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# Development of a Photovoltaic Emergency Power System

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## Abstract

This paper describes the efforts in closing the “skills gap” that exists between the current workforce and the needs in the photovoltaic (PV) industry by educating engineering students through the development of a project for the course titled ‘Photovoltaic Systems’. The aim of the course project is to provide students with the hands-on skills and practical knowledge that will enable them to succeed in the field of solar PV.

“Development of a Photovoltaic Emergency Power System for a Hospital in Malawi” was selected as one of the course projects in the fall of 2012, as requested by an American doctor working in Malawi. The goal of the project was to specify, design, implement, and test a stand-alone solar PV system which supplies electric power in an emergency situation. Students were able to refine system requirements, determine the energy produced by the solar panels based on the solar irradiance at different tilt and azimuth angles, and properly size the system. In May 2013, the system was successfully installed in the Embangweni hospital located in Malawi. Since then, it has operated smoothly and effectively. The details of the development of the course project will be presented in the paper along with both direct and indirect assessments of the outcome of the project.

## Introduction

Tremendous efforts have been made to develop alternative energy technologies in response to the increasing shortage of fossil fuels and the increasing emissions of greenhouse gases and other pollutants. Solar energy offers the potential to provide a clean, reliable, and more sustainable energy future. With the cost reductions in photovoltaic (PV) technology and installment, solar power is rapidly growing and becoming increasingly affordable. In the report ‘Green Jobs: Towards Decent Work in a Sustainable, Low-Carbon World’, the United Nations predict that 6.3 million solar PV jobs worldwide will be expected by 2030[1]. The Solar Foundation’s National Solar Jobs Census 2014 found that the solar industry continues to exceed growth expectations, adding workers at a rate nearly 20 times faster than the rate of the overall economy[2]. Several countries have reported a “skills gap” that exists between the current workforce and the needs of the PV industry[3]. To respond to the industry needs and to close this “skills gap”, a course titled ‘Photovoltaic Systems’ was developed in the School of Engineering at Grand Valley State University. This course aims to teach students the fundamentals of PV systems and provide them with hands-on skills and practical knowledge that will enable them to succeed in the field of solar PV.

This paper first describes the objectives and contents of the course and then presents the implementation of one of the course projects. In the end, both direct and indirect assessments of the outcome of the project are provided.

## Course Overview

'Photovoltaic Systems' is an electrical engineering course targeted towards graduate and selected undergraduate students. The goal of the course is to introduce students to the field of photovoltaics. The course begins with the fundamentals of semiconductors, solar radiation, and the operation of solar cells. It introduces students to the architectures of different PV systems and system components such as batteries, inverters, solar panels, etc. It provides technical, practical, and economic considerations in designing PV systems. Upon completion of this course, students will be able to:

1. Demonstrate an understanding of the operating principles of solar cells;
2. Calculate the power produced by the PV module as a function of module tilt and azimuth angle;
3. Describe the basic components and main performance parameters of PV systems;
4. Design, troubleshoot, and test PV systems;
5. Effectively communicate technical concepts.

To provide students with hands-on and real-world experiences, a major course project is included. The objective of the project is to introduce students to the process of product design and realization, and more specifically, (1) to generate system requirements, specification documents, design documents, and test plans; (2) to properly size system components such as batteries, inverters, charge controllers, and solar panels for a specific location; and (3) to test and troubleshoot a PV system.

Before the semester starts, the course project solicitation is posted and project proposals from both for-profit and non-profit organizations are collected. After careful review, proper projects are identified. Each project is then assigned to a team of three students. For the 2012 course offering, two such projects were selected. One was to develop a photovoltaic emergency power system (PVEPS) for the Embangweni hospital in Malawi as requested by an American doctor working in Malawi. The goal of the project was to specify, design, implement, and test a stand-alone solar PV system which supplies electric power in an emergency situation.

## Background of the Malawi Project

Over 90% of Malawi's electricity comes from hydroelectric power plants. The power generated from these power plants cannot meet the basic essential demands of the population. As a result, scheduled rolling blackouts are implemented[4]. This issue plus the frequent unscheduled power outages has created a devastating situation in many fields, especially in medical facilities. For example, in the middle of child birth, power outages often occur and doctors are forced to deliver babies under the light of flashlights and carry out suctions manually. Doctors have lost countless patients on the operation table due to the power outages. This project was intended to improve the situation in the Embangweni hospital and to provide a unit that would be used in the operation room when the power goes out.

**System Requirements Refinement**

Based on the project proposal, students met with Dr. Martha Sommers, who had been working in Embangweni hospital for over 15 years, over video chat to further refine the system specifications. Table 1 shows the finalized PVEPS system requirements.

Table 1 PV emergency power system requirements

| ID | Requirements |
|---|---|
| 1 | Power generated by solar panel(s) shall be stored in lead-acid AGM batteries |
| 2 | The batteries shall be able to power the following devices for two consecutive days:<br>1. Two White LED lights (continuous)<br>2. The suction machine (used 3 hrs. each day)<br>3. Two "car-charging sockets" for charging 12VDC appliances (used 3 hrs. each day)<br>4. One 5V DC USB charger for charging cell phones and tablets |
| 3 | The system shall contain on/off switches to individually control each appliance |
| 4 | The system shall display the status and usage of the batteries |
| 5 | The system shall contain a back-up charge system that can charge the batteries during the rainy season in Malawi (4 months) |
| 6 | The system, with exception of the solar panel(s) and associated wires, shall be self-contained in a single container |
| 7 | The mobile container shall meet the check-in luggage requirements of airlines |

In addition to the above requirements, the following assumptions were derived to supplement them:

- The system will have circuit breakers
- The full charge recovery time of the system will be within two days (days of autonomy)
- The wall power supply for the system will be compliant with the European standard of 220-240V 50Hz
- All parts will be compliant with export laws for use within Malawi
- Battery life time will be at least 2 years
- Budget: $1000

**The PV system design**

After learning the operations of solar cells, solar radiation, architectures of stand-alone PV systems, and how to properly size each system component, students developed the system level schematic based on the system requirements. Figure 1 depicts the system schematic of the PVEPS.

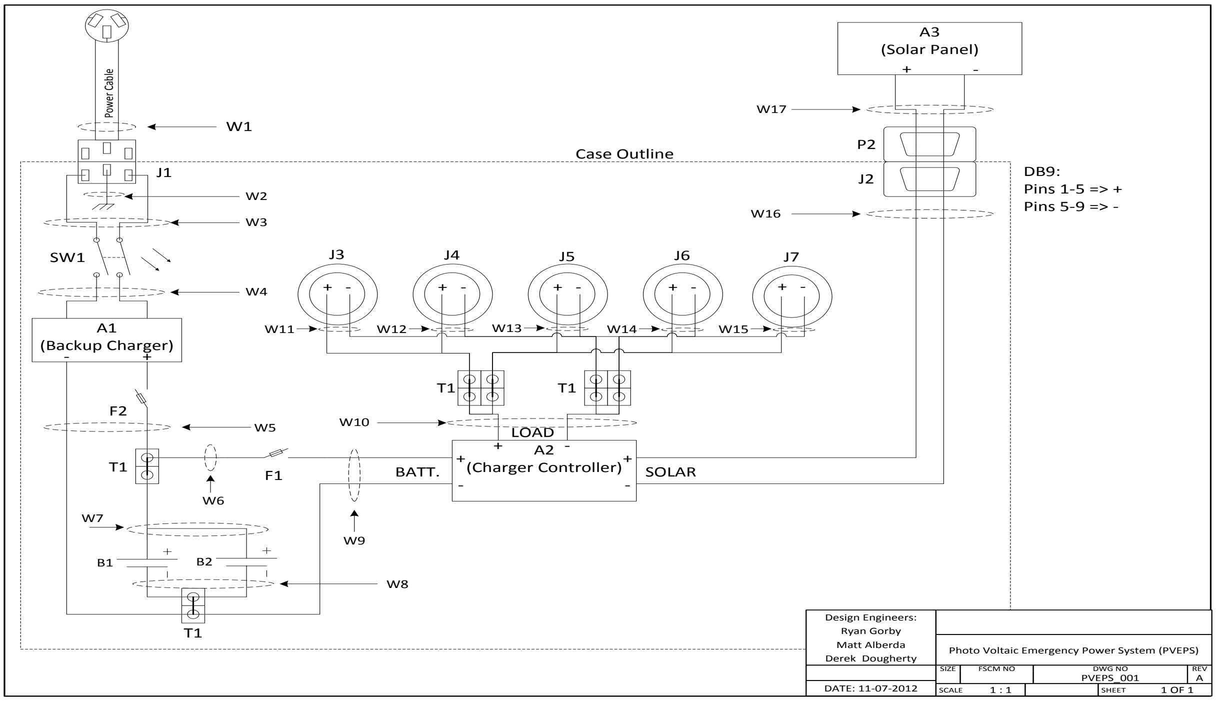


Figure 1 the system level schematic of the PVEPS

The detailed component level design is described in the following subsections.

*Load Requirements*

When designing a PV system, the first objective is to determine the energy required by the loads. The specific loads were not defined in the project requirements and were selected based on the performance and cost. The system voltage was chosen to be 12 volts, based on standard 12V AGM lead acid batteries. Two rechargeable LED lights and two DC socket outlets were selected. For the suction machine, either AC or DC power supply units could be used. After comparing the energy consumption of the two types, it was determined that the DC powered suction machine would be the best choice for the portable system. The daily energy requirement of each load is summarized in Table 2.

Table 2 The daily energy requirement of the loads

| **DC Loads** | **Nominal Current (Amps)** | **Nominal Voltage (Volts)** | **Nominal Power (Watts)** | **Daily Energy Requirement (Wh)** |
|---|---|---|---|---|
| Lamp 1 | 0.20 | 12.00 | 2.40 | 28.80 |
| Lamp 2 | 0.20 | 12.00 | 2.40 | 28.80 |
| Socket 1 | 0.50 | 12.00 | 6.00 | 18 |
| Socket 2 | 0.50 | 12.00 | 6.00 | 18 |
| DC Suction Machine | 3.00 | 12.00 | 36.00 | 108 |
| | **DC Current Totals:** 4.44 | | **DC Pwr. Totals:** 53.28 | **Total Daily Energy:** 201.60 |

*Energy storage consideration*

Energy generated from the sun is inherently variable with time. Therefore, most of the standalone PV systems utilize battery systems to store the generated energy and to provide sufficient energy for the load. Due to their wide availability and cost effectiveness, lead-acid battery is often the choice for the PV systems. To size the batteries for a specific system, the total capacity of the battery needs to be determined. The capacity of a battery is rated in total charge storage capability. The common unit for rating charge capacity of a battery is amp hour. The total amp hour required for a system can be found from equation 1.

AH = DOA * (DLE / IE / Sys_V) Eqn. 1

Where AH is the total amp hour, DOA is days of autonomy, DLE is daily load energy, IE is the inverter efficiency, and Sys_V is the system voltage. IE = 1 if no inverter is included.

The total capacity required for the battery was calculated to be 33.60Ah. The batteries used in the PV systems are often deep-cycle lead acid batteries. To balance the lifetime and cost, the battery was kept at 50% discharge, which resulted in a capacity of 70Ah. Two Sun Xtender PVX-420Ts batteries were selected for use in this system, each with a capacity of 42Ah. The two batteries were connected in parallel to provide the total required charge and to minimize the total space required.

*Sizing the solar panel*

Proper sizing of the PV Panel ensures that the system can be recharged and is able to deliver the required energy in the specified days of recovery. Three main factors are to be considered: total daily energy, solar insolation, and the solar generation factor. These factors are related by equation 2:

$$RPP = \frac{Q_{pv}}{PSH} * \frac{1}{K_{gen}} \quad \text{Eqn. 2}$$

Where RPP = Required Panel Power, $Q_{pv}$ = Total Daily Energy, PSH= Peak Sun Hour, and $K_{gen}$ = Generation Factor

The Total Daily Energy, $Q_{pv,}$ is the daily energy required by the loads. This is the energy the PV system needs to supply during the solar charging cycle. The generation factor, $K_{gen}$, takes into consideration the system loss, such as the energy loss in cables, charge controller, and battery. A typical value of 30% was selected.

The solar charging cycle is determined by the total daily solar irradiance divided by 1kW/m$^2$/day, which is denoted as Peak Sun Hours (PSH). The average solar insolation at different tilt angles for Lilongwe, Malawi is shown in

Table 3[5]. It can be seen that for a fixed angle system an optimal tilt angle is 28$^o$ at which an average solar insolation of 5.78 kWh/ m$^2$/day is supplied.

Table 3 Monthly Averaged Solar Insolation (kWh/m$^2$/day) for Lilongwe, Malawi[5]

| Lat -13.983 Lon 33.94 | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Annual Average |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SSE HRZ | 5.17 | 5.35 | 5.53 | 5.48 | 5.25 | 4.96 | 5.07 | 5.67 | 6.48 | 6.67 | 6.24 | 5.38 | 5.60 |
| K | 0.45 | 0.48 | 0.53 | 0.59 | 0.63 | 0.64 | 0.64 | 0.64 | 0.65 | 0.62 | 0.56 | 0.47 | 0.58 |
| Diffuse | 2.48 | 2.43 | 2.13 | 1.69 | 1.29 | 1.14 | 1.21 | 1.38 | 1.59 | 1.97 | 2.28 | 2.44 | 1.83 |
| Direct | 3.86 | 4.14 | 4.90 | 5.81 | 6.61 | 6.69 | 6.62 | 6.79 | 7.18 | 6.68 | 5.65 | 4.23 | 5.77 |
| Tilt 0 | 5.06 | 5.25 | 5.45 | 5.42 | 5.21 | 4.92 | 5.03 | 5.62 | 6.40 | 6.56 | 6.11 | 5.26 | 5.52 |
| Tilt 13 | 5.09 | 5.13 | 5.50 | 5.74 | 5.81 | 5.64 | 5.70 | 6.10 | 6.61 | 6.45 | 6.15 | 5.32 | 5.77 |
| Tilt 28 | 4.91 | 4.77 | 5.30 | 5.83 | 6.21 | 6.18 | 6.17 | 6.35 | 6.51 | 6.02 | 5.91 | 5.16 | 5.78 |
| Tilt 90 | 2.24 | 1.74 | 2.23 | 3.26 | 4.31 | 4.72 | 4.51 | 3.90 | 2.90 | 1.83 | 2.39 | 2.40 | 3.04 |
| OPT | 5.10 | 5.25 | 5.51 | 5.84 | 6.29 | 6.38 | 6.30 | 6.36 | 6.61 | 6.56 | 6.16 | 5.32 | 5.98 |
| OPT ANG | 9.00 | 0.00 | 9.00 | 25.0 | 38.0 | 43.0 | 41.0 | 31.0 | 17.0 | 1.00 | 9.00 | 11.0 | 19.6 |

The required panel power for the system was calculated to be 49.83W. A single 50W solar panel would meet the system requirements and still be easily mobile.

*Power conditioning and control*

A device is needed to regulate the power from the solar panel, to manage charging/discharging batteries, and to control the charge flow between the source and load. Such a device is called a solar charge controller. Solar charge controllers need to have the properties listed in Table 4 and be sized properly based on the rated power of the solar panel and the system voltage. Due to the cold temperature and the "edge of the cloud" effect, the solar panel could potentially supply current higher than that of the rated current. To accommodate this, a 25% current is added on top of the required current. In this project, a maximum of two 50W solar panels could be connected to the system. The current required of the solar charge controller would be 100W/12V (1+25%) = 10.42 A.  The Morningstar ProStar PS-15 charge controller which has the current capability of 15A was selected for the system.

Table 4 Basic requirements of the solar charge controller

| **Basic requirements of a charge controller** |
|---|
| Battery status and faults indication |
| Short-circuit protection — solar panel and load |
| Overload protection – solar panel and load |
| Reverse polarity protection |
| Reverse current protection at night |
| High voltage disconnect |
| High temperature disconnect |
| Lightning and transient surge protection |

*Packaging*

A Pelican 1550 case was selected to hold most of the components, and 3D modeling was carried out using Solid Works to ensure all critical parts were fitted together. Figure 2a shows the front panel design and Figure 2b shows the 3D model of the system. The photo of the assembled system is shown in Figure 3.

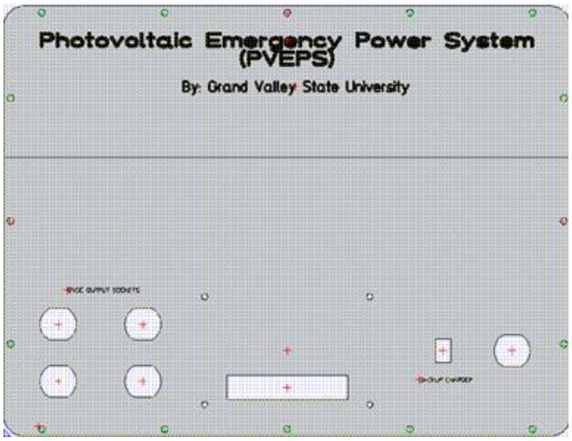


Figure 2a The front panel design

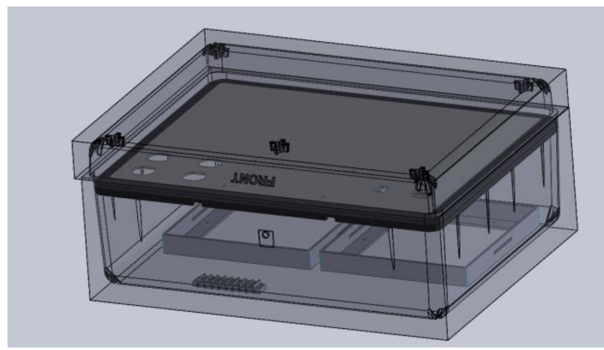

Figure 2b 3D model of the system package

Figure 3 The photo of the PV emergency power system

*System Testing*

The system was tested against the system requirements. The tested parameters were load capacities under different load conditions, solar panel open-circuit voltage, short-circuit current, charging currents, and maximum power under different light conditions. The test results warranted that the system met all the design requirements.

## Project Assessment

Since the focus of the project is on PV system design and the design process in general and not on the particular product at hand, students were assessed directly on the ability to apply the learned concepts and knowledge in class. All students were able to develop the system schematics and properly size the system components including the battery, the solar charge controller, the solar panel, and the cabling. Students were also assessed on their ability to follow the design process. All students were able to define the system requirements, write the system specifications and the design documents, and build and test the prototype. The system was delivered to the Embangweni hospital in May 2013 and has functioned well since then.

Indirect assessment was also assessed through the feedback from both the students and the hospital personnel. During the end of the term student evaluation, all students thought that the class was taught well and enjoyed taking the class. Some of the comments on the project were:

- I do appreciate that the project was well-defined by the instructor, has real world implications and provides a critical need for the hospital in Malawi.
- Knowing our hard work may provide someone a second chance at life is the greatest reward for us.

The feedback from the Embangweni hospital was extremely positive. They were excited when the unit was installed and were more excited when it was in use. The system is used every Sunday and frequently during the week when there are power outages. Since the system was a great success, more systems with minor improvements are desired. This year, three improved PVEPSs will be designed, built, and delivered to the Embangweni hospital.

## Conclusions

A project was developed for the electrical engineering graduate course to design and build a PV emergency power system for a hospital in Malawi, Africa. Throughout the project, students learned to apply the concepts and knowledge learned in class to solve real-world problems. Students were able to refine system requirements and write system specifications and design documents while also gaining hands-on experiences. The system was designed and each component was properly sized and selected. After testing, the unit was delivered to the Embangweni hospital in Malawi and has operated smoothly since. The feedback from both the students and the hospital was extremely positive. Lessons learned from the 2012 course offering have been incorporated into the course.

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