AC 2012-2999: PROJECT-BASED RENEWABLE ENERGY COURSE FOR UNDERGRADUATE ENGINEERING STUDENTS

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Abstract: Fossil fuels have been the most significant energy resources for long time and supply more than 67% of the world electric energy needs. On the other hand, the electricity generation from renewable sources is less than 3% if hydropower generation is excluded. The industrialization of modern civilization demands more electricity than ever, which leads to significantly increased consumption of fossil fuels if alternative technologies are not explored. Well-trained engineers, scientists, and researchers could lead the way in development of the sustainable alternative energy technologies and could reduce the burning of fossil fuels which are critical for other purposes such as lubricant and creating manmade substances like plastics. To join into this effort of producing the future engineers with alternative energy background, a course is developed at York College of Pennsylvania for the undergraduate studies. The objectives of this course are to provide students with theoretical and practical knowledge reinforced by hands-on experience. To obtain these objectives, a semester long photovoltaic system project is included in the renewable course. This paper presents the course structure, project report, and student survey of the course, as well as plans and expectations for future success. The project report discusses the team structure, component selection, system simulation, and experimental results. The student survey indicates that the project improves the student's understanding of the renewable energy prospects and issues, and allows them the opportunity to be instrumental in the future of alternative energies.

Background and Motivation: The electricity generation from renewable resources is growing rapidly and the total generation increases 3.1% annually (U.S. Energy Infromation Administration, 2011). The most significant contributors are hydro-power and wind. Hydro-power is one of the oldest forms of renewable energy, and therefore the vast majority of possible large-scale hydro energy resources have been explored. Fig. 1 shows electricity generation from renewable resources in the U.S. from 1949 – 2009 (U.S. Energy Information Administration, 2011). Fig. 1 also shows that hydroelectricity reached the peak around the year of 1997, and the difference between the hydro-electric power and other renewable is increasing every year.

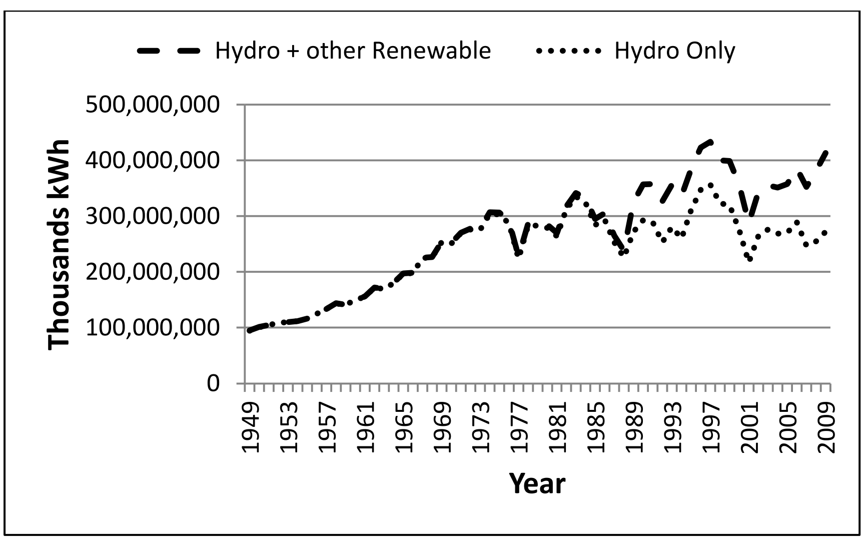

Fig. 1: Electricity from Renewable Sources in U.S.

Among other renewable resources, electric power generated by wind is the fastest growing energy field. Over the past decade, wind electric power grew from 18 gigawatts of installed capacity in 2000 to 196.6 gigawatts in 2010 worldwide (U.S. Energy Infromation Administration, 2011). Solar photovoltaic (PV) and solar thermal also showed a promising growth over the past decade and could be a potential solution of the world energy crisis. The Energy Information Administration shows that the worldwide electric power production from wind and solar will increase by 7.4% and 10.61%, respectively for the next 25 years (U.S. Energy Infromation Administration, 2011). The trend of renewable energy growth should be clear from facts presented above.

In most scenarios, renewable resources are available for free such as wind and solar, but harvesting of the quality electrical energy from them is challenging. The future of the cleaner energy challenge relies on well trained work force and innovative thinking. The undergraduate engineering education is a suitable place to start the training on renewable energy technologies. There is a long term demand and need in offering program study and courses in the areas of renewable energy and power system. This is because there is and will be demand of power engineers knowledgeable in renewable energy and conversion technologies. Aside from the field of power engineering, energy industries are also looking for engineers with renewable energy background because of the predicted high growth in the renewable electric energy and the public interest in cleaner energy. Most engineering students start their professional career right after they finish the undergraduate degree, and by providing a background in renewable energy will help them to research alternative energy options in their perspective professional career. Engineering programs around the world are trying to satisfy this need by incorporating renewable energy courses into the curriculum (Santoso & Grady, 2005; Li & Soares, 2011; Yildiz & Coogler, 2010). To join into this effort, a project based renewable energy integration course is developed in the Electrical and Computer Engineering program at York College of Pennsylvania.

Course Synopsis: The engineering elective course on renewable energy integration was first offered in the summer semester of 2011 as a three credit-hour course, where 11 students were enrolled. This course is focused primarily on solar electric power systems, with a secondary focus on wind powered systems, based on the steady growth in those areas over the past decade and projected a high growth in the future. To a lesser extent, this course also discusses other renewable resources and related technologies. A photovoltaic systems project was included to reinforce the renewable technology ideas and provide students with hands on experiences. Therefore, this course includes the following key areas of the renewable energy integration issues:

- Photovoltaic power
- Wind energy and wind power systems
- Other renewable sources (hydro, tidal, etc...)
- Energy storage
- Power electronic interface
- Stand-alone and grid-connected renewable power systems

Students are expected to be knowledgeable in the areas of electric circuits, electricity, magnetism, and mechanics, so desired pre-requisites are fundamental of electrical engineering and engineering physics.

Course Syllabus: The course is divided into three parts.

- Part I: Photovoltaic Power Systems: Theory, current technology, and use
- Part II: Wind Power: Theory, current technology, and use
- Part III: Energy storage theory and methods, power electronic interfaces and other supporting electronics and controls, and stand-alone and grid-connected renewable energy systems.

Due to the diverse topics that need to be covered in this course the following books were used as references (Patel, 2006; Masters, 2004; Ackermann, 2005; Messenger & Ventre, 2010). Based on the instructor's research and textbook contents the following syllabus was developed. The syllabus has two basic components:

1. Lecture and literature review
2. Project

Lecture and literature review: Lectures were designed to serve two purposes. The first is to provide students with broader background in renewable energy development and future trend. The second is to provide students with technical tools to analyze and design renewable energy systems. To satisfy these purposes the following topics were covered:

- Renewable energy development around the world
- Renewable energy development in the USA
- Photovoltaic (PV) fundamentals
  - Photovoltaic cell model
  - V-I and P-V curve
  - PV array ratings
- Wind energy fundamental
  - Wind speed, power output, rotor efficiency, and tip-speed ration (TSR)
  - Types of wind turbines
  - Speed control of wind turbines
  - Environmental aspects
- Energy storage
  - Various energy storage options
  - Students were asked to research energy storages issues and submit a paper
- Fundamental of power conversion and alternating current
- Generators, drives, and transformers
- Integration issues
- Grid connected and stand-alone photovoltaic power system design
  - An appropriate paper on photovoltaic system design was assigned and students were asked to summarize the paper
- Grid connected and stand-alone wind power system design
  - An appropriate paper on wind power system design was assigned and students were asked to summarize the paper
- The future of renewable energy, energy storage, integration, and utilization techniques

A project was incorporated to provide students with more insight to a renewable system design and integration issues. The project is described in the following section.

Project: A multi-disciplinary team of eleven junior and senior engineering majors of electrical, computer, and mechanical engineering disciplines was tasked with designing, assembling, and testing a single 500 watt photovoltaic setup that they could simulate, assemble, and test in order to validate their simulation results. Due to the size of the class, the students were all assigned to the same project. A primary reason for focusing on a photovoltaic solar system rather than any other alternative energy system is because of the promising future in the field, as well as ease of testing. Wind and hydro, arguably the two other largest renewable energy resources, provide challenges because of their spatial and resource requirements. Solar power is available virtually anywhere, and parameters can easily be adjusted. The experience gave the students an opportunity to reinforce the classroom lessons on solar energy and to apply it in a real-life situation using the same equipment as large scale solar installations. Students worked with suppliers and manufacturers to acquire equipment and testing supplies, troubleshoot devices, and to better understand how solar power is harnessed in large scale operations. The students designed experiments to test different aspects of the system, including panel orientation, battery charging algorithm, and charge controller configuration.

The team was given a maximum budget of $3,000 to spend on all aspects of the system which include the PV panels, required power electronics, energy storage devices, and other miscellaneous components.

System Design: Students were given approximately three weeks of classroom background on photovoltaic systems before being asked to purchase components. With that knowledge, individuals were assigned components to research and asked to work together to design a system to meet the objectives described above.

Solar Panel: As mentioned above, the objective of the project was to design a system rated for 500 watts. Since panels typically do not offer rated maximum power ratings higher than 250 W, the team decided on obtaining two panels. These panels would be mounted on custom portable stands that could be easily adjusted depending on the time of the year, the angle of the sun, and other variables. The panels needed to be weatherproof so they could withstand the elements of nature, and needed to have a plug-and-play interface for convenience. In many respects, the team was making the same decisions that system integrators make on a regular basis when designing a PV system.

Ideally, the test setup would consist of four-125 watt photovoltaic (PV) solar panels with a nominal output voltage of 12 V, to allow for optimal testing versatility. They could be setup to output 12 V, 24 V, 36 V, or 48 V configurations. Testing could have also been done on the effects of hooking panels in series or in parallel. Unfortunately, for the purposes of this experiment, it was more cost effective to obtain two panels, each with a nominal voltage of 24 V. Having two panels would also make testing different panel orientations easier, and still allow the system to be relatively portable. This configuration allows testing in parallel and in series for a 24 V or 48V system, respectively. A 12 V or 36 V systems could also be tested using two-24 V panels; however, the results would suffer from very poor efficiency.

After reviewing more than ten different solar panels, the team collectively decided on obtaining two 224 W Sharp solar panels at a cost of $765.00 each, the price per watt came to approximately $3.41. The panels have an open circuit voltage of 36.6 V and provide maximum power at 29.3 V and 7.66 A, according to the PV curve. The panels have a sturdy frame for mounting hardware and come with industry-standard MC-4 connectors for a secure electrical connection.

Charge Controller: Charge controllers are needed on a PV system because the solar panels alone cannot effectively or safely charge the batteries used for energy storage. The charge controller is a component that goes inline between the solar panels and the battery bank capable of regulating current flow to properly charge the batteries. The charge method of most charge controllers is either a pulse-width-modulation (PWM), or maximum-power-point-tracking (MPPT) charging algorithm. A PWM controller charges uses a static, predefined algorithm, does not change based on system conditions. This differs from a MPPT type controller which has a dynamic charging algorithm, capable of adjusting itself to the most efficient and effective parameters given a certain input from the solar panels. This dynamic charging algorithm makes MPPT units more efficient than the PWM; however, the tradeoff is that the MPPT units are considerably more expensive.

A few generalizations were made as to what type of charge controller would best fit the needs of the project. As mentioned above, the system was to be rated for 48 V, due to our available battery configuration, meaning that for a 500 W system, the charge controller should have at least a 15 A current rating. Considering the allowed budget, purchasing a MPPT type unit would not be feasible, considering that a PWM unit would meet the requirements.

Another consideration for the charge controller was on-board data logging capabilities. Several controllers researched by the team qualified as acceptable units considering our project's scope; however, many lacked sufficient data collection abilities. Because this project was research based, the team felt that data logging was a beneficial feature that should be met by the charge controller unit that is selected.

Considering all of the specifications described above, the charge controller that was selected was a Morningstar PWM Tri-Star unit. This controller has selectable operating voltages of 12 V, 24 V, and 48 V. The unit's rated current is 45 A, which far exceeds the required 15 A, while also providing clearance for additions to the system in the future. This unit was selected over others because it incorporated PC connected monitoring and data logging capabilities, while also having a stand-alone logging feature. Another desirable feature of this controller was the option for adding a meter to the face of the controller. This meter makes all the controller parameters available on an onboard LCD screen for real time monitoring and diagnostics. Discussions with Morningstar's technical support revealed that this charge controller is approximately 98% efficient. The Morningstar PWM Tri-Star charge controller was ruled to be the best fit for the application. After the purchase and some testing, the team felt a need for an additional controller. The team contacted the supplier and they generously agreed to donate one Tri-Star TS-60 MPPT Charge Controller for the project. The addition of this unit would allow the team much more versatility, and also the ability to compare and contrast the theoretical versus the experimental differences between the two controllers.

Inverter: A power inverter is needed to convert DC power, sourced either from the PV array or battery bank, into 120 VAC, 60 Hz power that can be used to supply most traditional household devices in the United States, or could potentially be connected to the grid. When connected to the grid, a grid-tie inverter can send power from the renewable resource or from energy stored in the battery bank, back out to be used by other consumers. A grid-tie inverter must synchronize with the power on the grid. Any phase difference between the grid power and the inverter output results in a loss of power. Most grid-tie inverters also have one or more receptacles for local loads. With this setup, the inverter can power a load and send extra power back to the grid simultaneously, given that sufficient power is being input. If the load is drawing more power than the input can supply, the inverter can actually draw power off the grid. In large scale implementations, grid-tie inverters have the potential to save or make money, and can cut down on the amount of electricity used from fossil fuels and other sources.

A stand-alone, non-grid-tie inverter is simpler and is generally less expensive. The inverter can produce AC power which is generally less precise than the pure-sine wave that can be found from a typical wall outlet. A pure- (or true-) sine wave output is the ideal option, although it is more expensive than a standard inverter, but provides a lower quality of power.

The team selected two different inverters; one grid-tie and one non-grid-tie inverter to test the solar panel system. The PowerJack 1200 W grid-tie inverter was chosen primarily because of its low price and its ability to meet the scope requirements of the project.. The 1200 watt rating was deemed to be more than sufficient for future installations and at an 87% advertised efficiency, it seemed promising. It also has a pure sine-wave output that can properly sync with the grid. The main issue with this inverter was that there was not an option to automatically switch back and forth from pulling power from the grid or from the solar panels.

The Schumacher 410W non-grid tie inverter was chosen by the team to perform off-grid testing on different types of inductive, resistive, and capacitive loads, and to reinforce the functionality of the other components in the system. The Shumacher’s modified sine wave is effectively closer to a square wave than a sine wave, but still serves is purpose in generating alternating current. This inverter was purchased because occasionally while testing different loads on the grid-tied inverter, it was not clear whether the power being consumed by the load was being drawn from the solar panels or the grid. With the addition of this inverter, it ensured that the power was only coming from the solar arrays, and allowed the team to perform more adequate tests on the loads.

Batteries: There are many different options for energy storage of renewable energy systems on the market today, each with their own advantages and disadvantages. Options for energy storage include batteries, flywheels, compressed air, superconducting magnets, and ultra-capacitors. After learning about the differences in the classroom setting, students were able to decide on batteries as the most practical form of energy storage for the project due to their size to weight ratio and their cost. This is the most commonly used energy storage device and has a charging and discharging efficiency of 80% to 90%. Batteries can be broken into two categories: primary batteries and secondary batteries. The most popular primary-style of batteries is zinc-carbon batteries and alkaline batteries. The most popular secondary-styles of batteries have a chemical composition of lead acid, nickel-cadmium, nickel-metal hydride, lithium-ion, or lithium-polymer.

Lead acid batteries are the oldest technology batteries, but are still the most popular due to their cost to energy ratio. Other technologies of secondary batteries listed above do have better discharge curves and cost to weight ratios, but they are more expensive, less robust, and less stable. Battery capacity is measured in ampere-hours (ah). When sizing batteries for a renewable energy project it is important to know the expected load. The load on a battery is measured by hourly rate, otherwise known as “C-Rate”. This is a ratio of the amps the battery will be supplying to the amp-hour (ah) rating on the batteries indicating capacity. The higher the C-Rate, the less efficient the battery; however, a battery is rated at

35 ah does not mean it can supply 35 A for 1 hour. In reality, most 12 V lead-acid batteries can only supply their amp hour rating for approximately 20 minutes. It is important to keep the C-Rate low so the batteries can discharge more efficiently. For this renewable energy project, the desired C-Rate was specified to be 0.05, meaning that it is capable of lasting for 20 hours.

When selecting a battery for renewable energy systems, the overall load must be known and the amount of time the batteries must support the system must be known so the battery bank can be appropriately sized. For this project there was no specified load, as many different loads were to be tested. The load would also be interchanged depending if a gird-tie inverter or a non-grid-tie inverter was being used. Four 12 V, sealed lead acid, AGM batteries rated for 35 ah each were selected for our application because of they boast one of the highest energy to price ratios of the potential batteries. Buying four 12 V batteries allowed for the versatility of connecting the batteries in any of the three different system voltages (12 V, 24 V, or 48 V) that the selected charge controllers could operate at. For a 12 V system, the four batteries could be connected in parallel providing 135 ah in system capacity. For a 24 V system, the batteries could be connected in series and parallel to allow for a 70 ah of system capacity. Lastly, for a 48 volt system required all four batteries to be wired in series providing 35 ah.

The gird-tie inverter selected by the team requires an input range from 28-55 V. Due to this requirement, when testing with the grid tie inverter the four batteries would have to be connected in series. The non-grid-tie inverter used was rated at 12 V on the DC side requiring all the batteries to be connected in parallel. A complete setup is shown in Fig. 2.

Fig. 2: Complete PV System Setup

Simulation: Simulations are a great way to replicate actual systems and to acquire theoretical results for real-world scenarios. Simulink by Mathworks is widely used in industrial, educational, and research and development applications, and is a great tool for modeling, simulating and analyzing different solar configurations. Toolboxes are available which make modeling solar panels, wind turbines, and all of the other power components including inverters and charge controllers simple and accurate. These components can be seen connected together and monitored by oscilloscopes, voltmeters, and ammeters in fig. 3. The output port series resistance and switching loss current seen in fig. 1 were chosen based on the specification of 87% efficiency provided by the manufacturer's web page.

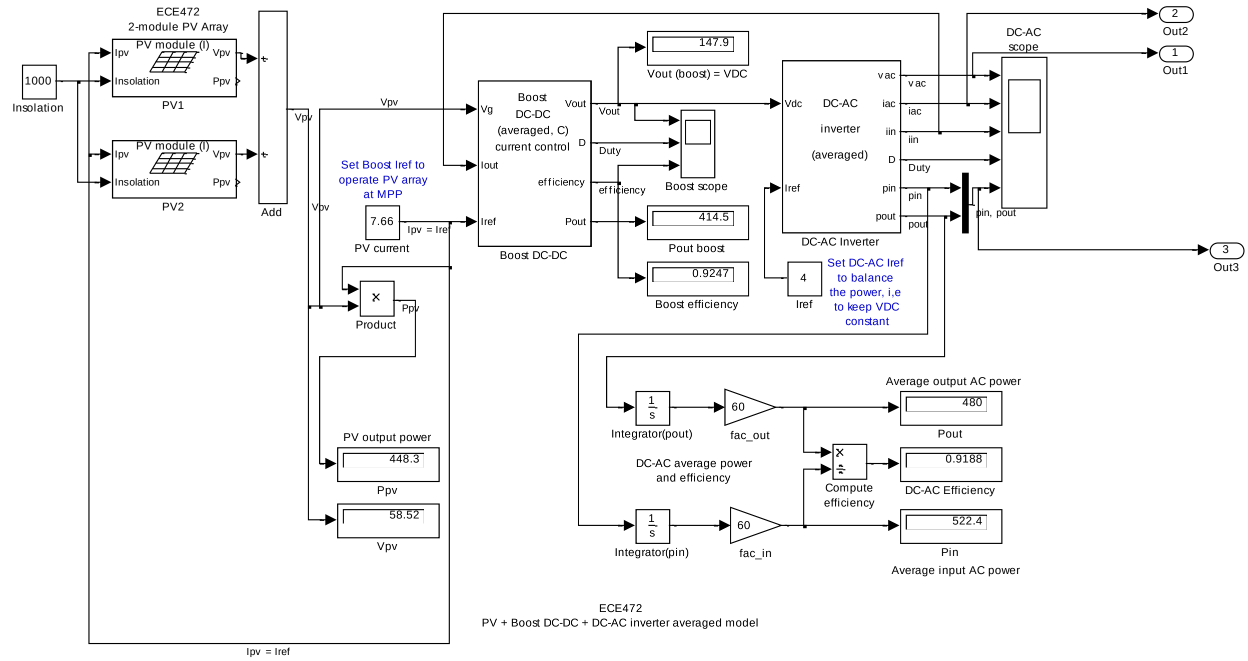

Fig. 3: Simulation Setup

The simulation can then create a graphical analysis as shown in figures 4, 5, and 6 below. In fig. 4, the output power of the inverter is 945 W while DC power output from solar panels is 1051 W, resulting in a 89.9% efficiency. Fig. 5 shows the voltage output by the grid tie inverter. It can be noted that the inverter will output the proper voltage needed to be tied to the grid. Fig. 6 shows the AC output current. Notice that it is a clean sinusoidal in phase with the voltage because the load is accepting all of the available power. These figures for the modeled inverter are under ideal conditions, and the actual inverter should be tested and verified with power monitoring equipment before being tied to the grid or any of the other system components.

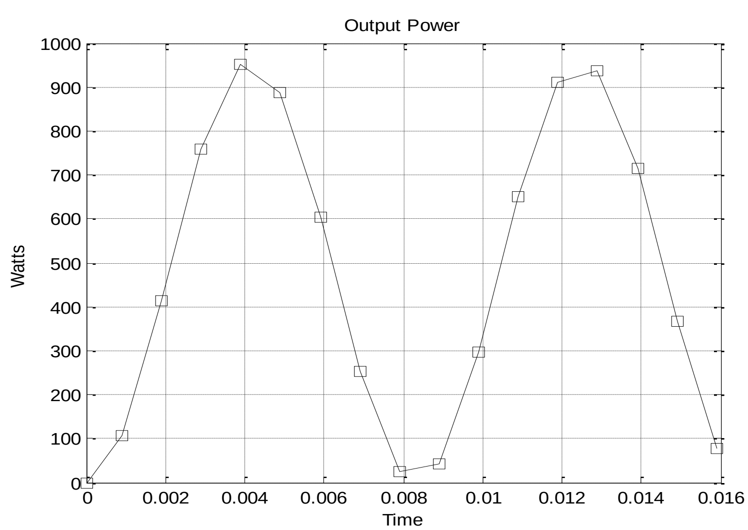

Fig. 4. Output Power (in Watts)

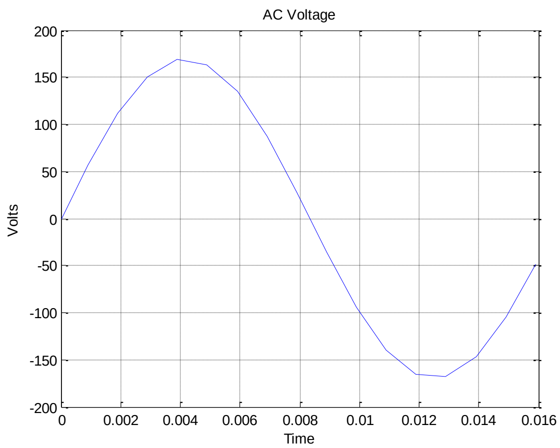

Fig. 5: AC Output Voltage (in Volts, RMS)

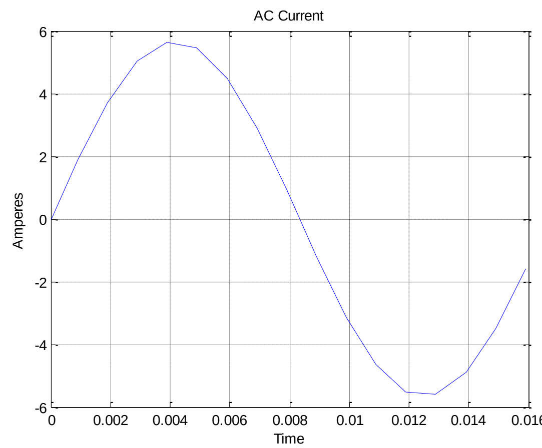

Fig. 6: AC Output Current (Amperes)

Testing and Results: The following sections describe the testing of the selected equipment. It is important to note that testing was done in York, Pennsylvania, during the summer months of July and August. Results will vary based on weather conditions, time of year, and location.

Solar Panels: The test setup allowed the team to measure and record many different aspects of the system, both as a unit and individually. In Fig. 7 below, it can be seen that the VI curve matches relatively closely to the expected curve that was provided by the PV panel manufacturer, seen in Fig. 8. The error is because getting data points at very low resistances was difficult because the load was heating up quickly. If there were more data points taken from more sophisticated and precise equipment, it is assumed that the curves would have much more closely resembled those that are shown on the datasheet.

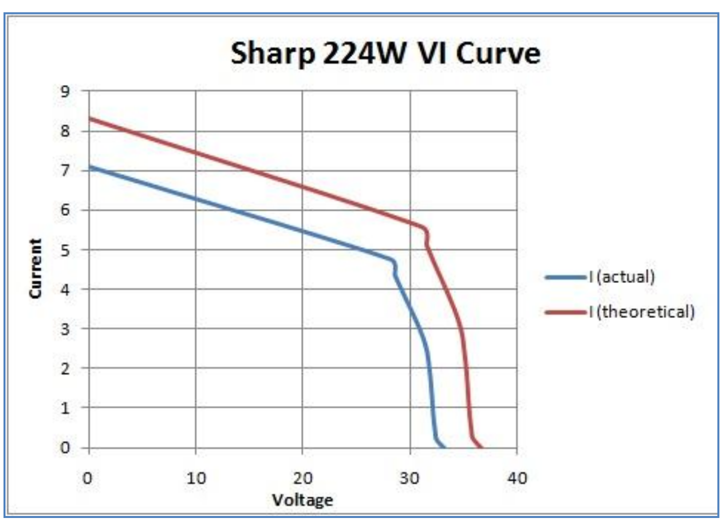

Fig. 7: Experimental VI Curves

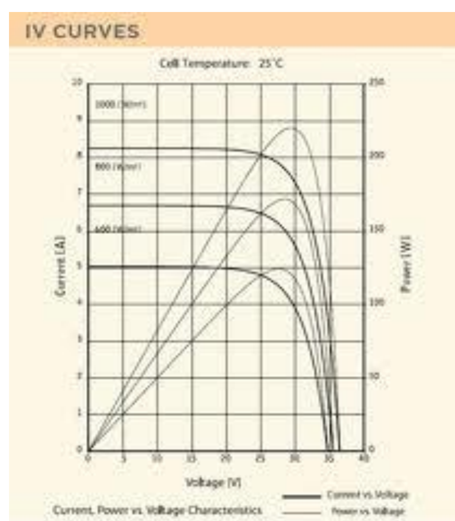

Fig. 8: Datasheet VI Curves

Creating a power curve was more difficult than anticipated because controlling the load while maintaining constant conditions from the solar panels was nearly impossible. This is something that the team would have liked to have done if there was more time for testing in the semester. Fig. 9 shows the array power with time over the course of one day.

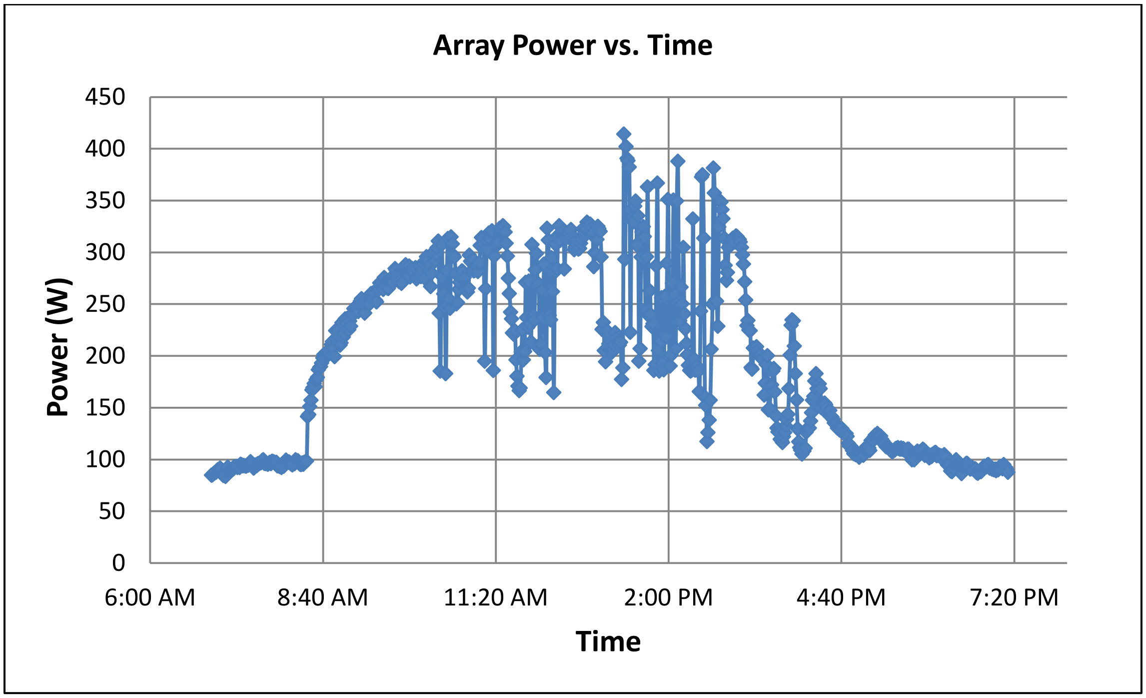

Fig. 9: Array Power vs. Time

Initially there was some concern as to why the data recorded in fig. 9 looked erratic. The team realized that because the system consisted of only two PV panels, the sample size of the data was relatively small. Considering the passing of clouds over the course of an entire day, a single cloud could easily affect both panels negatively. This is not the case in large PV systems consisting of more panels. In those systems, a single cloud will not decimate the entire system for a brief time, as seen in the many troughs in the data pictured in figure 9.

Charge Controller: The first step taken by the team was to determine the proper functionality of the charge controller. This was done by bench testing the controller using standard lab equipment to simulate the solar power going to the controller. The charge controller bench test setup began with a DC power supply, rated at 48V, attached to the solar panel terminals on the controller which was set for 12 VDC charging. The team expected to see the relationship between the incoming power provided by the power supply and the output power to the battery terminals. After turning on the power supply, there was no response seen from the controller. After consulting the data sheet, it was determined that the controller received its operating power from the battery terminals, and not the incoming power provided by the solar panels. After attaching a 12 V battery to the controller and again applying voltage to the charge controller, the device powered on. It quickly became apparent that a larger power supply would be required to satisfy the input of the charge controller. Even with the larger power supply, the voltage did not exceed 16 V due to its inability to source adequate current. The testing also showed that the batteries would not be charged at all unless panel voltage was above the battery voltage. The team was expecting the controller to act as a variable, or dynamic, DC to DC converter, that would change from a Buck or Boost converter as needed; however was not the case. This meant that the system running two panels in parallel would not be feasible if the batteries were at 48V, as the panels only output a maximum of 30 V under optimal conditions. Seeing as the highest voltage attained was 16 V, only testing the system at 12 V was feasible. Low voltage testing showed that once the panel voltage dropped below the battery voltage, current reversed direction and after approximately 1 minute the controller shut off the flow of reverse current. From bench testing the controller, the team was able to conclude that design assumptions for the system voltage were incorrect, and this adversely affected the performance of our system.

The wiring configuration for the Tri-Star controller is straight forward. It has inputs for the solar panels and connections for the battery pack. The entire connection of the system can be seen in Fig. 10.

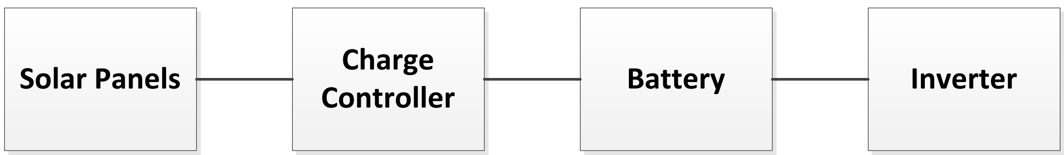

Fig. 10: Charge Controller System Integration Configuration

Upon initial testing, the team realized some problems with the setup. The major issue was that the grid-tie inverter in the system has the ability to draw approximately 30 amps to supply the grid. Because of the capacity of the battery bank for the system, drawing 30A continuously would drain the batteries at a significant rate. Upon testing, the team depleted fully charged batteries in approximately 45 minutes. The preferred system configuration was such that the load would draw directly from the power provided by the solar panels, and in the absence of solar power, the load would be switched to take from the battery. When the load was absent, excess power generated would be directed to the batteries for storage. This configuration was not what the selected charge controller was designed for.

After some research, it was found that with the addition of another controller identical to the one the team already acquired would allow configuring one controller in charge mode and another in load mode. One controller would be placed in-line between the batteries and the solar panels to act as the charge controller, and a second controller would be placed in-line between the batteries and load to act as a load controller, as seen in fig. 11.

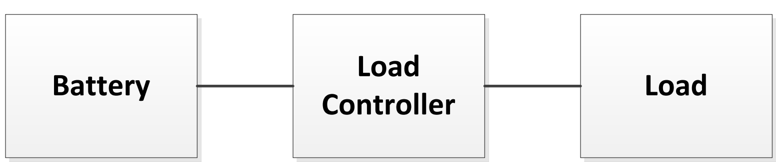

Fig. 11: Load Controller System Integration Configuration

When the batteries were charged, the load controller connected the batteries to the load. When the battery charge dropped below a specified threshold, the controller would disconnect the load so that the batteries could be safely charged back to full capacity. When full capacity is achieved, the load controller could detect that it was safe to discharge the batteries and switches the load back on again. Essentially, the load controller could act as a "smart" switch which monitors the battery such that it discharges the battery and allows for safe charging of the battery. Without this load control functionality, the batteries could be unsafely discharged. While the load controller was switching on and off the load, the charge controller was continuously working and charging the batteries as long as solar power remained available.

After discussing the above-mentioned research and voicing questions and concerns with technical support with the current controller's manufacturer, Morningstar, they generously offered to donate a unit for York College of Pennsylvania's use in the engineering program to conduct research. They kindly sent their Tri-star MPPT 60A unit, the top-of-the-line Morningstar controller. The advantages of the MPPT controller are the increased performance due to a more complex adaptive algorithm. For installations that are restricted either by space, or need the best performance possible, an MPPT controller is the ideal choice. However for many hobbyists and budget installations, the PWM controller is a good alternative. The addition of this controller would allow the system to support grid-tied, battery backup functionality which the team originally desired. The complete connection configuration can be seen in the diagram in Fig. 12 below.

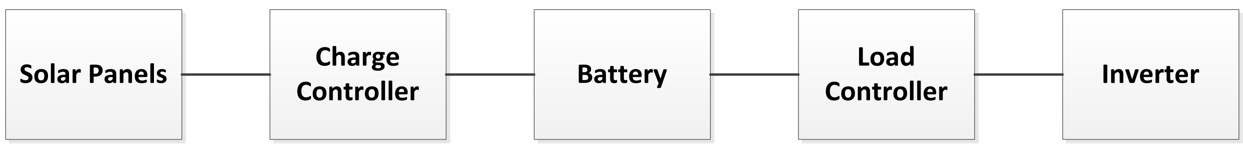

Fig. 12: Both Charge and Load Controller Integration Configuration

The team was fortunate to utilize the same brand of charge controller and load controller because they both utilized the same free data collection software, which made it easy to log and record data. Using a serial connection to the controllers, the software could communicate with the units and record the desired data. The software allows for many different types of data recording and monitoring. An option for data recording is being able to select the parameters from a controller for recording to a CSV file format. The software gives the ability to log any amount of parameters from the units. It also allows the ability to log parameters from different units to the same CSV file, and also recording multiple CSV files at the same time.

Another advantage of the logging software is that the sampling rate can be adjusted from one second, upwards to intervals of days and weeks. This logging feature was ideal for our data collection needs. Also available within the software was the ability to display the parameters from the controller right on the screen of an attached PC. This was useful for real-time monitoring of the system separate from the controller's meters. The logging and monitoring ability of the controllers made them a very valuable asset to the research project.

Another major issue that was encountered was the difficulty of using the grid-tie inverter as the load on the load controller. The team experienced a scenario that the load controller would fault when attempting to switch the inverter on. The fault that was occurring was an "External Short" fault. Unfortunately, little documentation and support was provided by inverter manufacturer, which made it difficult to identify what the fault's root cause. Occasionally, when manually switching the inverter on by hand, the load controller would accept the load and begin functioning as expected, however correct operation appeared sporadic and unpredictable. The system was intended to stand alone for some time and it would operate as expected with not faults or problems, which was not the case. A proposed solution for this switching error was to use a large inductor to slowly ramp the input voltage from the controller to the inverter such that a current spike or other transient was not experienced, and safe and guaranteed switching of the load would occur. This solution did eliminate the fault experienced by the load controller, but it instead caused the inverter to fault.

Overall, the charge controllers were well researched and were decided upon because of their data logging capability. In hindsight, there could have been better components selected that fit our exact system configuration needs. These reflections will be discussed later. The data that was collected was accurate and helpful for our research, although some of the desired results were unobtainable. The team believes that with more clearly defined specifications and expected outcomes, as well as more information about the inverter, the functionality of the system would have been greatly increased. The team was still generally satisfied with both the performance of the Morningstar charge controllers and the technical support received by the company.

If given more time to work on the project, some future testing goals for the charge controllers would be to fully test the differences between the PWM charging system versus the MPPT charging system. This was not possible given that there were no plans to receive a MPPT charge controller by donation more than half way through the project work period. Comparing the efficiencies and charge rates would have been useful knowledge to obtain to learn more deeply the differences in charge controller types. Ultimately, the conclusion from this testing would provide the validation for the large cost difference between PWM and MPPT controllers.

<u>Inverters:</u> The two most popular solar configurations, grid-tie and standalone, were tested as part of the project. A simple grid-tie system was tested by simply having the solar panels fused and ran directly into a grid-tie inverter with no other devices needed. Most grid-tie inverters are capable of handling 28 V to 55 V as a DC input and will use a pure-sine wave inverter to sync with the grid. This is helpful because power can be supplied to the grid without any other devices, which also means that there is better efficiency and lower system cost.

Due to issues between the grid-tied PowerJack inverter and the TriStar charge controllers mentioned above, two different test setups were necessary (one for an off-grid inverter and one for the grid-tie inverter). The off-grid 12 V inverter test setup is shown in fig. 13:

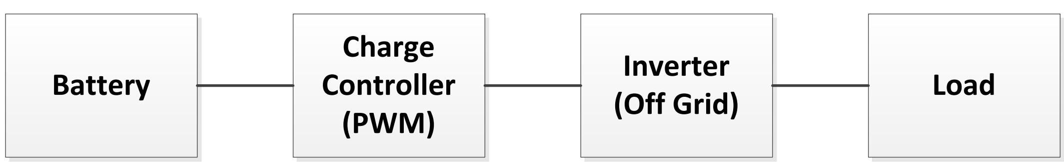

Fig. 13: Off-Grid Setup

The TriStar PWM charge controller was used to measure voltage and current between the battery and the 12V inverter. Data points were recorded at 30 second intervals for 10 minutes. The Fluke 43B power quality analyzer was used to measure the apparent power and power factor between the inverter and the load at the same intervals. The average voltage on the DC side was 12.02 VDC, with an average current of 5.62 A. This yields an average power of 67.49 W. On the AC side, the average apparent power was 59.85 W with a power factor of 1.00 – yielding an average power of 59.85 W. The average efficiency of the 12 V off-grid inverter was found to be 88.68%.

The test setup for the grid-tie inverter can be seen in fig. 14. Only one solar panel was used was due to the voltage limits on the grid-tie inverter, which operates at 28-55 VDC. A single panel was averaging 30-32 VOC. Two of these panels in series could have been outside of the 55 VDC range and possibly damaged the inverter. The panels could have been placed in parallel but this would not have affected the efficiency data.

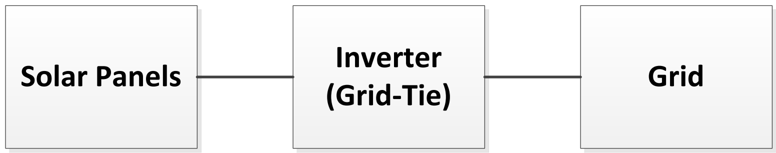

Fig. 14: Grid-tie setup

The average solar panel voltage was 27.91 VDC with an average current of 1.17 A – an average of 32.64W. Although the voltage is slightly below the "minimum" rating on the inverter, it was determined from previous testing that the inverter did continue to operate correctly until falling below 26 VDC. This test provided a good worst-case scenario to measure efficiency with. An average apparent power of 84.25 W was measured on the AC side, with an average power factor of 0.31. This makes the average power output only 26.25 W – an efficiency of only 80.64%.

In order to further test the inverters power quality, a small household fan was used as a load allowing the team to calculate the power factor. The fan is both a resistive and inductive load so it will require some amount of reactive power. The fan by itself had a power factor of 0.53. In order to limit the reactive power, a capacitor was be added in parallel. The targeted power factor was 0.9. Through some calculations, a 10μF capacitor was decided to be the best for this application. After the capacitor application the power factor improved to 0.97.

Batteries: The batteries were tested under different loads and C-Rates. These tests used the MorningStar TS-45 PWM charge controller in load control mode. The charge controller monitored the battery terminal voltage and disconnected them from the load when the terminal voltages dropped below certain threshold. The batteries were discharged while they were connected in parallel for a 12 V system. The voltage level disconnect threshold was set to 11.7 V which was a predetermined value that the charge controller had equating to the batteries being discharged to 23% remaining. Figure 15 shows the batteries being discharged at a rate of 0.19C.

Figure 16 shows that batteries are being discharged at a rate of 0.02 C. This is due to not as much internal resistance and efficiency losses with the batteries at high current discharges. The difference in Fig. 15 and fig. 16 show the benefit in discharging the batteries at a low C-rate. The batteries are able to supply a greater amount of energy over time because energy is not lost due to internal resistance and ineffiecinces.

Fig. 17 and fig. 18 show the batteries being charged through a charge cycle using the MorningStar TS-60 MPPT charge controller. The MPPT chargeing algorithm tracks the maximum power power point of the solar panel while charging the batteries.

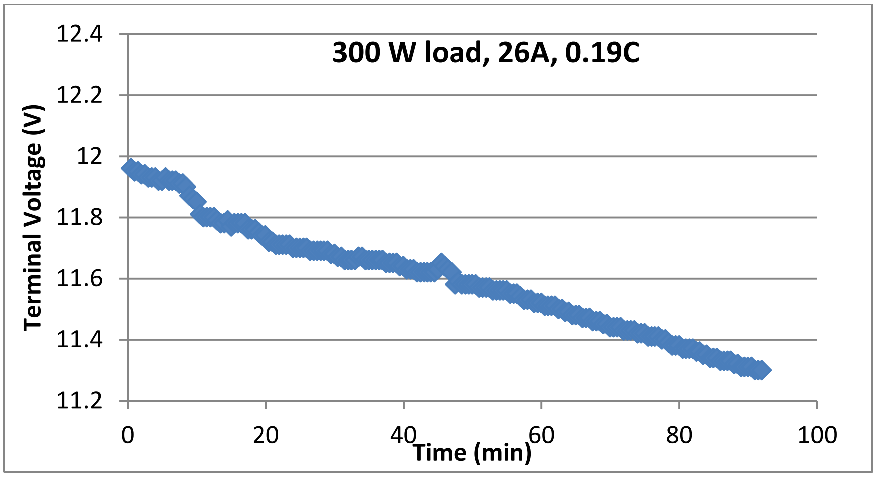

Fig. 15: Battery Discharge Curve (0.19C)

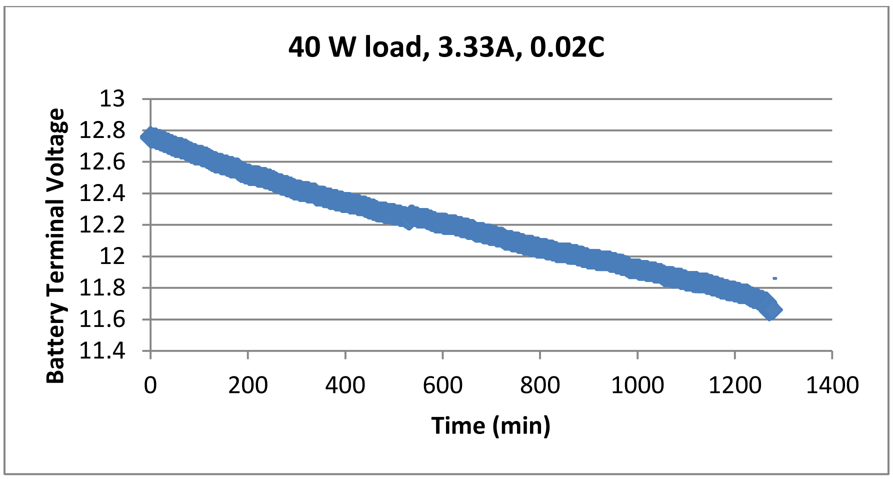

Fig. 16: Battery Discharge Curve (0.02C)

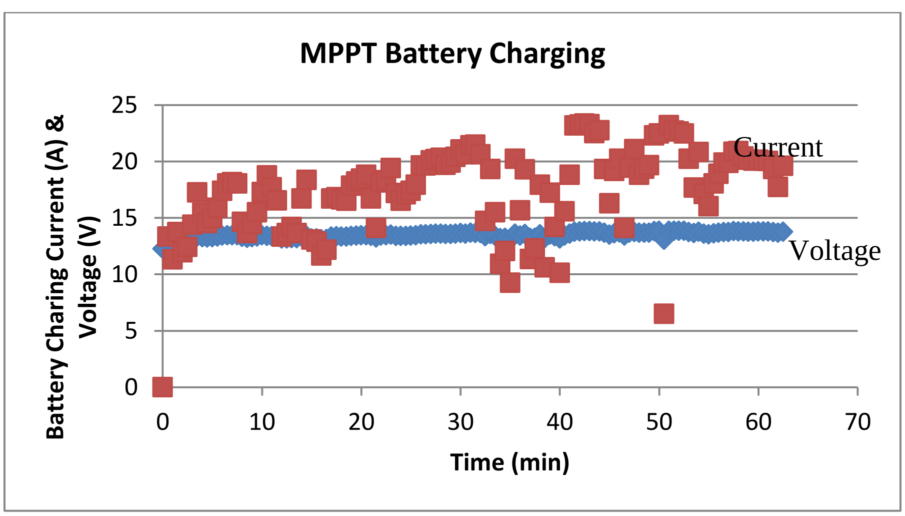

Fig. 17: MPPT Battery Charging Voltage and Current

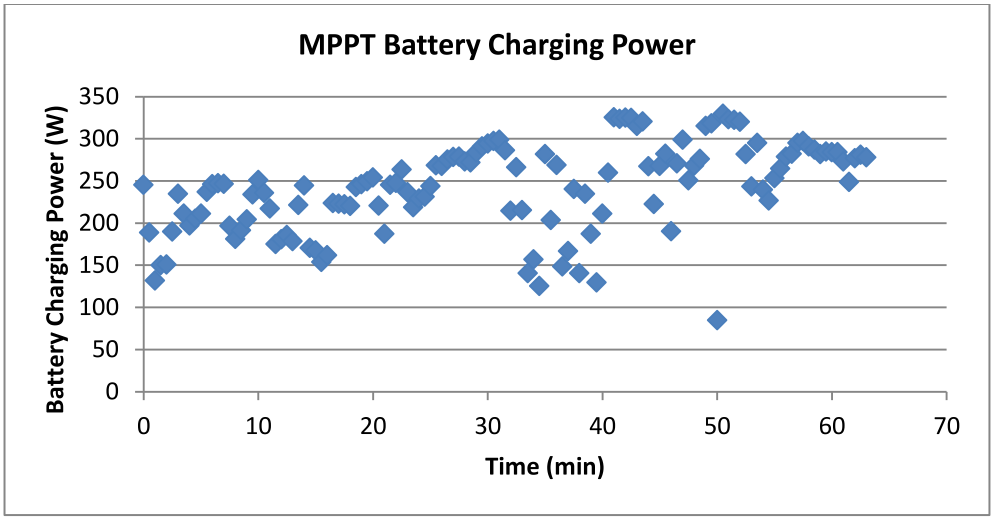

Fig. 18: MPPT Battery Charging Power

Solar Panel Orientation: For the orientation of the two 224W Sharp solar panels, the team utilized the equations below that orient the panels in the best position for maximum average collection in the summer and winter seasons.

Winter Panel Angle = Location Latitude + 15 degrees

Summer Panel Angle = Location Latitude - 15 degrees

Since the latitude of York, PA, USA is approximately 39.97 degrees, team members designed stands that could be oriented at 25, 40, and 55 degrees from the horizon while facing south. This allowed examining the effects of proper and improper orientation of the panels and allowed the rest of the subsystems to be consistently tested at specific orientations. The panel stands were designed and constructed in a manner that allows them to be easily stored and transported.

Lessons Learned: Given the budget and desired configurations at the time, the team made educated decisions on what components would be best to purchase. Unfortunately, some of the selected components were not capable of yielding the anticipated results. Given what the team had learned there are several things that would have been done differently.

The team collectively made a good choice by purchasing the Sharp 224 W panels. Since panel selection, the students in the class have learned the actual way to decide on panels by looking at things like heat losses, inverter losses, charge controller losses, and wiring loses. If the team wanted to obtain 500W of output from the panels, inefficiencies of the system and sunlight in the area, usually a factor of about 1.2, should have been considered. This provides the total number of panels needed to support the desired system.

With the total number of panels identified, array configurations could be more accurately outlined and planned. This is decided based on the DC system voltage. The DC system voltage should be compatible with the charge controller as well as the inverter of the system. The array should be situated in series and parallel combinations so that the open circuit voltage is above the DC system voltage and the nominal voltage of the array should be approximately that of the DC system voltage. For the configuration, the team used two 224 watt panels with a 1200 watt, which is not an ideal system. The team could have selected power electronics with a lower rating; however choices were limited because of the small demand for small systems like the team wished to implement. The open circuit voltage of the two panels is approximately 72 V and 48 V nominally. Thus, the panels in series worked ideally for a 48V system; however to satisfy a 1200 W load, the team should have been multiplied the panel rating by a factor of 1.2 to achieve 1440 W panels. If using the 224 W panels, the team would have needed to purchase six panels and wire them in series to receive the ideal 1344 W. This would have allowed an entire day worth of loading by the grid-tie inverter, which was not the intention of the equipment

The purpose for buying the MorningStar controllers was because of its data logging functionality. The charge controller could work with the 48 V system voltage and was rated for a max continuous current of 45 A. When both panels were arranged in series, a maximum current of 15 A would have been drawn through the controller, well within the specifications of the controller. Even at a full 1200 W load, the 25 amps drawn from the 48 V system would still be well within the controllers operating range. The team could have considered a lower-rated charge controller, however having an oversized controller allows for future expansion on the system.

If the team was to conduct the experiment again, a controller with three inputs (the solar input, the battery input, and the load input) would have been selected. The ideal controller would pass current directly from the solar input to the load, and would not continuously charge and discharge the batteries increasing longevity. Ideally, the controller would provide enough solar input to the load, and all additional power would be used to charge the batteries if not already fully charged. These type of controller are available, however they did not fit in the budget and did not have data logging capabilities, making experimentation more difficult. Ideally, using a custom data-logging program on a microcontroller would have been used to record data.

The battery bank was a rack of four 35 ah 12 V batteries providing a total of 48 V to the system. These batteries were used mainly because of availability. If calculations were done to provide for the 1200 W load for 16 hours per day, assuming that the panels would provide maximum output for 8 hours per day, then four 400 ah batteries would be needed and arranged in a 48 V configuration. Since the team was interested in measuring charge and discharge rates in the experiment, it was necessary to utilize batteries. They were also practical because of budget and spatial constraints. However, if the experiment was to be conducted again, appropriately sized batteries would have been selected based on the load over a specific time period.

The inverter was selected based on the future aspirations of the class. A 1200 W grid tied inverter was purchased with the intention of handling both solar panels as well as a wind turbine in future years. Hooking this inverter directly to the battery bank would have exhausted the batteries within one hour. Even if larger batteries were selected, the issue would still occur because the discharge rate of the batteries would be larger than the charge rate from the panels.

Having a system capable of being either on-grid or off-grid is very unique and advantageous for testing purposes, however not very practical on a tight budget. There are systems which combine grid-tied with battery backup technologies; however the batteries are typically only used in the occurrence when the grid power is offline. The easiest way to implement the desired setup is through a grid-tied inverter which also takes a battery input. When the inverter references the grid and reads no voltage, the batteries would be utilized when no solar power is available. In the system constructed by the team, both were systems were attempted; however the budget was a primary factor in unsuccessful implementation.

Student Survey: Students were surveyed at the end of the semester about the course and the project. The survey was taken by each student in the class (11 total). 94% students found the course materials interesting and motivational, 93% students rated the course very high, and 90% students said that they would take the course again. A summary of the student comments is shown in Table I.

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Conclusions: Semester long projects integrated within the course allows students not only to learn the material on renewable energy, but also to live it. This is very crucial in particular to renewable-energy-based engineering given its historic past and it's promising future. The course provided theoretical background on renewable energy integration and also the opportunity to apply learned principles on a small scale project. Students realized the practical challenges in integration issues and gained insight to tackle these issues in the future, while allowing them to use problem solving skills learned in other disciplines. The team realized some design and equipment selection mistakes, but most importantly know how to combat the issues in future projects. In future years, it will be encouraged that the team use a microprocessor to log data. The project could use four – 125 Watt, 12 Volt panels to provide 12 V, 24 V, 36 V, and 48 V capabilities. Not only did the students learn, but the staff also learned what methods worked well and which had a lesser effect. The program now has the necessary equipment to perform further experimentation in the future, which includes thorough testing of the MPPT controller and of new configurations. Projects can now be executed on a more limited budget and with shorter lead time, allowing more time for experimentation and learning. Overall, the course and the project gave students an introduction to contemporary issues of renewable energy integration, while providing a real-world team environment that students are likely to find themselves in following graduation.

Future Work: This is the first time offering of the course at York College of Pennsylvania. In future, this course would like to add wind energy into the project and design and implement a hybrid renewable energy system. Future students can also continue experimentation on the existing equipment, using knowledge gained by the inaugural class.

Table I: Summary of Student Comments

Course	Project
What did you like most about the class? • The real world applications and need for alternative energy resources. • Showed the need for alternative energy and showed relevance of different types of energy production. • The project was a good way to learn about how to design and build a PV system. • Interesting view into other jobs in ECE	What did you like most about the project? • That we were able to learn about renewable energy by having hands on experience with solar panels, power electronics, and power systems. • The hands on experience of the entire design process. It was neat to see it develop week to week and it was nice to see the issues that are involved with designing a standalone system. • Hands on way to learn about PV system design. No better way to learn other than doing a project like this.
What did you dislike most about the class? • That the class only met once a week • Length of class/ only meeting once a week hard to work on a project only meeting once a week • More guidance and simulation of the project before the ordering of parts. • The tests were a little abstract	What did you dislike most about the project? • Meeting once a week made it difficult to make progress. Also, there are a select few people doing the majority of the work while others are not participating as much. • The breakup of work was certainly an issue. There were a few people doing a ton of work because that is what was necessary for their assignment, while in some cases very little work was done because that is what was required of them. • Difficult to design and implement with the whole class by only meeting once a week for class.
Overall • Overall, this was a very interesting course. It will become more structured as you teach the class. • I really liked the application of alternative energy to the power grid. • Project was by far the best part of the class • Was good for first time teaching it	How would you improve the project? • Having even a set aside 30 minutes during another day of the week, even if just to discuss progress would make communicating within the team better. • Distribution of labor needs to be adjusted some. Gets everyone involved more. • Have more defined short term goals throughout the project timeline • Better definition of overall project goals, a better idea of what the final project should be and have this defined before component selection is completed.

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