Background

The objectives of this experiment are:

- To characterize the laboratory photovoltaic panels, and find numerical parameters of the equivalent circuit model for use later in the semester.
- To test the sine wave inverter provided.
- To charge the deep-discharge lead-acid batter using the Direct Energy Transfer approach.

This experiment is designed for the mobile PV carts of the ECEN4517/5517 lab, and it requires a sunny day! In case of bad weather, follow the directions in the appendix at the end of this document.

A schematic of the electrical circuitry in the mobile cart is given below.

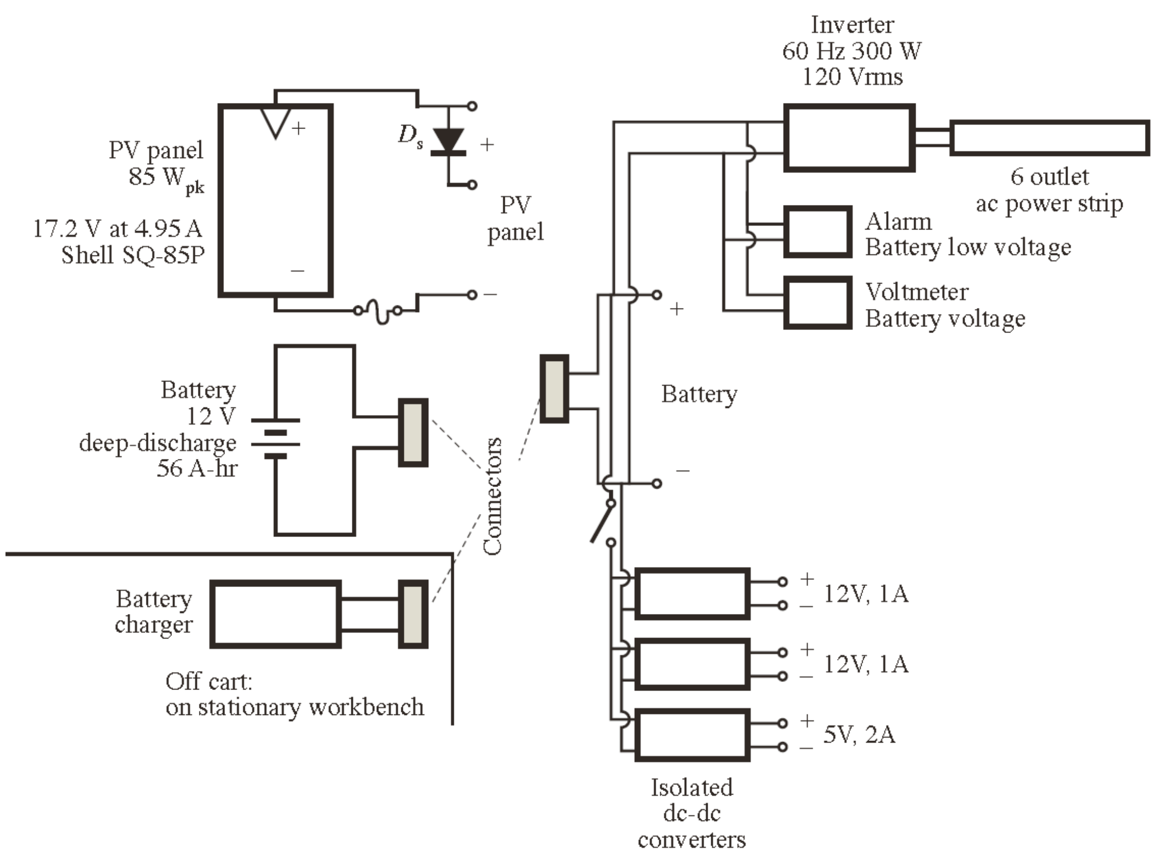

Figure 1: Electrical diagram of the laboratory photovoltaic (PV) cart.

The cart includes an inverter for powering test equipment such as oscilloscopes and meters, as well as isolated dc-dc converters for powering electronic circuitry. At the beginning of the lab session, unplug the battery from the battery charger, and plug it into the cart to power the inverter and dc-dc converters.

Batteries

The batteries used in this laboratory are valve-regulated absorbent glass mat (VR-AGM) sealed lead-acid batteries, intended for deep-discharge solar power system applications. They are rated 56 amp-hours and 12 V; a fully-charged battery can be discharged at a constant 2.33 A rate, and will last for 24 hours before becoming fully discharged, for a total capacity of (2.33 A)(24 hrs) = 56 A-hrs. The batteries contain six series-connected cells; each cell voltage is 2.4 V when fully charged and 1.75 V when fully discharged (at 25 deg C).

Battery life, or the number of charge/discharge cycles, is a function of the depth of discharge. It is undesirable to fully discharge the battery, because this reduces the battery life. On the laboratory PV carts, a buzzer will sound when the state of charge falls to approximately 50%; please do not discharge the battery beyond this point. You will be able to get approximately 250 W-hrs from a fully charged battery before the buzzer sounds.

Table 1: Battery state of charge (SOC) versus terminal voltage under equilibrium open-circuit conditions.

State of Charge (SOC)	Terminal Voltage
100%	12.80 V or greater
75%	12.55 V
50%	12.20 V
25%	11.75 V
0%	10.50 V

PV panel

The SQ85 PV panels consist of 36 series-connected silicon cells, arranged as follows. The left half of the panel contains 18 series-connected cells, protected by a single backplane diode. The right half of the panel contains the remaining 18 series-connected cells, with a second backplane diode. Both of these are connected in series. These connections are illustrated in Fig. 2.

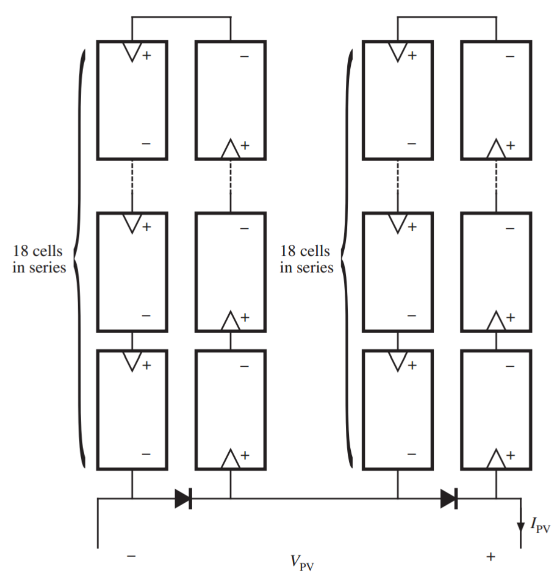

Figure 2: Connections of the 36 individual silicon PV cells and the two backplane diodes within the SQ-85P panel.

Laboratory Procedure

1. If you haven't done so already, unplug the battery from the bench battery charger, and plug it into the cart to power the inverter and dc-dc converters. Record (and understand) the specifications printed on the nameplate of the photovoltaic panel.

2. You will need at least the following items; load them onto the cart: a rheostat for loading the PV panel, a light bulb for loading the inverter, test leads with banana plugs, two multimeters (at least one having a 10 A or 20 A scale), and an ac power meter. You may also power other instruments, laptop computers, etc. from the cart inverter. Wheel the cart outside, to a sunny location.

3. Record the battery voltage and the time of day. Then turn on the inverter, and load the inverter output using the light bulb provided, along with any other instruments (multimeters etc.) that you intend to use. Use the ac power monitor ("Kill-a-Watt") to measure the inverter output power. Record all readings of the ac power monitor. Reset the ac power monitor, and set it to start recording energy (kW-hr) consumed. Continue with the remainder of the experiment, with the inverter continuing to be loaded. You will use this data to calculate the total energy consumed, and to estimate the depth of discharge of the battery.

PV panel characteristics

4. Orient the cart and the panel angle so that the panel faces the sun. Measure the solar irradiance using a pyranometer obtained from your TA (we only have a few of these in the lab but this step only takes a minute—if necessary, perform this measurement later). Connect the rheostat to the panel output, with meters to measure the panel voltage and current. Adjust the rheostat, cart orientation, and panel angle, as necessary to maximize the power output of the panel. Record the voltage, current, and time of day.

5. Measure a complete *i-v* curve, including the short-circuit current, open-circuit voltage, maximum power point, and enough other points to obtain a reasonable experimental *i-v* curve.

6. Cover four cells along the left side of the panel, and repeat steps 4 and 5.

7. When you are done with step 6, then record the energy consumed reading of the ac power monitor at the inverter output. Remove the load from the inverter, and record the time of day and the battery voltage.

Charging the battery

8. Do not overcharge the battery! Overcharging causes outgassing and can damage the battery. At the beginning of the experiment, the battery is fully charged, so this step should not be attempted until you have partially discharged the battery by operation of the inverter for several minutes or more.

   Connect the PV panel through the series diode D_s (built into the cart, as shown in Fig. 1) to the battery. Be sure to connect the negative terminal of the panel to the negative terminal of the battery, and the positive terminal of the panel (through the diode D_s) to the positive terminal of the battery. Measure the panel voltage and current, and record your readings. Does the PV panel operate at its maximum power point?

9. Fold down the PV panel, and return the cart to its dock underneath your lab bench. Disconnect the battery from the cart, and plug it into the battery charger. Check with your TA to make sure that the battery charger is set to the correct charge profile; incorrect settings may overcharge the battery and damage it.

Calculations

10. Go to the NREL website at http://www.nrel.gov/midc/srrl_bms/display/ and estimate the direct normal insolation at the time that you made your maximum power measurement of step 4. Calculate the estimated panel efficiency.

11. Plot the *i*-*v* curves measured in steps 5 and 6.

12. The standard electrical equivalent circuit model for a photovoltaic cell is illustrated in Fig. 3. The current source I_0 models the photo-generated current, and is approximately proportional to the solar irradiation (insolation). The diode exhibits an exponential *i*-*v* characteristic, according to the conventional diode equation:

$$I_D = I_{D0}\left(e^{V_D/V_{TH}} - 1\right),$$

where $V_{TH} = kT/q$ = 26 mV at room temperature. Resistor R_p models current due to leakage and defects, and is usually of large value. Resistor R_s models bulk and contact resistance.

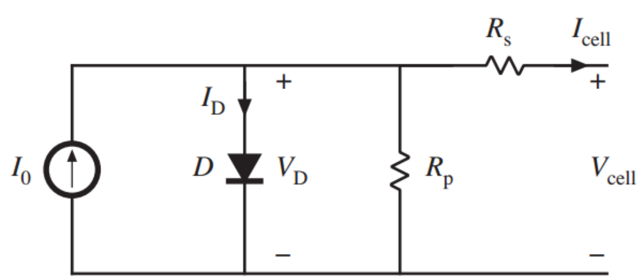

Figure 3: Equivalent circuit model of a photovoltaic cell.

Find values of I_0, I_{D0}, R_p, and R_s, such that the model of Fig. 3 predicts the curve you measured in step 5. You may assume that all cells are identical, so that the total panel voltage V_{PV} is equal to 36 times the voltage of one cell V_{cell}. Plot the *i*-*v* characteristic predicted by your model, and overlay your experimental data points. Compare the model-predicted open-circuit voltage, short-circuit current, and maximum power point voltage and current, with your measured data. You may use LTspice or MATLAB (both provided on the lab computers) to assist with this part.

13. Use your model to plot the predicted panel *i*-*v* characteristics when all cells are uniformly illuminated at 250, 500, 750, and 1000 W/m^2. Also plot the power vs. voltage characteristics.

14. Assume that I_0 in your model of step 12 is proportional to insolation. Plot the *i-v* curve predicted by your model for the conditions of step 6, and overlay your measured data points. Does your model agree with your measured data? Which, if any, backplane diodes conduct? Plot the power vs. voltage characteristic, and find the voltage and current at which maximum power is generated for the conditions of step 6.

15. Use your data recorded in steps 3 and 7, along with the manufacturer's specified inverter efficiency of 95%, to estimate the total Ampere-hours that were supplied by the battery while you performed steps 3 to 7. What was the state of charge (SOC) of the battery at step 7? Compare with the battery voltage and the characteristics specified in Table 1.

16. On your *i-v* curve data generated in step 5, find the operating point for battery charging (step 8). Calculate the power.

    Fig. 4 below illustrates the use of a buck converter, connected between the PV panel and the battery, with a maximum power point tracker (MPPT) that adjusts the duty cycle of the buck converter such that the PV panel operates at its maximum power point. If the buck converter losses are negligible, how much would this increase the battery power? The battery current?

    Suggest an approach that would be capable of operating the PV panel at its maximum power point under the shaded conditions of steps 6 and 14, in addition to the unshaded operating points.

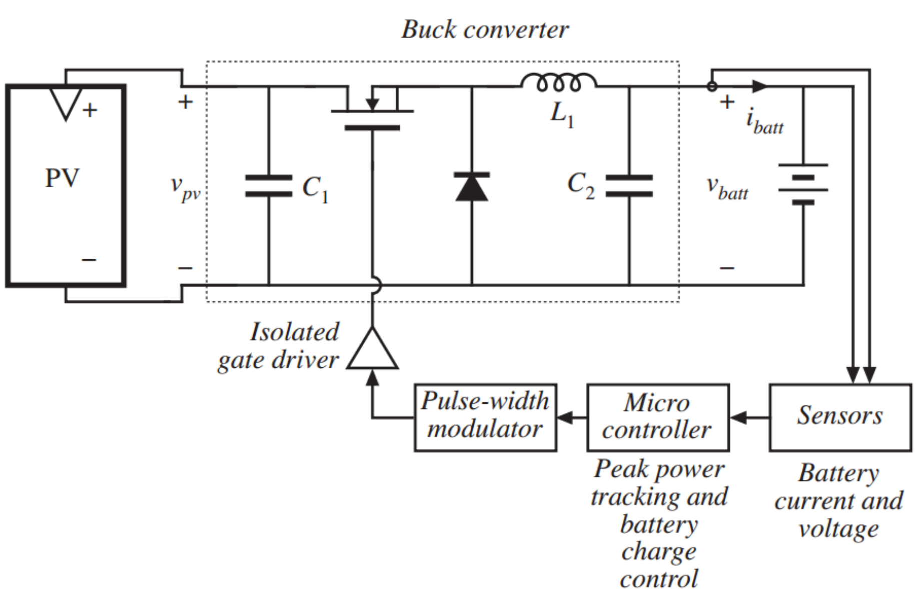

Figure 4: Addition of a buck converter with MPPT controller, between the PV panel and the battery.

Appendix A – Alternative Procedure for Bad Weather Day

In case of bad weather steps 4, 5, 6, and 8 can still be performed outside when the solar irradiance is as low as approximately 250 W/m^2; there must be enough solar irradiance so that shading cells in step 6 significantly changes the measured *i*–*v* curve. With solar irradiances in the 250 to 1000 W/m^2 range, the power and current will be reduced but useful *i*–*v* curves can still be measured. So if your lab day is cloudy, go outside with a pyranometer and see if you can measure at least 250 W/m^2; note that when the sun is behind a cloud, the greatest solar irradiance may be in a different direction.

Sometimes the weather simply does not cooperate on your lab day. In that case, here is the alternative plan:

Do all of the steps (other than 4, 5, 6, and 8) inside at your lab bench. The bulk of your time will be spent developing the equivalent circuit model, step 12 and the following steps. Use the data for normal operating cell temperature (NOCT) conditions provided on the SQ85-P (85-W) PV panel datasheet (available on the course website in the Experiment 1 folder) and develop a model that matches this data. During this time, you can discharge the battery according to steps 3 and 7, and then answer step 15.

There is more than one week before the lab report is due. It will be necessary to come in on your own, when the weather is good, to perform steps 4, 5, 6, and 8. It may be possible to do these steps in lab next week, since Experiment 2 is not expected to require the entire 4 hours of lab. With this data, you can then adjust your PV panel model (step 12) and complete your lab report.