Design and development of a solar powered mobile laboratory

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Abstract. This paper describes the design and development of a solar powered mobile laboratory (SPML) system. The SPML provides a mobile platform that schools, universities, and communities can use to give students and staff access to laboratory environments where dedicated laboratories are not available. The lab includes equipment like 3D printers, computers, and soldering stations. The primary power source of the system is solar PV which allows the laboratory to be operated in places where the grid power is not readily available or not sufficient to power all the equipment. The main system components include PV panels, junction box, battery, charge controller, and inverter. Not only is it used to teach students and staff how to use the lab equipment, but it is also a great tool to educate the public about solar PV technologies.

1. Introduction

Our climate is changing. According to the data collected at NASA’s Goddard Institute for Space Studies (GISS), the average global temperature has increased by 0.8°C since 1880, two thirds of which has occurred since 1975 at a rate of 0.15°C-0.2°C per decade [1]. This temperature increase is mainly caused by the emission of greenhouse gasses, 25% of which are accounted for by energy production [2]. Despite the fact that increasing awareness of climate change has led to initiatives from governments, businesses, and the society to tackle this problem, greenhouse gas emissions have not been reduced to safe levels. The global temperature is predicted to continue to increase between 3.7°C and 4.8°C by 100 [3], which would lead to serious consequences for food security, fresh water availability, and the frequency and intensity of storms [4]. To reach the goal of keeping global warming below 2°C, greenhouse gas emissions need to be reduced by 40%-70% by 2050 compared to the levels in 2010 [5]. This is an ambitious goal. To make this happen, seeking alternative renewable energy sources and further increasing the awareness of the importance of adapting to renewable energy is necessary in preventing climate change.

Solar energy is the most clean, abundant, and renewable alternative energy resource available. Solar photovoltaic (PV) is viewed as a quick, scalable, and sustainable solution to mitigate climate change. In many countries, the initiative of solar installation is one of the most prevalent issues that their governments are reaching out to solve. According to Green Tech Media research, global solar PV installations have grown 34% in 2015 compared to that in 2014 [6]. The US installed 7.26 GW of PV in 2015, 16% above that in 2014[7]. In Germany, PV-generated energy amounted to 34.9 TWh in 2014 and covered approximately 5.7% of Germany’s net electricity consumption8. Studies have also

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been carried out on the stand-alone PV systems. Benghanem et al. reported a methodology for setting up several PV water pumping systems for irrigation purposes in Algeria [9]. Song et al. designed stand-alone PV systems to power aerators for natural purification of acid mine drainage [10]. Sakiliba et al. assessed the stand-alone residential solar PV applications in sub-saharan Africa [11]. Most of these studies focused on the applications of the solar PV not on educating the public about PV technologies. In addition, most installations occurring in remote regions hinder the public knowledge of the renewables used. We have developed a solar powered mobile laboratory (SPML) that can be used to showcase PV technologies and help educate both the public and students on the importance of solar PV.

The SPML is a mobile platform that provides an alternative and flexible method for schools, universities, and communities to give students and staff access to laboratory environments. The primary power source of the SPML is solar PV which allows the laboratory to be operated in places where the grid power is not readily available or is not sufficient to power all the equipment. In the SPML, the grid electricity is used to supplement the solar power.

In this paper, detailed design and development of the solar powered mobile laboratory will be presented.

2. System Requirements and Functional Specifications
After studying a list of typical laboratory equipment, the system requirements and functional specifications were determined and listed in Table 1.

| Alternative Power System requirements |
|--------------------------------------|
| 001 The primary power of the SPML system shall be supplied by the solar PV. |
| 002 The SPML system shall be capable of receiving power from grid through two NEMA 5-15 receptacles when: the solar power system is not capable of supplying power AND two NEMA 5-15 receptacles are available on the site where the system is deployed. |

| Circuit requirements |
|----------------------|
| 003 Two power receptacles shall be provided for charging two laptop computers. |
| 004 Two power receptacles shall be provided for charging two cellular telephones. |
| 005 Two power receptacle shall be provided for two soldering station. |
| 006 One power receptacle shall be provided for one laser engraver. |
| 007 One power receptacle shall be provided for one ventilation system dedicated to the laser engraver. |
| 008 One power receptacle shall be provided for one projector. |
| 009 Two power receptacles shall be provided for two 3D Printers. |
| 010 One power receptacle shall be provided for charging one tablet computer. |
| 011 Two power receptacles shall be provided for two desktop computers. |

| Monitoring and Control requirements |
|------------------------------------|
| 012 The SPML system shall be capable of operating when exposed to environmental conditions typical to Pennsylvania for the months of February through October. |

| Solar Power and Storage System requirements |
|--------------------------------------------|
| 013 The SPML system shall have an array of three to five solar panels capable of charging a battery bank. |
| 014 The solar panel array shall be mounted to the roof of a vehicle and fold flat for transport. |
| 015 The SPML system shall have a bank of batteries capable of powering the LED lighting, two Cube 3 3D printers, one iMac desktop PC, and two soldering stations for three hours |
016 The SPML system shall have an inverter capable of converting the DC power of the solar panels to AC power.

3. System Architecture
The functional block diagram of the SPML is shown in Figure 1. Solar PV modules are used to generate direct electric current (DC) upon exposure to solar radiation. The outputs of the PV modules are connected through the junction box. The battery is used to store and regulate energy generated by the PV modules. The charge controller provides the maximum power point tracking (MPPT) function and controls the charging and discharging of the battery. To be compatible with the load power requirements, the inverter converts the DC power to AC power. The switch is used to automatically switch the grid connection to the inverter if sufficient solar energy is available.

![Functional block diagram of the SPML](image)

Figure 1. Functional block diagram of the SPML

4. System Design
This section provides the detailed design of each component of the solar powered mobile laboratory system. The design is based on the IEEE standards for sizing PV components in stand-alone PV systems [12].

4.1 Determination of Load Energy Requirements
The devices that were selected to be powered by the solar power are the LED lighting, two 3D printers, an iMac computer that controls the 3D printers, and two 40W soldering stations. These were chosen because they were identified as important, high-use loads and the power consumption is low enough to ensure proper operation for three hours with a small number of PV modules. The average power consumption is 402W and the average energy consumption for a three-hour operation is 1206Wh.

4.2 Sizing the Inverter
With an average power consumption of 402W, an inverter of 2000W with an efficiency of 94% was selected. It is sufficient to cover any starting power surge and leave room for future expansion.

4.3 Sizing the Battery
Since solar energy inherently varies with time, most of the stand-alone PV systems incorporate batteries to store the generated energy and to provide sufficient energy for the required load. The daily energy needed by the load of the battery consists of the load energy consumption and the energy losses of the inverter and wiring. Considering a typical 2% loss in the wires, the daily load on the battery is calculated to be

\[ 1206 \frac{W}{h} / 94\% / (1 - 2\%) = 1309 \frac{Wh}{day}. \]

The required capacity of the battery can be computed from Equation 1 where factors of days of autonomy, battery charge/discharge losses, depth of discharge, and losses due to the lower operation temperature are taken into consideration:

\[
\text{Capacity (Ah)} = \frac{\text{Wh/day}}{V_b} \frac{\text{DOA}}{D_T D_{ch} DOD} \quad \text{------------------------ (1)}
\]

Where \(V_b\) is the battery voltage, \(D_T\) is the temperature derating factor, \(D_{ch}\) is the charge/discharge derating factor, DOA is the number of days of autonomy, and DOD is the depth of discharge. Assuming a combined 12% loss from low temperature operation and battery charge/discharge, one day of autonomy, and 70% of depth of discharge, the capacity required for a 12V battery is 177Ah. A 12V 200Ah deep cycle AGM battery was selected for this system.

### 4.4 Sizing the PV Panel

Proper sizing of the PV panel ensures that the system is recharged and able to deliver the required energy in the specified days of recovery. The required panel power is determined by the total daily energy need, solar irradiation, solar panel losses, and losses in wiring and the charge controller. Since solar irradiation changes with time, monthly average daily irradiation is often used. The SPML system will be deployed in the Pittsburgh region; hence, the solar irradiation in Pittsburgh is referenced and can be found in Table 2, where the monthly average daily irradiation and the yearly average daily irradiation are shown for the panel tilt angles of 0°, latitude – 15°, latitude, latitude + 15°, and 90°, respectively.

Table 2. Solar Radiation for Flat-Plate Collectors Facing South at a Fixed Tilt (KWh/m²/day)

| Tilt (°) | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Year |
|---------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|------|
| 0       | 1.7 | 2.5 | 3.5 | 4.6 | 5.5 | 6.1 | 5.9 | 5.2 | 4.2 | 3.0 | 1.8 | 1.4 | 3.8  |
| Lat. -15| 2.4 | 3.2 | 4.1 | 4.9 | 5.5 | 5.9 | 5.9 | 5.5 | 4.8 | 3.8 | 2.4 | 1.9 | 4.2  |
| Lat. 2.6 | 3.4 | 4.2 | 4.8 | 5.2 | 5.4 | 5.5 | 5.3 | 4.8 | 4.1 | 2.6 | 2.1 | 4.2  |
| Lat. +15| 2.7 | 3.5 | 4.1 | 4.4 | 4.6 | 4.7 | 4.8 | 4.8 | 4.6 | 4.1 | 2.7 | 2.2 | 3.9  |
| 90      | 2.5 | 3.0 | 3.1 | 3.1 | 2.9 | 2.5 | 2.6 | 2.9 | 3.2 | 3.3 | 2.3 | 2.0 | 2.7  |

It can be seen from Table 2 that in the time frame of February to October, the lowest average daily irradiation is 3.5 PSH when the panel is tilted at an angle equal to (latitude + 15° = 55°). The decision to go with the fixed tilt angle instead of one- or two-axis tracking is based on the available space for the tracking mount and cost. When deployed in a site, the system will be parked to ensure that the panels are facing south and tilted at an angle of 55° from the horizontal.
Assuming a 12% loss in wiring and the charge controller, the required panel power is determined to be
\[
\frac{1309\text{ Wh/day}}{\frac{88\% \times 88\% \times 3.5\text{ PSH}}{100}} = 483\text{ W/day}.
\]
Three 160W PV panels would meet the daily energy needs of the required loads.

4.5 Sizing the Charge Controller

The main requirements of the charge controller are: (1) it can charge a 12V battery bank; (2) it can handle the combined current output of the 3 solar panels in parallel; (3) it has the ability to disconnect the battery bank from connected loads if the batteries drop below a certain voltage. The total current from the three parallel-connected panels is 40A. The Conext MPPT 60-150 charge controller, which has a rated input current of 60A, was selected for the SPML system. This MPPT controller has separate wire terminals for the array, battery bank, and a low power auxiliary output which enables the controller to disconnect the load when the batteries discharge to a programmable voltage. This auxiliary output will be used to switch a relay that disconnects the inverter from the battery bank when the batteries reach a programmed low voltage limit. As the current output of the auxiliary output is limited, a small pre-stage relay is required to drive the coil of a larger relay, which will be the one to disconnect the inverter from the batteries.

4.6 Balance of System (BOS) Design

The required current capacity, minimum required wire gauge, and the number of conductors for the solar powered mobile laboratory are summarized in Table 3. The DC wiring and AC wiring are sized to handle 156% and 125% of the peak current, respectively, per the National Electrical Code (NEC), except where an equipment manufacture specifies a current limit. All ground wires are 6AWG bare stranded wire.

| Cable Position                        | Max Current (A) | NEC (A) | Min Wire (AWG) | Size Conductors |
|---------------------------------------|-----------------|---------|----------------|-----------------|
| 1. Solar Modules to Combiner          | 9.60            | 14.98   | 14             | 10              |
| 2. Combiner to Charge Controller      | 48.00           | 74.88   | 6              | 2               |
| 3. Charge Controller to Battery       | 48.00           | 74.88   | 6              | 2               |
| Breaker                               |                 |         |                |                 |
| 4. Battery Breaker to Battery Bank    | 52.83           | 82.41   | 4              | 2               |
| 5. Battery bank to Inverter           | 52.83           | 82.41   | 4              | 2               |
| 6. Inverter to Transfer Switch        | 16.67           | 20.84   | 10             | 2               |
| 7. Transfer Switch to Load Center     | 16.67           | 20.84   | 10             | 2               |
| All Ground Wires                      |                 | 6       | 1              |

4.7 Junction Box, Disconnect, and Load Center Enclosure designs

A Junction box was selected to combine the power from the three solar panels. The short circuit current of each module is about 9.6A. Each string is connected to a 15A DC breaker with 14AWG conductors in the junction box. An enclosure was designed to host the various DC circuit breakers and bus bars that are used to protect and disconnect the equipment in the system. One such breaker is a 60A circuit breaker that is used to disconnect the solar array. In order to handle the 48A current from the solar array, the size of the conductors between this breaker and the charge controller is 6AWG. The load disconnect relays are mounted in a small enclosure that can be mounted close to the inverter. The system also has a circuit load center for the connection of AC load. Since the peak continuous AC current that the inverter can supply is 16.67A, all AC circuits downstream of the inverter were sized
with 10AWG conductors. All specified loads will be located on the same circuit and will be protected by a 15A breaker. The cabling from the AC load center panel to the specific devices can be standard 14AWG indoor wiring.

5. System Schematic
The detailed circuit schematic of the SPML is illustrated in Figure 2. Five 160W solar panels were incorporated in the schematic to provide room for future expansion.

6. System Testing
The system was built and tested according to the IEEE Standards.\textsuperscript{15} The tested parameters were load capacities under different load conditions, inverter efficiency, battery charging currents, and maximum

\textbf{Figure 2.} Circuit schematic of the SPML
power under different light conditions. The test results warranted that the system met all the design requirements.

7. Conclusions
A 480W solar powered mobile laboratory was successfully designed and built. The SPML is a mobile platform that provides an alternative and flexible method for schools, universities, and communities to grant students and staff access to laboratory environments. The lab provides equipment like 3D printers, computers, and soldering stations. The primary power of the system was supplied by three 160W solar PV modules connected in parallel. The grid electricity is used to supplement the solar power. To provide consistent power to the required loads, a 200Ah battery was included. To properly charge/discharge the battery, a 60A MPPT charge controller was selected. A 2000W inverter was sized to convert the DC power from the battery to the AC power required by the lab equipment. A relay is designed to disconnect the inverter when the battery voltage reaches its low voltage limit. In addition to teaching students and staff how to use the lab equipment, the SPML is a great tool to educate the public about solar PV technologies.

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