Experiment A6
Solar Panels I
Procedure

Deliverables: **Full Lab Report** (due the week after break), checked lab notebook

Overview

In Week I, you will characterize the solar panel circuits (as shown in Figure 1) with respect to load and distance from light source. This week, a halogen lamp will be used as a light source in a laboratory setting. Next week, you will go out and perform field tests. Note the solar panel is a non-ideal power supply and has an internal resistance R_S, similar to the battery in the first electronics lab. Please take the time to understand everything this week, as it will provide a foundation for the independent study that you will perform next week.

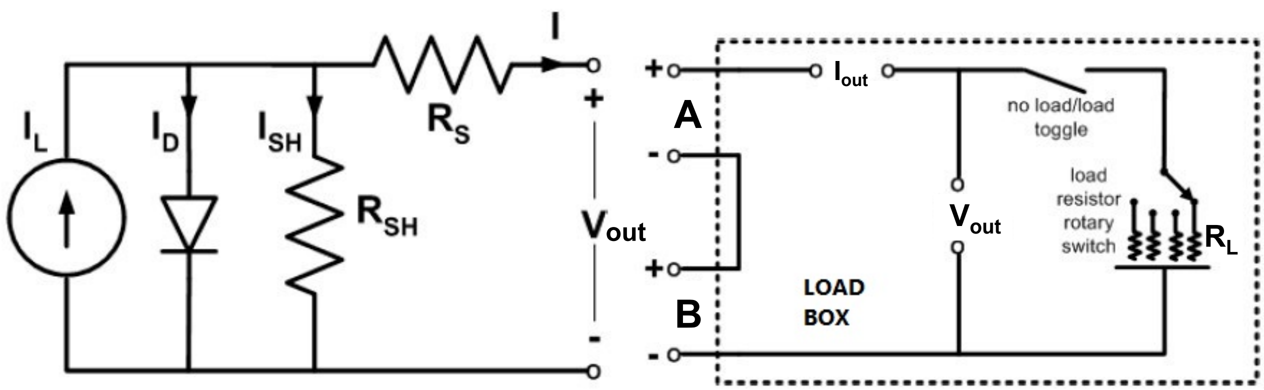

Figure 1: The circuit on the left represents the solar panel. It is connected to the load box on the right, which is used to vary the load resistance R_L.

Performance Characterization

The student will measure the power output of a single solar panel while varying the following parameters:

(a) load level R_L(varying of electrical resistance and light intensity)
(b) separation distance of panel to light source

Power, in a direct current (DC) circuit, is the product of current and voltage: $P = I\ V$. Therefore, at each measurement, a closed circuit current and closed circuit voltage with an input impedance is required. In exercise (a), the student will determine the proper input impedance (resistance) for maximum power output; the irradiance will be measured to determine true power input in exercise (b).

Laboratory Equipment

Please record the laboratory equipment being used and all of the following tables and parameters into you lab notebook.

Solar Panel:

Solar Panel Bar Code: ____

Active Surface Area: ____

Experimental Setup

1. Set the toggle switch to "Short" or "Closed"(load toggle in Figure 1).
2. Plug the red banana cable on the solar panel into the red receptacle A on the load box.
3. Plug the black banana cable on the solar panel into the black receptacle B on the load box. (Refer to Figure 1 for further clarification.)
4. Connect the "*V*" leads of the load box (V_{out} in Figure 1) to the Keysight Precision DMM using the BNC coaxial cable with banana plug adapters on the end.
5. To measure the current, use the orange handheld DMM set to the 200mA range, and connect it to the "*I*" leads on the load box (I_{out} in Figure 1) using the banana plug cables.
6. Locate the **Irradiance Sensor** (dark blue box). It has twelve different settings that can be chosen by turning the small knob for sensitivity and scaling of the voltage output. Setting (9) is recommended for this laboratory exercise.
7. Connect the Irradiance Sensor leads to the "Sensor Interface Box": The black wire should be on the top pin (GND), then red on the +5V pin, and yellow or white on the "SIG." pin. Ignore the loose green wire. (The sensor interface boxes have a pin-out diagram on the bottom left corner.)
8. The sensor interface box should display a voltage that will increase linearly with irradiance. Professor Patrick Dunn has created a document that explains how to determine the irradiance in $\mu W/cm^2$ from the voltage output of the sensor. This document can be found on the lab website along with the handout and score sheet.

NOTE: Alignment of the solar panel is important; care should be taken in centering it directly under the lamp for accurate measurements.

Part I: Load Curve

The solar panel is a non-ideal power supply with an internal resistance. As a result, the output voltage, current, power and efficiency all depend on the load resistance. In this portion of the lab, you will determine the optimal load resistance for the solar panel for a given irradiance.

1. To record the effect of resistive loads on output power of the solar panel, center a single panel on the scissor-lift, lab jack directly beneath the light source.
2. Measure the distance from the light bulb to the solar panel and record it in your lab notebook.
3. Shown in the right half of Fig. 1, the load box contains a number of resistors that can be selected by turning the knob. Be sure the resistance knob is turned counterclockwise. This is the similar to the first electronics lab, but with all the resistors conveniently packaged in a switching box.
4. The BK Precision AC power supply or "Variac" is used to control the voltage across the lamp V_{IN}, which ultimately changes its brightness. (Note that the AC power supply is NOT the same as the DC power supply you used in A4.) You will measure the efficiency of the solar panel as a function of the "load" resistance for three different Variac settings: 120V, 110V, and 90V.
5. **Make sure the dial on the variac is set to zero.** Turn on the variac and slowly turn the big dial to the desired setting V_{AC}. Refer to the markings around the big knob rather than the needle indicator. (If the circuit breaker trips and you lose power, ask the TA to reset the breaker switch.)
6. Place the irradiance sensor in the center of the solar panel.
7. As you increase the variac voltage the lamp will get brighter. As the lamp gets brighter, the voltage reading from the irradiance sensor should increase. Record the irradiance sensor voltage when you reach the desired variac setting and set the sensor off to the side.
8. Measure the output voltage and current as a function of the resistive load R_L. Each clockwise click on the knob increased the load resistance R_L by 200 Ω. Record the data in your lab notebook in a table similar to the ones shown below. You will use this data to calculate power and efficiency for the deliverables.

Pro-Tip: Be careful to keep the solar panel and irradiance sensor in the same position for each successive measurement.

9. Repeat the experiment for the other two variac voltages.
10. When you are all finished, disconnect everything from the load box, and set it off to the side.

Table 1a: Variac lamp voltage V_{AC} = 90V

Load, R_L [Ω]	**I_{out} [mA]**	**V_{out} [V]**	**$P = I\ V$ [mW]**
Short circuit current, I_{SC}			
Open circuit voltage, V_{OC}			
200			
400			
600			
800			
1000			
1200			
1400			
1600			
1800			
2000			

Irradiance Sensor Voltage:____

Irradiance Sensor Setting:_______________________________________

Variac Voltage:____

Table 1b: Variac lamp voltage V_{AC} = 110V

Load, R_L [Ω]	**I_{out} [mA]**	**V_{out} [V]**	**$P = I\,V$ [mW]**
Short circuit current, I_{SC}			
Open circuit voltage, V_{OC}			
200			
400			
600			
800			
1000			
1200			
1400			
1600			
1800			
2000			

Irradiance Sensor Voltage:____________________________________

Irradiance Sensor Setting:______________________________

Variac Voltage:______________________________________

Table 1c: Variac lamp voltage V_{AC} = 120V

Load, R_L [Ω]	**I_{out} [mA]**	**V_{out} [V]**	**$P = I\ V$ [mW]**
Short circuit current, I_{SC}			
Open circuit voltage, V_{OC}			
200			
400			
600			
800			
1000			
1200			
1400			
1600			
1800			
2000			

Irradiance Sensor Voltage:____

Irradiance Sensor Setting:__________________________________

Variac Voltage:____

Calculating the Efficiency

The efficiency of the solar panel is the amount of electric power generated divided by the total power from the incident light. That is, you can calculate the efficiency by dividing the power dissipated in the load resistor by the power measured by the Irradiance Sensor:

$$\eta_{panel} = \frac{I_{out} V_{out}}{E_0 A_{panel}} \tag{1}$$

where I_{out} and V_{out} are the current and voltage through the load resistor, A_{panel} is the area of the solar panel, and E_0 is the light intensity calculated from the Irradiance Voltage (see the “Irradiance Measurement” document on the lab website).

Part II: Separation Distance

In this part of the lab, you will measure irradiance as a function of distance from the lamp and compare your data to the *inverse square law*.

Note: The Load Box and Solar Panel will not be used in this part.

1. Place the irradiance sensor on the lab jack such that it is centered under the lamp.
2. Use banana to BNC coaxial cable adapter to connect the output of the sensor interface box to the Keysight precision DMM. You will now use the precision DMM to get a more accurate measure of the irradiance sensor voltage.
3. Turn the knob on the lab jack to change the distance. Measure the irradiance as a function of distance. You should choose at least 8 different distances, starting with approximately 90 cm (the maximum allowable distance due to laboratory setup). There are also wooden blocks that may be used to vary the height.
4. At each distance, change the variable AC transformer to the same values as those used above. Record the voltages from the irradiance sensor in Table 2.
5. When you are all finished, **turn the variac dial back to zero and turn off the variac.**

Table 2: Separation Distance

No. Blocks	**Distance [cm]**	**Irradiance Voltage**		
		Variac V_{AC} = 90 V	**Variac V_{AC} = 110 V**	**Variac V_{AC} = 120 V**

Part III: Practical Implementation of Solar Energy

In this portion of the lab you will create your own "Solar Microgrid". The microgrid consists of the solar panel, a 12V lead acid battery, and a charge controller. Solar panels obviously do not produce energy at night, so the 12V battery is used to store energy produced during the day. Directly connecting ~20V DC output of the solar panel to charge the 12V battery would damage it, so the charge controller is used to step down the 20V DC to 12V DC. Additionally, the charge controller contains two 5V USB outputs for charging various consumer electronics.

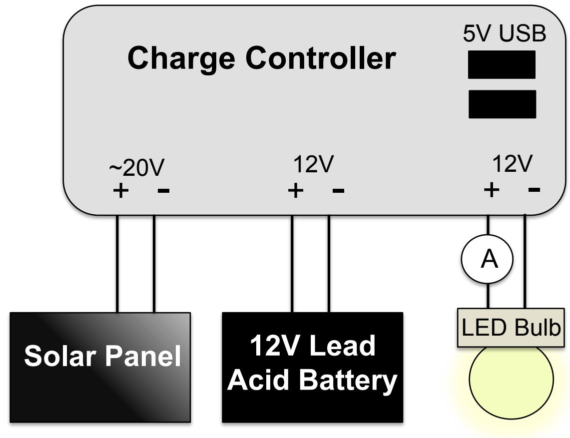

Figure 2: A schematic of the Solar Microgrid.

1. Sketch the schematic shown in figure 2 in your lab notebook.
2. Connect the solar panel to the banana plugs on the far left of the charge controller.
3. Place the solar panel directly under the lamp, and set the variac to 120 V.
4. Check that the battery is securely connected to the screw terminals of the charge controller. **Caution: This powerful battery is NOT a toy. It can cause painful shocks and burns and even cause fires.**
5. Look at the screen on the charge controller. What do you see? Flip the panel upside-down. Does the screen on the charge controller change?
6. Using the 10A socket with the minigrabber cables, connect the handheld DMM in series with the LED bulb, as shown in Figure 2. Turn on the LED bulb, and you should see a value for the current on the multimeter.

   Caution: You must use the 10A setting, or you will burn out the DMM!
7. Place the LED bulb upside down in the metal Bunsen burner stand. Measure the voltage across the screw terminals on the bottom of the LED bulbs using the Keysight precision multimeter.
8. Plug the USB power monitor stick into one of the USB charging ports. Choose a device and plug it into the other end of the USB power monitor. (Possible devices include your cell phone or tablet or the rechargeable flashlight or fan provided by Prof. Ott.)
9. Copy Table 3 into your notebook. Fill it out by recording the current for the LED bulb and current and voltage for two different USB devices. (Be sure to write down the actual names of the USB devices you used, not just "USB Device 1".) Put the solar panel directly under the lamp to simulate day and turn it upside down to simulate night.

10. When you are all finished, **turn the variac dial back to zero and turn off the variac.** Turn off the LED bulb and disconnect the handheld DMM.

Table 3: Energy usage of various electronic devices.

	USB Device 1		USB Device 2		LED Bulb	
	Voltage	Current	Voltage	Current	Voltage	Current
Day						
Night						

Week I Deliverables – Your results from this week and next are to be compiled in a lab report **no longer than 8 pages**. Please include the following items from this week in your report. (See the score sheet for a breakdown of the points.)

1. A plot of the solar panel efficiency η_{panel} vs. load resistance R_L for the three different Variac settings. (Recall the Variac controls the brightness or irradiance of the lamp.)

2. A table containing the maximum power output by the solar panel, the load resistance that yielded the maximum power, and the estimated internal resistance of the solar panel ($Rs = V_{OC}/I_{SC}$) for all three variac settings. Does the solar panel also exhibit impedance matching?

3. A simple plot of measured irradiance E_0 vs. distance r on a *linear scale* for the three different Variac settings.

4. The irradiance vs. distance should obey an *inverse square law*. Plot the logarithm of irradiance vs. the logarithm of distance, log(E_0) vs. log(r). Apply a *linear* fit to each the data sets. In the caption, comment on the slopes. Are they consistent with an inverse square law? (This plot should contain three different data sets for the three different Variac settings.)

Suggested Talking Points

- Why does the efficiency depend on the load resistance? Can you come up with an equation that predicts power vs. load resistance? (Hint: The solar panel is a non-ideal power supply with an internal resistance R_S.)

- Do some research on the inverse square law and discuss your measurements of irradiance vs. distance accordingly.

- Next week, you will need to perform some independent analysis on the practical use of solar energy. Think about the solar microgrid and its principal components. How much would it cost to implement it on a much *larger scale*? (i.e. a large building, an entire city, an entire country, the entire world, the entire solar system)

Appendix A

Equipment

- Sensor Interface Box (SIB) w/ 9V power supply
- Light Sensor Box (Irradiance Sensor/Light-to-Frequency Converter) w/ 24” wire lead cable ending in snap connector to SIB input pins
- Load Box
- Solar Panel w/ 24” wire leads ending in male banana connector
- Multi-meter w/ 24” wire leads ending in male banana connector
- BK Precision AC Power Supply
- Halogen lamp Fixture w/ GE Lamp: GE 90w 1900lm M/N 66286 PAR 38
- Scissor lift
- Meter Stick
- 2 Extech handheld digital multimeters
- Keysight precision digital multimeter
- **Mohoo 20A Charge Controller Solar Charge Regulator Intelligent USB Port Display 12V-24V**
- **Eversame USB Digital Power Meter Tester Multimeter Current and Voltage Monitor, DC 5.1A, 30V**
- **ExpertPower EXP1272 12V 7.2 Amp-hour Rechargeable Battery**
- **ChiChinLighting 12v LED Bulb Daylight AC DC Compatible 7 Watts 6000k Low Voltage**
- Porcelain Medium-Base Light Bulb Socket with Pull Switch, 250 Maximum Watts, 250 Maximum Volts
- Bunsen burner stand