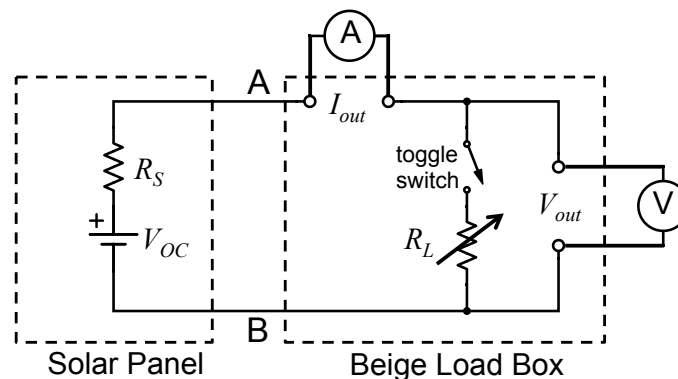# Experiment A5
Solar Energy I
Procedure

Deliverables: Full Lab Report (including A6, due in two weeks), checked lab notebook
Recommended Reading: Chapter 5; Section 10.4 of the textbook

Overview

In this lab, you will measure the power output of a solar panel and use it to calculate its efficiency η. A halogen lamp will be used to simulate the sun in a laboratory setting. The electrical power produced by the solar panel will be dissipated in R_L. The solar panel is a non-ideal DC power supply with an internal resistance R_S. As a result, the output voltage, current, power and efficiency all depend on the load resistance R_L and light intensity E_0.

Figure 1: The circuit on the left represents the solar panel. Note that the solar panel is a non-ideal power supply with an internal resistance R_S. It is connected to the load box on the right, which is used to vary the load resistance R_L. (The arrow indicates that R_L is a variable resistor.)

Part I: Efficiency vs. Load

Background

The electrical power output by the solar panel will be dissipated via joule heating in a load resistor. You will see that the power output and efficiency of the solar panel depend on the load resistance R_L, and there is an optimal value of R_L that yields the most efficient operation. The beige "load box" contains an array of load resistors that can be easily selected by turning a knob, as shown on the right hand side of Fig. 1.

The black "sensor interface box" has two displays that are used to measure the *voltage* output from analog sensors. It also has +3V and +5V DC outputs that can provide power to analog sensors. You will use it to measure the voltage output from the irradiance sensor. The irradiance sensor is an *analog transducer*, and the voltage it outputs is linearly related to the irradiance. There is a document on the A5 webpage that explains how to determine the irradiance in $\mu W/cm^2$ from the voltage output of the sensor.

Procedure

1. Measure the active area of the solar panel. You will use the dimensions to calculate the area A_{panel}.

2. Plug the red banana cable on the solar panel into the red receptacle A on the end of the load box.

3. Plug the black banana cable on the solar panel into the black receptacle B on the end of 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. Set up the Keysight DMM to measure DC voltage.

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. Make sure the small knob is set to 9.

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.

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

9. To measure the effect of resistive loads on output power of the solar panel, center the panel directly beneath the light source.

10. Measure the distance from the light bulb to the solar panel and record it in your lab notebook.

11. The BK Precision AC power supply or "Variac" is used to control the voltage across the lamp V_{IN}, which ultimately changes its brightness or "irradiance". (Note that the AC power supply is NOT the same as the DC power supply you used in A4.) You will measure the power output and efficiency of the solar panel as a function of the load resistance R_L for two different Variac settings, 140V and 120V, which correspond to different irradiances E_0.

12. Plug the halogen lamp into the variac. Turn on the variac and use it to adjust the lamp voltage to 120V. (If the circuit breaker trips and you lose power, ask the TA to help you reset the breaker switch.)

13. Place the irradiance sensor in the center of the solar panel. Make sure the active area of the sensor is facing upward toward the lamp.

14. 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.

15. Copy Table 1 into your lab notebook. Record the irradiance sensor voltage.

16. Take the irradiance sensor off of the solar panel and set it to the side, after you have recorded the irradiance sensor voltage.

17. An "open circuit" occurs when the load is infinite (i.e. R_L is removed from the circuit and there is nothing but air between the output terminals). Flip the toggle switch to "Open", and you should see the output *current* drop to nearly zero. The resultant voltage is known as the "open circuit voltage" V_{OC}. Record the open circuit voltage in your lab notebook.

18. Flip the toggle to "Closed", putting R_L back into the circuit.

19. A "short circuit" occurs when the load R_L is set to 0 Ω (i.e. it is replaced by a wire). Set the load knob to 0 Ω, and you should see the output *voltage* drop to nearly zero (a few milliVolts). The resultant current is known as the "Short circuit current" I_{SC}. Record the short circuit current in your lab notebook.

20. With the toggle switch set to closed, measure the DC output voltage and current as a function of the resistive load R_L. Each clockwise click on the knob increases the load resistance R_L by 200 Ω. Record the data in your lab notebook in a table similar to the one shown on the next page. 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.

21. Increase the brightness of the lamp by increasing the variac voltage to 140V, and repeat the experiment. Fill out another copy of Table 1 in your lab notebook.

Table 1: A template for the table you should put in your lab notebook.

Load, R_L [Ω]	I_{out} [mA]	V_{out} [V]
0 (short circuit)	$I_{SC} =$	
200		
400		
600		
800		
1000		
1200		
1400		
1600		
1800		
2000		
∞ (open circuit)		$V_{OC} =$

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 times the area of the panel

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

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 in Table 2. Copy Table 2 into your lab notebook and record the voltages from the irradiance sensor.

5. When you are all finished, **turn the variac dial back to zero and turn off the variac.** Disconnect all cables and return the lab bench to its initial state.

Table 2: The irradiance sensor output voltage is measured as a function of gap distance and halogen lamp intensity.

Distance r (cm)	Lamp Voltage V_{AC} = 90 V Irradiance Sensor Output (V)	Lamp Voltage V_{AC} = 110 V Irradiance Sensor Output (V)

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 output voltage V_{out} vs. load resistance R_L for the two different lamp irradiances.

    a. Use the '-o' and '-*' options in Matlab to connect the measured data points with lines.

    b. Include a legend that denotes the lamp irradiance E_0 in $\mu W/cm^2$ for each data set.

2. A plot of the solar panel efficiency η vs. load resistance R_L for the two different lamp irradiances.

    a. Use the '-o' and '-*' options in Matlab to connect the measured data points with lines.

    b. Include a legend that denotes the lamp irradiance E_0 in $\mu W/cm^2$ for each data set.

    c. Calculate the internal resistance $R_S = V_{OC}/I_{SC}$ of the solar panel for each of the lamp irradiances. Add a vertical line to the plot denoting each value of R_S.

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

4. Show that the irradiance vs. distance obeys an *inverse square law*.

    a. Plot the logarithm of irradiance vs. the logarithm of distance, $\log(E_0)$ vs. $\log(r)$, with both data sets on the same graph. (Do NOT use the loglog() function in Matlab.)

    b. Apply a *linear* fit to each the data sets. In the caption, comment on the slopes. Are they consistent with an inverse square law?

Talking Points

- Explain how the lamp brightness (irradiance) was controlled.

- Use the terms "voltage droop" and "impedance matching" appropriately to describe your plots.

- Discuss the plot of $\log(E_0)$ vs. $\log(r)$. Is the data linear? Are the slopes what you expect for an inverse square law?

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
- 2 BNC to banana adapters
- Set of banana cables (1 black, 1 red)