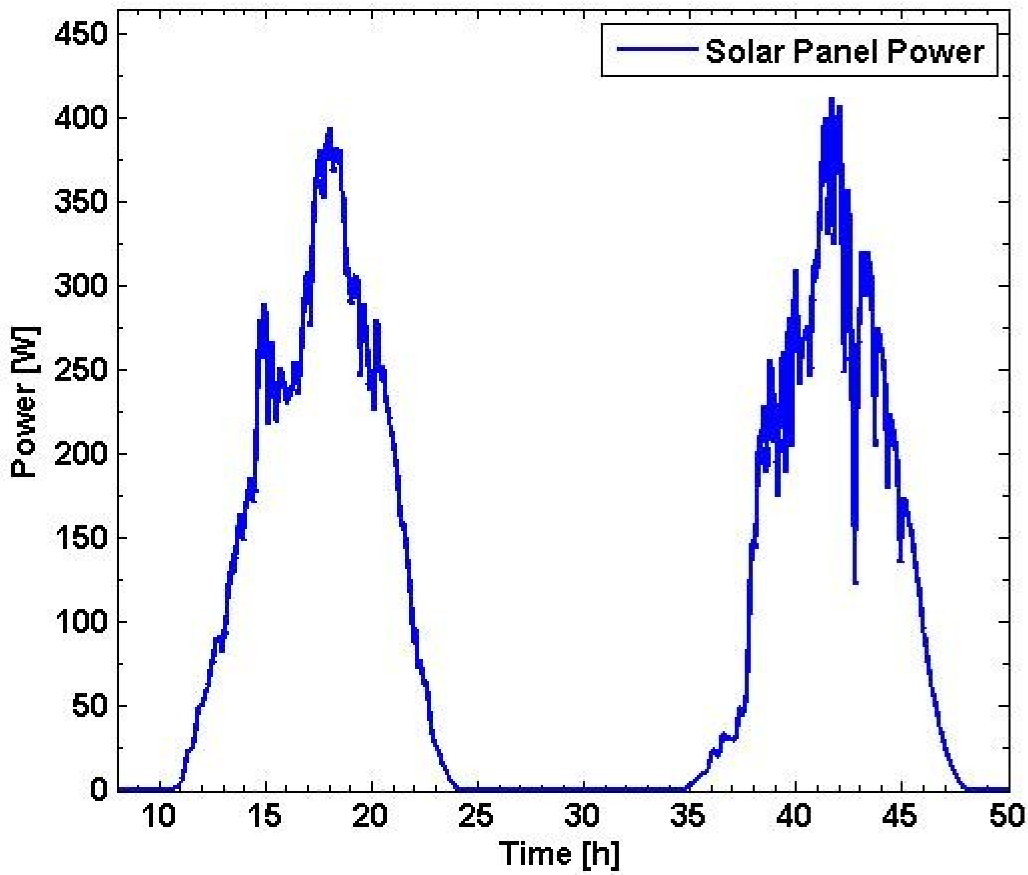

Figure 67: 650 W Two Day Test: Solar Panel Power

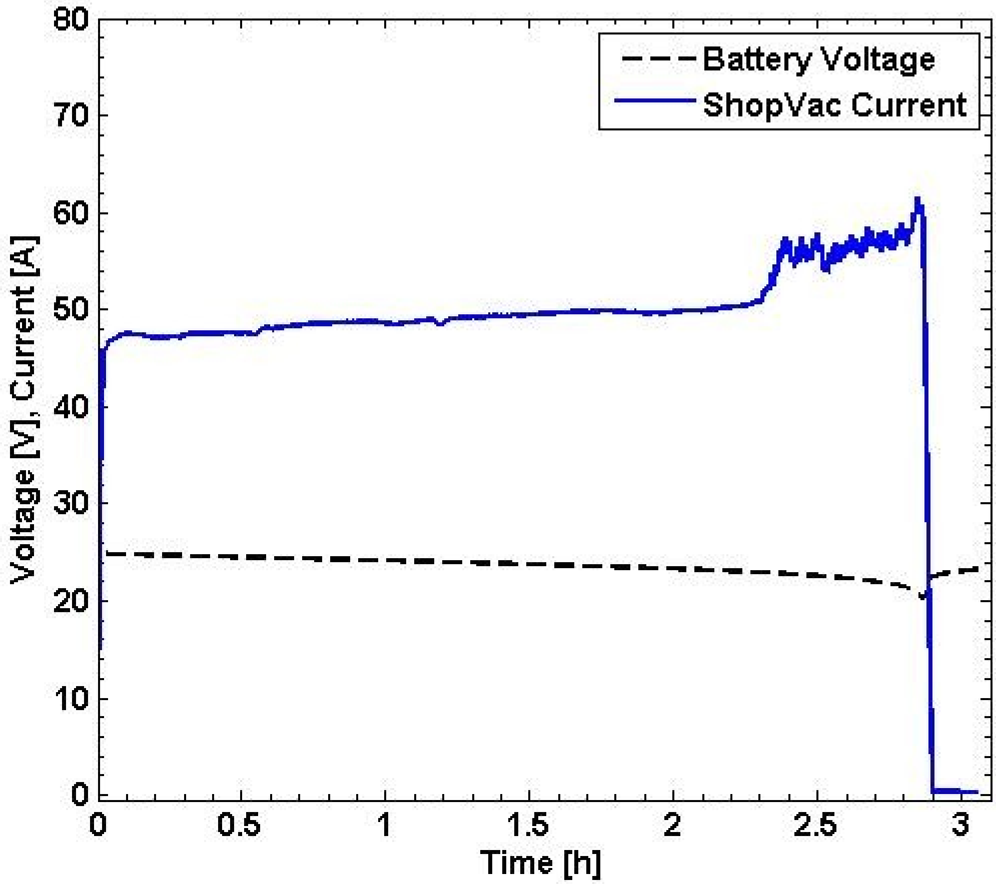

Figure 68: 650 W Two Day Test: ShopVac Voltage and Current

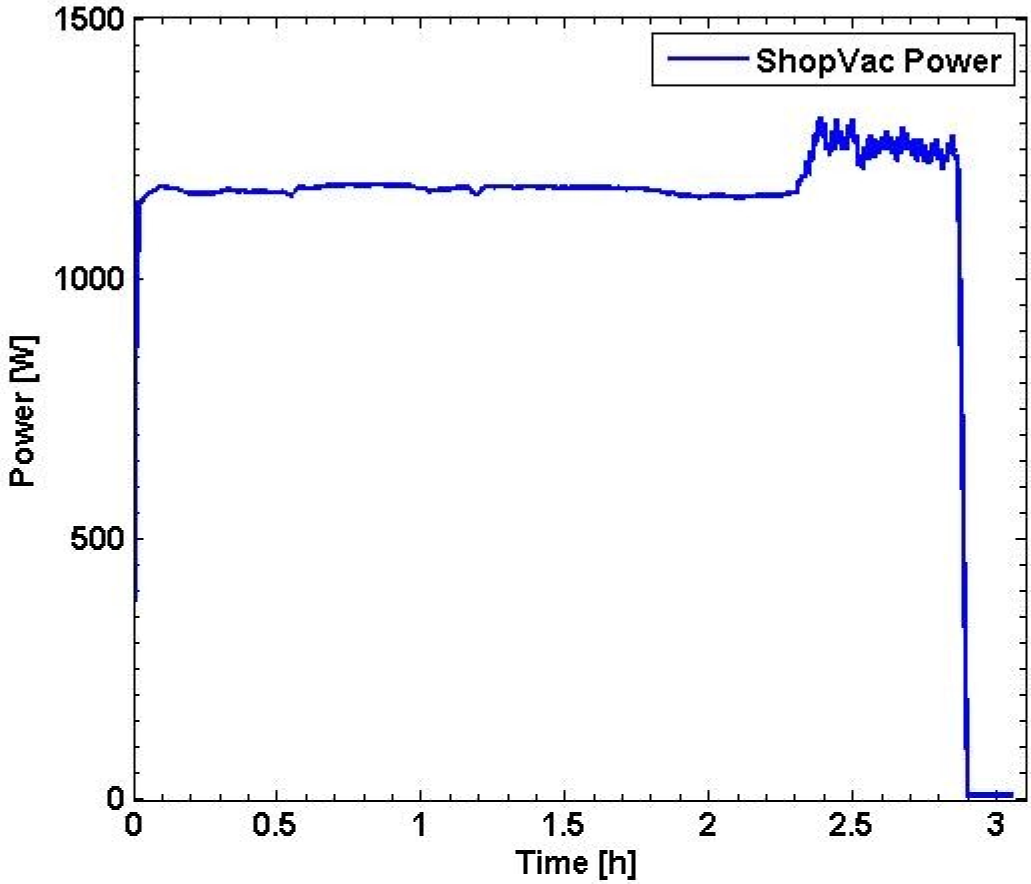

Figure 69: 650 W Two Day Test: ShopVac Power

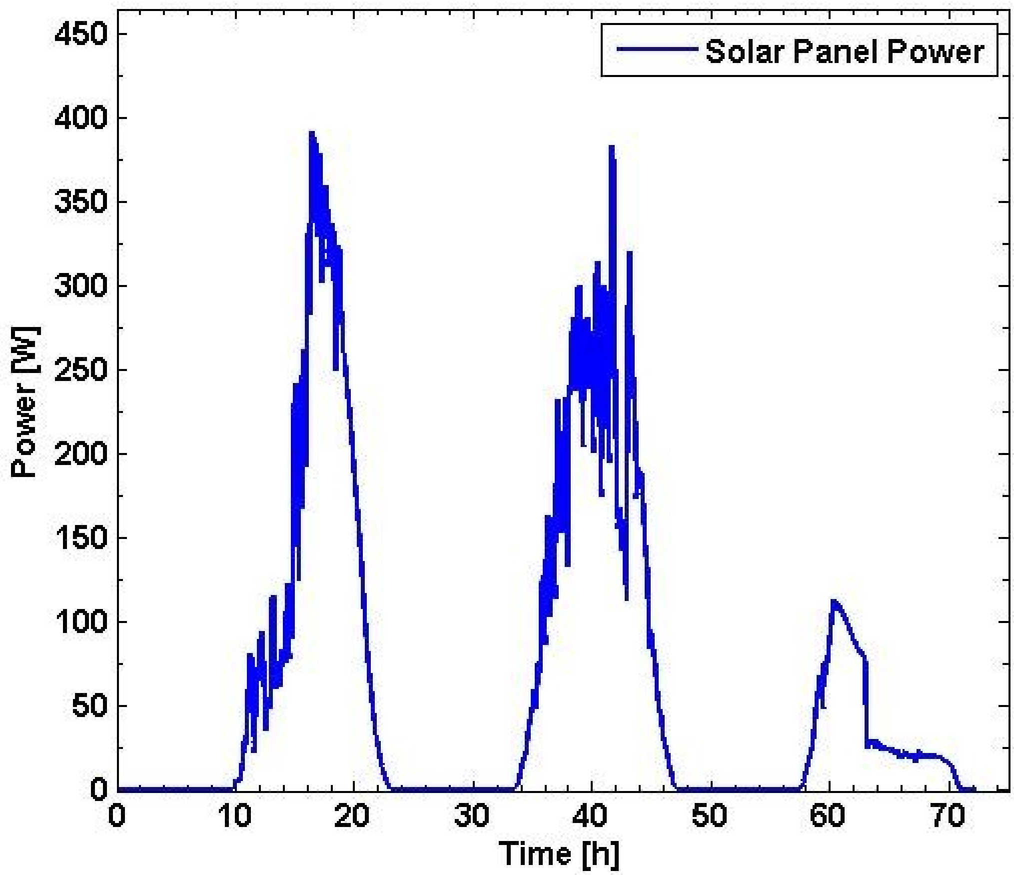

Figure 70: 650 W Three Day Test: Solar Panel Power

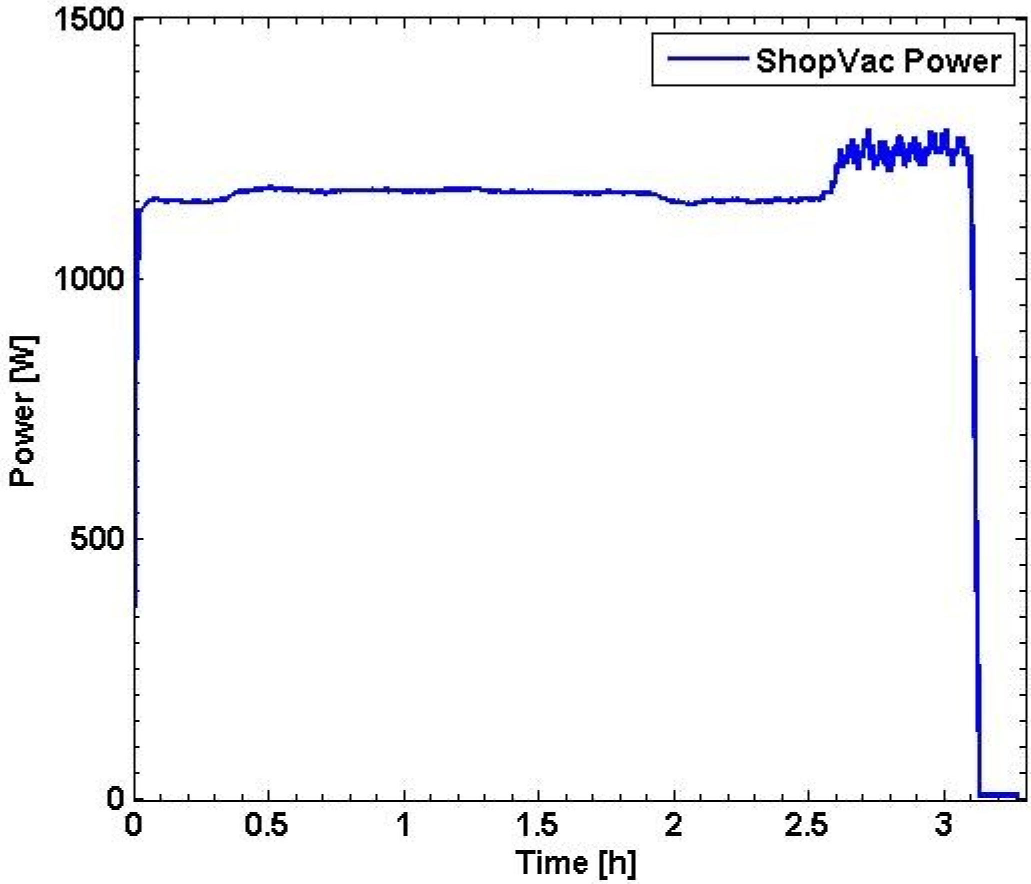

Figure 71: 650 W Three Day Test: ShopVac Power

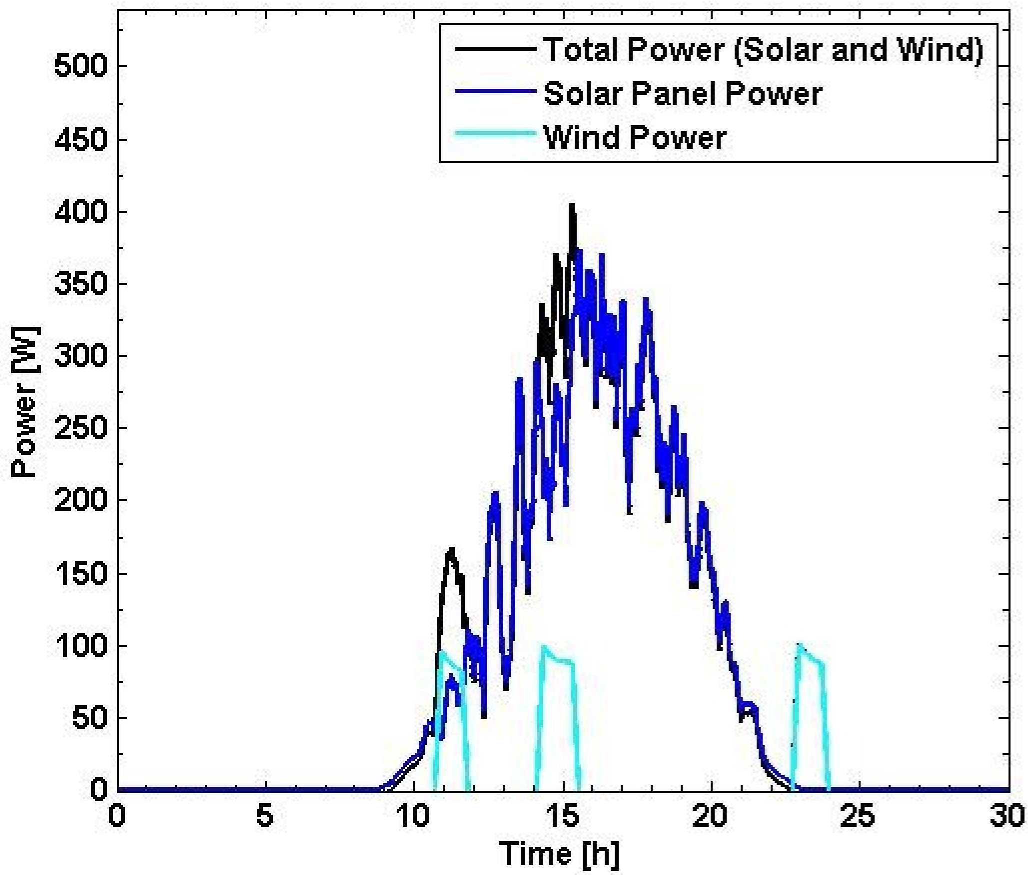

Figure 72: 650 W Sustainability Test: Solar and Wind Power

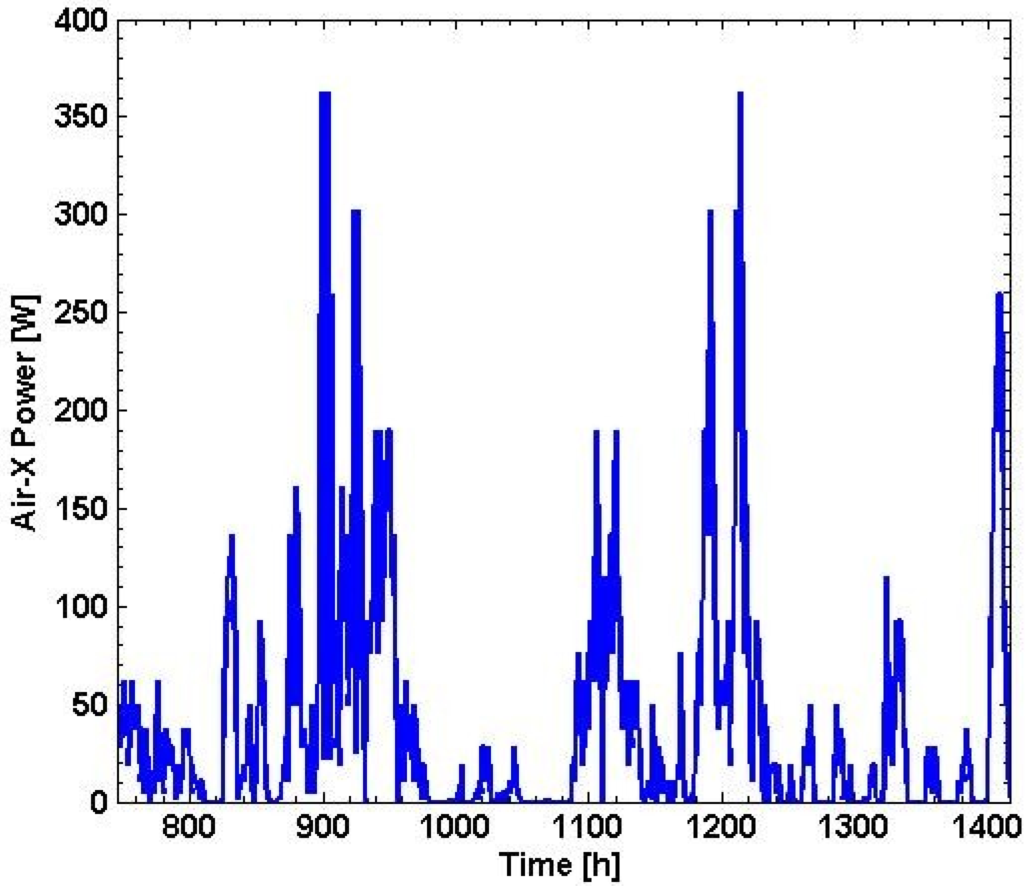

Figure 73: Air-X TMY Power February 1980

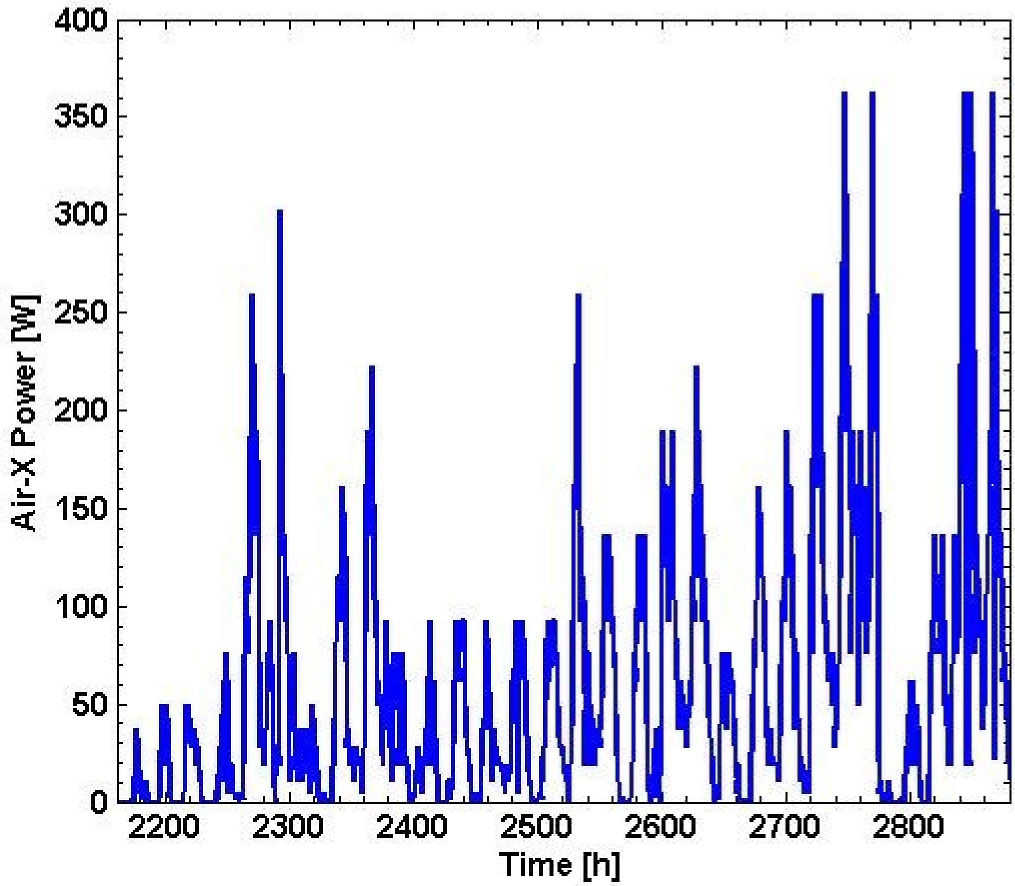

Figure 74: Air-X TMY Power April 1990

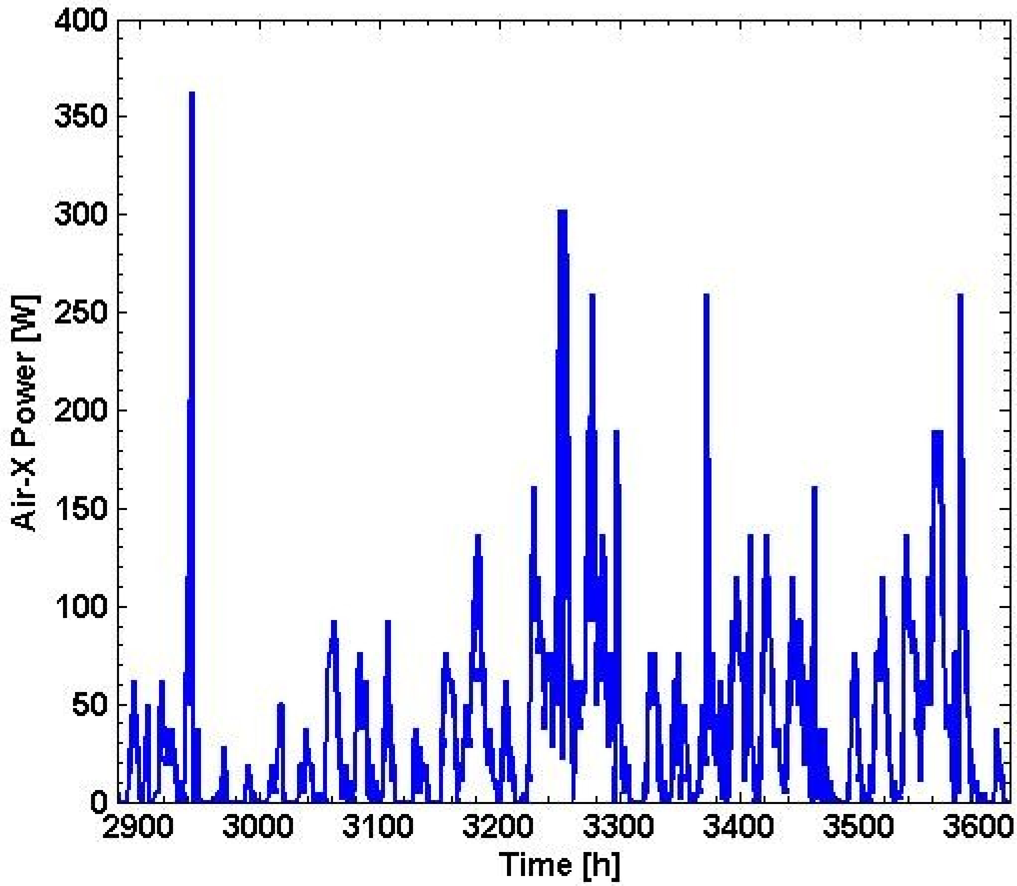

Figure 75: Air-X TMY Power May 1981

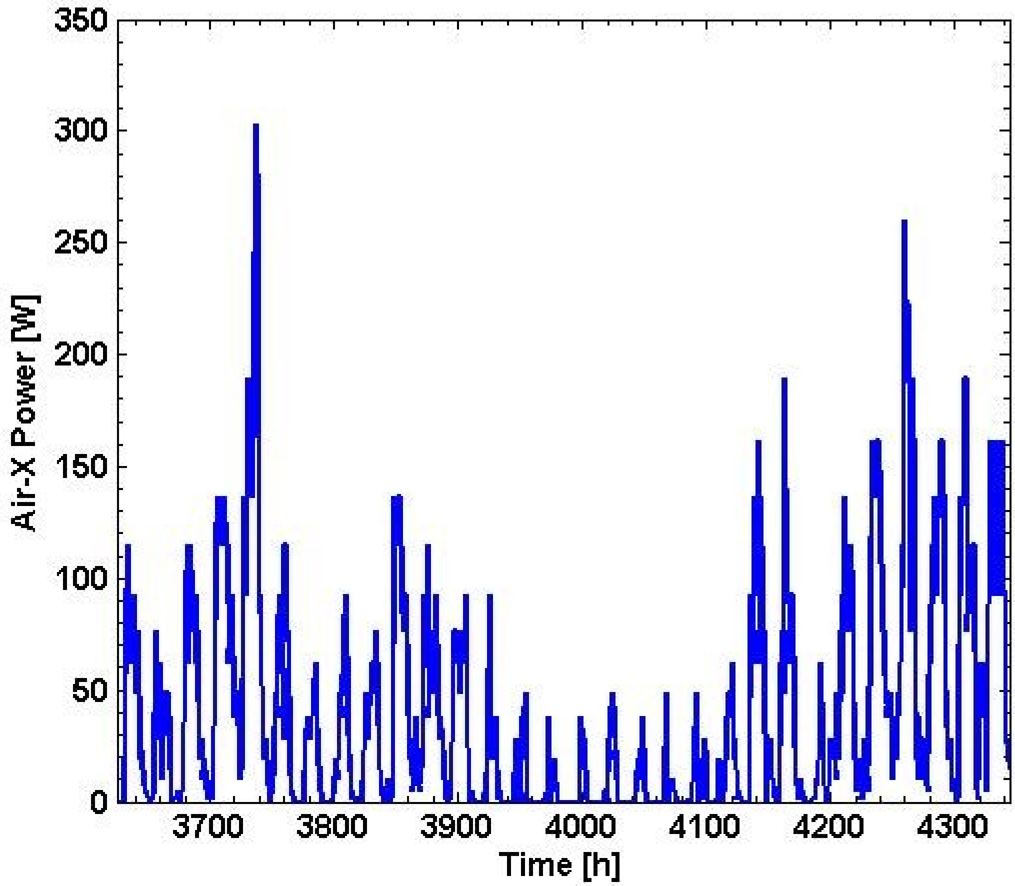

Figure 76: Air-X TMY Power June 1999

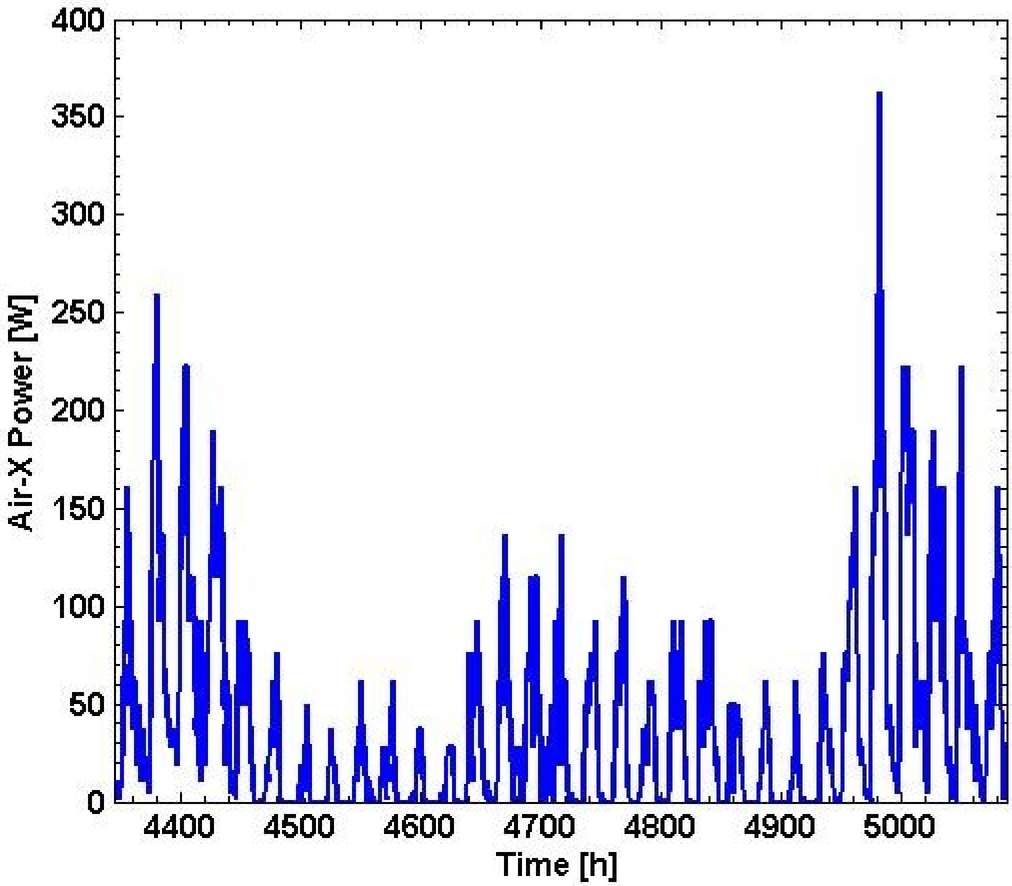

Figure 77: Air-X TMY Power July 2002

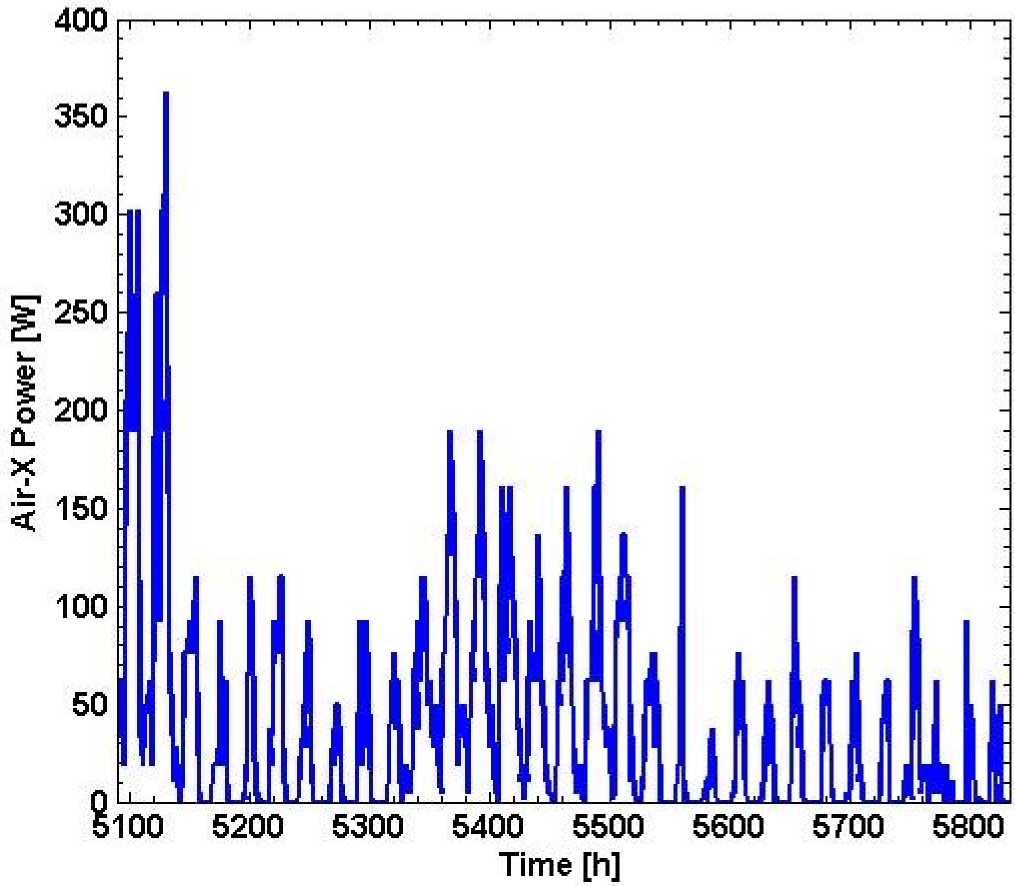

Figure 78: Air-X TMY Power August 1978

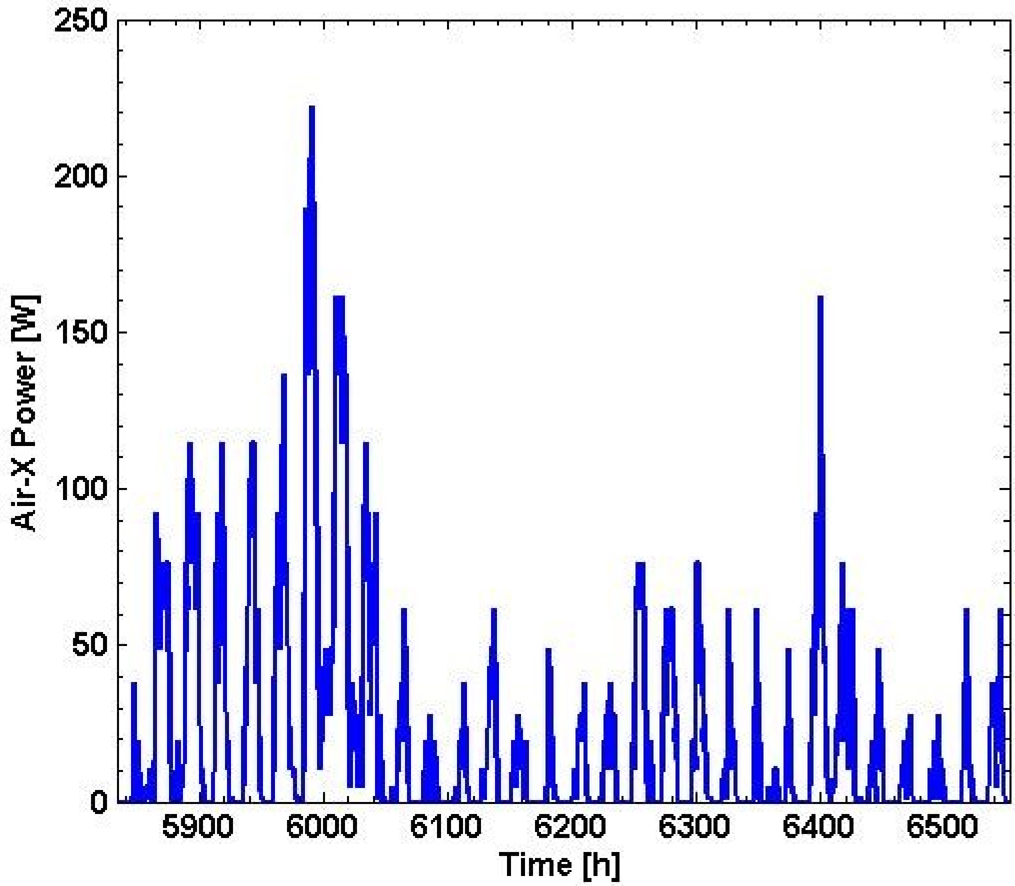

Figure 79: Air-X TMY Power September 2001

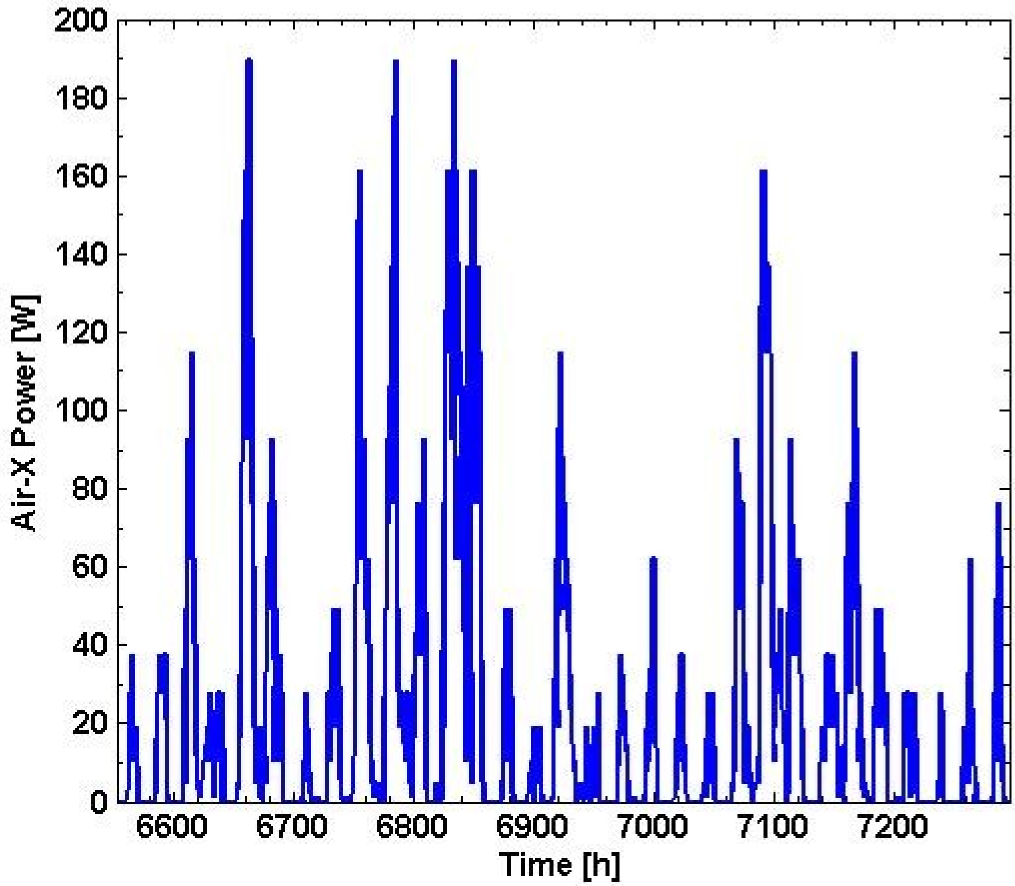

Figure 80: Air-X TMY Power October 2001

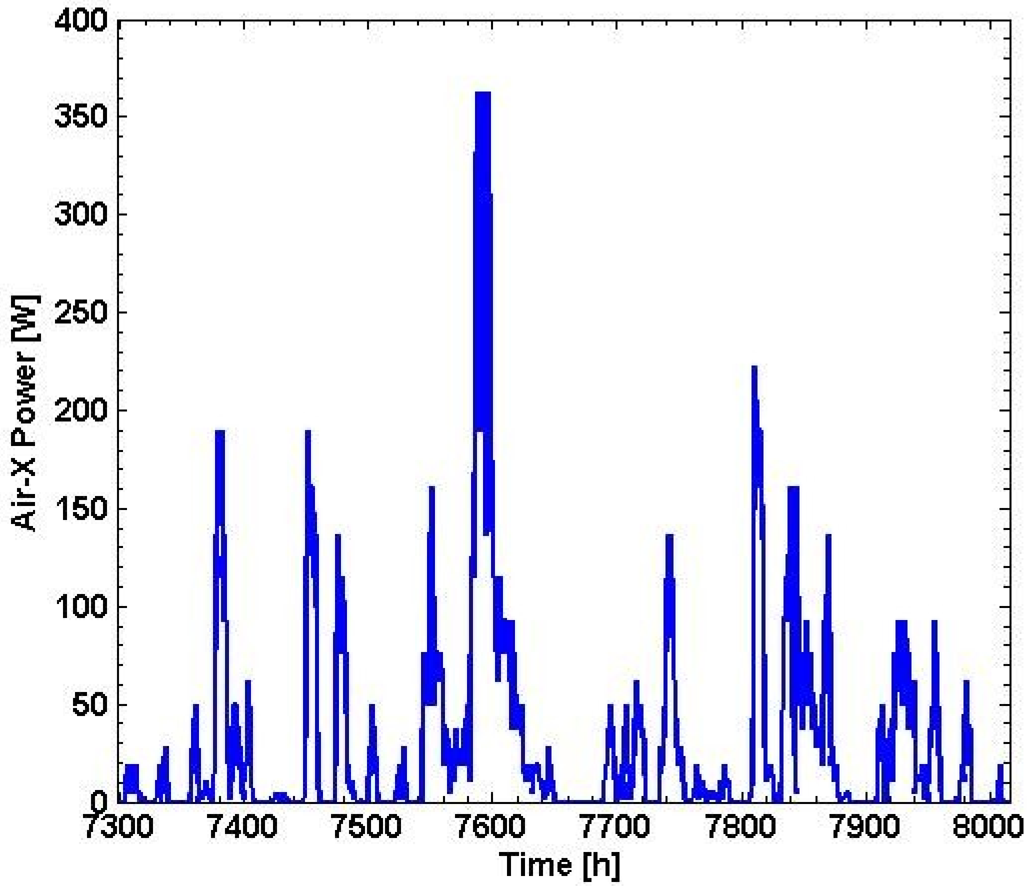

Figure 81: Air-X TMY Power November 1986

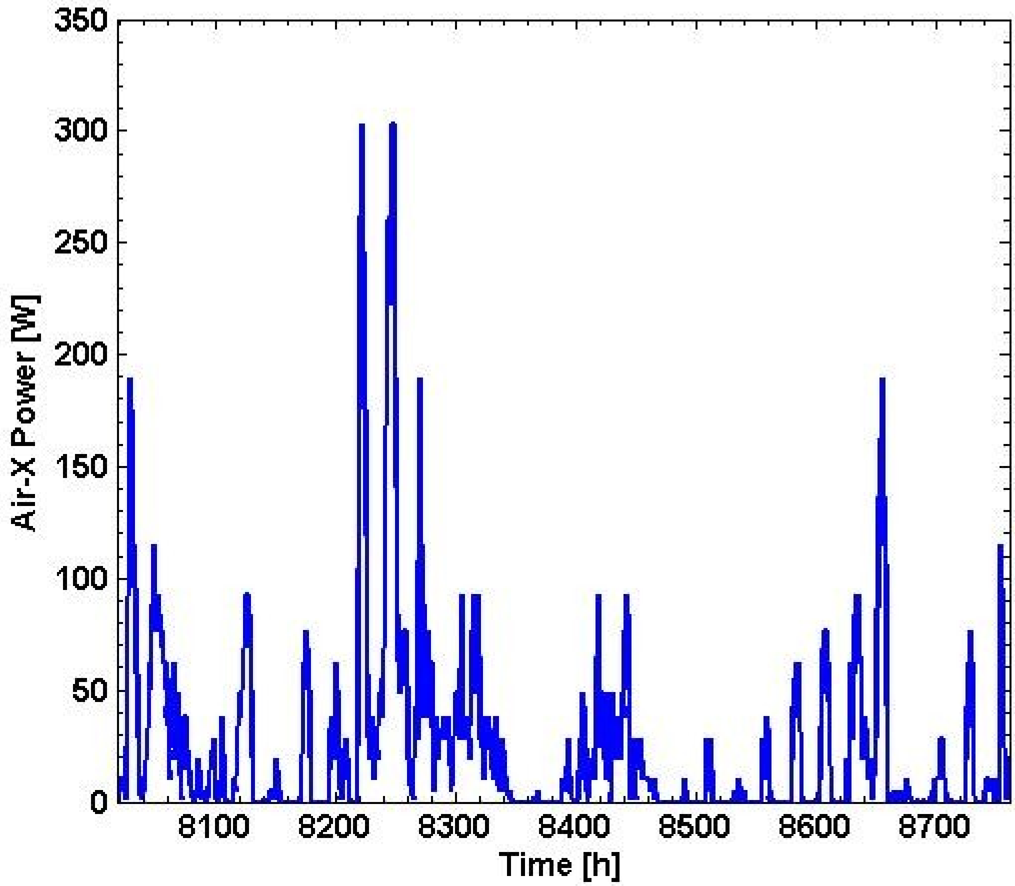

Figure 82: Air-X TMY Power December 1985

BIOGRAPHICAL SKETCH

Michael Anthony Acosta was born on December 26, 1983, to Miguel and Elisa R. Acosta in Corpus Christi, Texas. Michael was raised in Edinburg, Texas and graduated from Johnny G. Economedes high school. Following high school, Michael received his Bachelor of Science in Mechanical Engineering with a GPA of 3.68 from the University of Texas-Pan American in May of 2006. In August, 2006, he enrolled in the University of Texas-Pan American to pursue a Master of Science in Mechanical Engineering. His permanent address is: 3204 E. Benito A. Ramirez, Edinburg, TX, 78541.