ENGR 1181 | Labs 04 & 05: Solar Energy Labs

- Preparation Material (Lab 04)
- Lab Procedure (Lab 04)
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- Report Guidelines (Combined)
Preparation Material (Lab 04: Solar Meter Lab)
1. Overview of Solar Meter Lab

In Solar Meter lab, you will build a solar energy meter to measure the energy intensity from an overhead light bulb.

Learning Objectives – students will be able to:

1. Describe and build both a calibration and solar meter circuit
2. Convert decimal values to binary values
3. Discuss how a potentiometer works
4. Explain how a photodiode light sensor works
5. Compare a pictorial image of a circuit to a schematic wiring diagram
6. Use a Photodiode Light Sensor and a Binary Voltmeter circuit to measure the intensity of light (in Watts/m²)

![Solar Panels](image)

**Figure 1: Solar Panels**

On a bright, sunny day, solar energy strikes the earth at the rate of approximately 1000 Watts/m². This is called the solar energy intensity, and is collected by solar cells.
2. What is a Binary Voltmeter Calibration Circuit?

From Figure 2,

\[ N_{\text{binary}} = d_7d_6d_5d_4d_3d_2d_1d_0 \]  

(1)

The Decimal Equivalent of the Binary Number, \( N_{\text{binary}} \) is given by:

\[ N_{\text{decimal}} = d_7 \cdot 2^7 + d_6 \cdot 2^6 + d_5 \cdot 2^5 + d_4 \cdot 2^4 + d_3 \cdot 2^3 + d_2 \cdot 2^2 + d_1 \cdot 2^1 + d_0 \cdot 2^0 \]  

(2)

Binary numbers are used in almost all computers due to its use of digital electronic circuitry and logic gates. Numbers are written in a combination of bits. Counting in binary is straightforward. It works the same way that you have learned to count with Arabic numerals. Instead of 0-9, you now use only zeroes and ones. The pattern goes according to the following form:

**Table 1: Binary to Decimal Conversion**

<table>
<thead>
<tr>
<th>8-Bit Binary Number</th>
<th>Decimal Equivalent</th>
</tr>
</thead>
<tbody>
<tr>
<td>0000 0000</td>
<td>0</td>
</tr>
<tr>
<td>0000 0001</td>
<td>1</td>
</tr>
<tr>
<td>0000 0010</td>
<td>2</td>
</tr>
<tr>
<td>0000 0111</td>
<td>3</td>
</tr>
<tr>
<td>0000 0100</td>
<td>4</td>
</tr>
<tr>
<td>0000 0101</td>
<td>5</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>1111 1110</td>
<td>254</td>
</tr>
<tr>
<td>1111 1111</td>
<td>255</td>
</tr>
</tbody>
</table>
Observe Figure 2 and note the following:

1. The LEDs at the output of the Binary Voltmeter are labeled from D7 to D0
2. The LEDs have two digital states, on and off, representing the binary numbers “1” and “0”
3. D7 is the Most Significant Bit (MSB). D0 is the Least Significant Bit (LSB)
4. The 8-bit binary number can be converted to a decimal number using a formula

3. An example on calculating a decimal number from a binary number

For example, convert binary 0000 0101 into a decimal:

\[
\begin{align*}
\text{MSB} & \quad \text{LSB} \\
0000 & \quad 0101 \\
\end{align*}
\]

\[
= 0 \times 2^3 + 1 \times 2^2 + 0 \times 2^1 + 1 \times 2^0 = 5
\]

Figure 3: Example of calculating the decimal number from a binary number

4. How is a Binary Voltmeter Calibration Circuit calibrated?

To calibrate the binary voltmeter circuit, we will use a trimpot. A trim potentiometer also known as a trimpot is a resistive element which has a slider that traverses a resistive material. The resistive material can be carbon, ‘cermet’ (a ceramic type material), wound wire, or any of a number of synthetic substances. The mechanical parts of the potentiometer are a leadscrew, slider, and knob. Turning the knob causes the slider to traverse the resistive material, thereby varying the effective resistance as measured across terminals 1 and 2 or terminals 2 and 3. The resistance across 1 and 3 is constant, regardless of slider position, and is the resistance value of the potentiometer. Because it is a resistance element, its unit of measure is ohms, it is power limited, and it is not polarized. A schematic of the drawing is shown below.

Figure 4: A Schematic of a Trimpot
5. What is a Solar Meter Circuit?

Figure 5 is a schematic of a solar energy meter circuit. A “schematic” is a drawing of an electronic circuit made by an electrical engineer.

The parts (Components) to build the Solar Energy Meter circuit are:

**Light Sensor Board**
- Senses the sun’s energy
- Uses a Photodiode and an Operational Amplifier (Op-Amp)
- Has an analog output voltage signal of 0 – 5 Volts

**Binary Voltmeter Board**
- Changes the input voltage signal to binary “Bits”

**LEDs**
- Display an 8-Bit binary number

**Wires**
- Connect the parts together electrically
6. **How does the Light Sensor work?**

The Photodiode converts light photons to a current. The Amplifier converts the current to a voltage. The voltage output of the Light Sensor Board is proportional to the intensity of sunlight ($I_{\text{solar}}$ in Watts/m²). The calibration equation for the Solar Light Meter is:

$$I_{\text{solar}} = 5.0 \cdot N_{\text{decimal}} \text{ (in Watts/m}^2)$$

(3)

7. **Lab Preparation Assignment**

In order to finish your preparation for the Solar Meter Lab, students are required to:

- Take the Solar Meter quiz (on Carmen)
- Preview the following Solar Meter Lab Procedure
Lab Procedure (Lab 04: Solar Meter Lab)
Mayor Mia Taylor, a mayor of a city similar to a suburb of Columbus, is running for re-election. As she develops her platform for the upcoming election cycle, there has been some debate on whether or not homeowners who install solar panels should receive a tax break. Before she can form her opinion, her election committee has hired your consulting firm to write a memo on the practicality of installing rooftop solar cells on new and existing homes. With your team of engineers, you must conduct a series of experiments and analysis to develop a well-supported recommendation for Mayor Taylor. Your team’s systematic and economical procedure for testing has been described later in this document.

The memo must address:

1. The active area (in square meters) of solar panels required to provide enough energy to power (an) already constructed/pre-existing house in Columbus, Ohio using the incident values from the results.
2. Is installing solar panels on roofs of newly constructed homes feasibility?

The committee has narrowed the scope of the memo to the following considerations:

1. The average energy use per person in an Ohioan home is 33.15 kilowatt-hours per day.
2. The solar cell will experience six hours of sunlight.
3. The selected solar cell has an efficiency of 17%.
4. Calculations can be done for sunlight at bright or cloudy sky intensity.

Finally, your team’s work should be well-supported enough to withstand the scrutiny of Taylor’s opponents as well as the press.
Task 1. Build the Calibration Circuit and measure the Power Supply Voltage

1. Build the Binary Voltmeter Calibration Circuit in Figure 6.
2. Turn the DMM one click to the right for a DCV scale  
   *(Note: the DMM auto-ranges so you must keep track of the displayed units!)*
3. Plug the Modular Power Supply into an AC outlet
4. Verify that the Power Supply voltage is around 5V. If more than .4V deviate from 5V, obtain a member of the instructional team.

Figure 6: Physical Layout of Task 1
Task 2. Calibrate the Binary Voltmeter Circuit using the "TrimPot" as a variable voltage source

In your kit, the blue or grey component is a 10K Ohm Potentiometer (called a "TrimPot", shown in the picture on the left, Figure 7). A Trimpot is a variable resistance arrangement which allows for the voltage across it to vary. Notice that the TrimPot has three wires on the bottom and a small screw on top. The wires, called "Pins", are numbered 1, 2, 3, as shown. The circuit symbol for the TrimPot is shown in Figure 7.

**TrimPot Types**

![TrimPot and its corresponding schematic symbol](image)

Figure 7: TrimPot and its corresponding schematic symbol

![Physical Layout of the Binary Voltmeter Calibration Circuit](image)

You can measure the input voltage to the binary voltmeter by connecting a wire similar to what is circled in blue for this figure and placing the DMM between this red node indicated and the ground (the black node).

You must connect both sides of the breadboard.
Note: Be sure that your breadboard has a power supply and to connect the two grounds together on the breadboard (circled in blue).

1. Add the TrimPot and LEDs to the breadboard as shown above in Figure 8. Make sure you connect the short leads of the LEDs toward the circuit ground. Turn power onto the circuit by throwing the toggle switch to the left. Look for the green and red lights next to the switch to be on.

2. Use the TrimPot adjustment tool (shown in Figure 10) to turn the small screw on top or on the side of the TrimPot clockwise until the voltage on Pin 2 changes rapidly. If the voltage doesn’t change after a few turns, try turning the screw counterclockwise. Which end of the adjustment tool works best for this task?

3. Turn the screw on the TrimPot until the voltage stabilizes at a maximum voltage. The voltage obtained is that of the power supply (it should be close to 5.0 Volts). If the voltage is not close to 5 volts, report this discrepancy to the instructional team.

4. Confirm that all LEDs are turned on. If not, alert the instructional staff to help debug the problem.

5. Adjust the TrimPot so voltage is 1.0 mV (millivolts) or less. The binary number shown on the LEDs should be 0 0 0 0 0 0 0 0. Record this value in the Excel Worksheet Table A (below). Note: A LED off corresponds to zero. The Excel Worksheet Table A is located under the Solar Meter tab in the provided Excel Worksheet.

6. Then adjust the TrimPot so V Input = 0.5 Volts. Record the binary number you observe in the Excel Worksheet Table A and convert it to a Decimal Number. Do the conversion manually as described below.
1. Converting Binary Numbers to Decimal Numbers
An 8-bit Binary Number, \( N_{\text{binary}} \), can be written as a string of “1s” and “0s”:
\[
N_{\text{binary}} = d_7d_6d_5d_4d_3d_2d_1d_0
\]  

The Decimal System Equivalent of the Binary Number, \( N_{\text{binary}} \), is given by:
\[
N_{\text{decimal}} = d_7 \cdot 2^7 + d_6 \cdot 2^6 + d_5 \cdot 2^5 + d_4 \cdot 2^4 + d_3 \cdot 2^3 + d_2 \cdot 2^2 + d_1 \cdot 2 + d_0
\]  

Take data for all of the other voltage values shown in the Excel Worksheet Table A located in the excel file. Then make a graph of \( N_{\text{decimal}} \) vs. V Input.

![Figure 11: Binary Number to LEDs](image)

2. How the Light Sensor Board Works for Tasks 3 & 4
The Silicon Photodiode on the Light Sensor Board is sensitive to light. Look at the end of the Photodiode – you can see a tiny silicon chip (it’s about 2 mm square). When light strikes the silicon chip, it generates a current, \( i_p \), that is proportional to the intensity of light striking the silicon.

The black integrated circuit on the light sensor board is called an Op-Amp. The Op-Amp senses the current \( i_p \) and turns it into a voltage, \( v_p \), which you measure with the Binary Voltmeter.

The Solar Energy Meter is designed so that the intensity of light measured \( (I_{\text{solar}}, \text{ in Watts/m}^2) \) is related to the output of the meter \( (N_{\text{decimal}}) \) by the equation:
\[
I_{\text{solar}} = 5.0 \cdot N_{\text{decimal}} \quad (\text{in Watts/m}^2)
\]
Task 3. Build the Solar Energy Meter Circuit

1. Flip the toggle switch on the black box on the breadboard (the green light should go off).
2. Remove the TrimPot and its wires from the Breadboard.
3. Plug the Light Sensor Board into the breadboard exactly as shown in Figure 13.
4. Add an orange ground wire to the Light Sensor Board.
5. Add a yellow wire from V Out of the Light Sensor Board to V Input of the Binary Voltmeter Board.
6. Notice how the LED’s are placed far away from the light sensor. This is done to make it easier to distinguish whether the LED’s are on/off. Placing them directly under the light source creates glare and may make it difficult to determine the binary number.
7. Add a new capacitor to the circuit as shown in Figure 13.

Figure 13: Diagram of a Solar Meter Circuit
**Task 4. Use the Solar Energy Meter to measure the intensity of a light source**

1. Clamp the spotlight to the ring stand provided, starting with the light at a height of 23 inches above the Breadboard.
2. To obtain a clear reading of the LEDs, place a piece of paper or a hand over the LEDs on the breadboard. This should create a shadow to make seeing the LEDs better.
3. Record the results in the Excel Worksheet Table B when the light is positioned at various distances from the Solar Energy Meter. Use distances of 23, 19, 15, 11 and 7 inches.
Excel Worksheet Table B is located under the Solar Meter tab in the provided Excel Worksheet.

**Before continuing to Task 5, completed the following before leaving the Lab:**
1. Complete Tables A and B so that you can embed them in the Results Section of the Memo.
2. Get End of Lab Procedure signed!

**Final Questions:**

What function did the potentiometer perform in this circuit?

What functions do the LEDs perform in this circuit? Explain.

What is the decimal value for the following binary values?

100 =
1001 =
10000 =
010101 =

What function does the Light Sensor Board perform in this circuit? Explain.

**Task 5. To Be Completed Time Permitting**
1. Be sure to complete all binary to decimal calculations and create necessary graph in class.
2. When completed, check with a TA to ensure that your data is correct.
3. Answer questions located at end of lab with your group. If you do not have enough time in the lab period to finish answering the questions then please insert the questions throughout your lab memo.
Task 6. Clean-Up Procedure
1. If your lab is not the last lab of the week, disassemble your breadboard
2. Put items in the appropriate plastic storage box.
3. The work-area should be clean after you are done with your lab.

<table>
<thead>
<tr>
<th>Item Description (For 2 Kits)</th>
<th>Qty.</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 Volt Modular Power Supply</td>
<td>2</td>
</tr>
<tr>
<td>Banana leads, Red &amp; Black</td>
<td>2 pairs</td>
</tr>
<tr>
<td>DMM</td>
<td>2</td>
</tr>
<tr>
<td>Prototyping Bread Board, power and ground wired, and Op- Amp, TrimPot, and ADC plugged in, per Lab Procedure</td>
<td>2</td>
</tr>
<tr>
<td>Jumper Wire Kit</td>
<td>1</td>
</tr>
<tr>
<td>TrimPot Adjustment Tool</td>
<td>2</td>
</tr>
<tr>
<td>Ring Stand, with Clamp</td>
<td>1</td>
</tr>
<tr>
<td>Spotlight, with switched receptacle and power cord</td>
<td>1</td>
</tr>
<tr>
<td>Binary Voltmeter Board</td>
<td>2</td>
</tr>
<tr>
<td>Light Sensor Board</td>
<td>2</td>
</tr>
<tr>
<td>Red LED</td>
<td>8</td>
</tr>
<tr>
<td>Green LED</td>
<td>8</td>
</tr>
<tr>
<td>TrimPot, 10K, 25 turn (on breadboard)</td>
<td>2</td>
</tr>
</tbody>
</table>

Important Note: The Solar Meter Lab Memo is not due at the beginning of the Solar Cell Lab. The Solar Labs are a combined lab memo due after Solar Cell Lab is completed. The Report Guidelines covers both labs is present at the end of the procedure document for the Solar Cell Lab.

Task 7. Check-Out Policy
After you have finished the lab and the clean-up procedure, have your instructor or GTA sign the “End-of-Lab Signoff” line at the end of the rubric. You will lose 5 points if this is not signed by your Instructor/TA.
Preparation Material (Lab 05: Solar Cell Lab)
1. **Overview of the Solar Cell Lab**

In the Solar Cell lab, you will take various measurements from a solar cell activated by an overhead light bulb.

Learning Objectives – students will be able to:

1. Discuss the applications of solar cells.
2. Describe the materials and function of a solar cell.
3. Identify the advantages and disadvantages of solar cells.
4. Calculate the efficiency of a solar cell.
5. Distinguish between internal and external resistance.
6. Compare and contrast two given types of solar cells.
7. Optimize the power output of a solar cell.
8. Measure the power output of the solar cell under various simulated sunlight conditions.
9. Determine the effect on the power output of the solar cell at different times of day.

2. **What is a Solar Cell?**

A solar cell is comprised of silicon. The solar cell consists of two differently doped semiconductor layers. Silicon is normally an insulator where there are no free electrons. For this reason, the layers must be doped. Doping involves inserting an atom into the silicon crystal lattice which has a surplus or deficiency of valance electrons compared to the silicon atom (4 valance electrons). P-doping material has 3 valance electrons and thus produces an excess of holes (deficiency of electrons or positive) while N-doping material has 5 valance electrons and thus produces an excess of electrons (negative). Figure 16 shows how these two layers form a solar cell.

![Solar Cell Diagram](image)

Figure 16: A Solar Cell

The two layers have a concentration difference of holes and electrons. The important fact to note is that when N- and P-doped materials are layered, a surplus of positive and negative
charge carriers are produced so that when photons (light) hit the solar cell these additional charge carriers, which were initially in equilibrium, now cause an external voltage whose value is dependent upon the employed materials.

![Layers of a solar cell](image)

Figure 17: Layers of a solar cell

Figure 17 demonstrates the extra packaging components required to produce a working solar cell. Note especially the black anti-reflective coating to maximize photon absorption.

3. **What are the characteristics of a solar cell?**

   Energy generated by the solar cell is:
   1. Proportional to the intensity of the incident light
   2. Dependent upon the load applied to the solar cell
   3. Temperature dependent

   Advantages of the solar cell are:
   1. Energy source is FREE (sun)
   2. No emissions (earth friendly)
   3. No moving parts (low maintenance)

   Disadvantages of the solar cell are:
   1. Technology is presently very expensive
   2. Low power conversion efficiency (5 – 17 %)
   3. Intensity of light source impacted by geographical location and local weather conditions

4. **Calculations for the solar cell Lab: Solar Power Conversion Efficiency**

   When sunlight strikes the surface of a solar cell, it develops a voltage (V) and that voltage can be used to power any electrical device (like an iPhone charger).

   Electrically, the solar cell acts like a battery that supplies voltage (V) and current (I) to power any device (like the resistor, R) in the circuit diagram (Figure 18).
The solar cell generates power from sunlight and delivers that power to the resistor, where it ends up being dissipated as heat, or:

$$P_{\text{output from the Solar Cell}} = P_{\text{out}} = I \times V = I^2R = \frac{V^2}{R} \text{ in Watts} \quad (4)$$

The power conversion efficiency of the Solar Cell is:

$$\text{Efficiency} = \eta = \frac{P_{\text{out}}}{P_{\text{in}}} \quad (5)$$

$$\text{Power Conversion Efficiency} = P_{\text{out}} \cdot 100 \quad (6)$$

Where $P_{\text{in}}$ = the Power input to the Solar Cell from sunlight falling on it.
5. **Solar Cell Output as a function of Incident Light Angle**

![Diagram of a solar cell and its incident angle, \( \phi \)](image)

Figure 19: A drawing of a solar cell and its incident angle, \( \phi \)

The power output of a solar cell as a function of the angle \( \phi \) of the incident light is given by:

\[
P(\phi) = P_0 \cos(\phi)
\]

(7)

Where \( P_0 \) = the power output of the solar cell when \( \phi \) is zero degrees.

This calculation assumes a flat absorbing solar cell surface. An irregular surface which functions as a lens collects more of the incident light energy than a flat absorbing surface when the incident light is at an angle.

6. **Lab Preparation Assignment**

In order to finish your preparation for the Solar Meter Lab, students are required to:

- Take the Solar Cell quiz (on Carmen)
- Preview the following Solar Cell Lab Procedure
Lab Procedure (Lab 05: Solar Cell Lab)
ENGR 1181 Labs 04 & 05: Solar Energy Labs
Lab 05: Solar Energy Part 2 Lab Procedure

The tasks associated with this lab are as follows:

- **Task 1**: Use *resistance loads* to optimize the power output of solar cell A.
- **Task 2**: Use different *light intensities* to measure the power output of the solar cell under various simulated sunlight conditions.
- **Task 3**: Investigate different *light incident angles* to determine the effect on the power output of the solar cell at different times of day.
- **Task 4**: Measure the *power output* of solar cell B and compare it to Solar Cell A.
- **Task 5**: Data reduction, calculations, and analysis.

Before beginning the lab procedure, open the Solar Cell Worksheet provided on the ENGR 1181 website. All data will be recorded on this worksheet. Save the worksheet to your own drive before you record any data and remember to take a copy of it with you for your lab memo.
Figure 20a: Lab Equipment

Figure 20b: Laboratory Equipment (Solar Cells)

* Solar Cell A: 5.1 cm x 2.05 cm
* Solar Cell B: 5.6 x 7.7 cm
Figure 21: Lamp Stand Setup

Figure 22: Breadboard and its support platform
ENGR 1181 Labs 04 & 05: Solar Energy Labs
Lab 05: Solar Energy Part 2 Lab Procedure

Task 1. Investigate Power Output as a Function of Resistance
1. Set up Solar Cell A according to the Figures 22 and 23 below.
   a. Use Red wires (the Red banana plug cables) to connect the positive terminal of Solar Cell A to the positive terminals of the DMM and the Resistor Board.
   b. Use Black wires (the Black banana plug cables) to connect the negative terminal of Solar Cell A to the negative terminals of the DMM and the Resistor Board.

![Figure 22: Solar Cell A - connection diagram](image)

![Figure 23: Solar Cell A connected to the Resistor Board and the DMM](image)
Lab 05: Solar Energy Part 2 Lab Procedure

2. Place Solar Cell A on the desktop directly under the light source as shown in Figure 24. Adjust the clamp on the ring stand so the bottom face of the lamp is 7 inches above Solar Cell A. The distance measured should be from the bottom face of the lamp to the top of the solar cell, not from the bottom surface of the lamp to the tabletop.

3. After measuring the distance of 7 inches, plug in and turn on the lamp. Do not place the lamp closer than 7 inches to the solar cell, as the heat can damage the cell.

4. Wait 5 minutes to allow the solar cell to be heated by the light source. A cold solar cell produces more voltage than a warm solar cell, which is why five minutes is needed for the solar cell to reach a steady state temperature.

5. Fill in Table 1 on your Lab Worksheet by doing the following:
   a. On the resistor board, turn Switch 3 "on". Next, turn the DMM to the DCV setting and measure the voltage generated by the Solar Cell.
   b. Next, turn resistor board Switch 3 "off" and turn "on" the next resistor switch listed in Table 1. Measure and record the corresponding voltage.
   c. Repeat this process for all switch positions listed in Table 1. Be sure to turn "on" only one switch at a time!
   d. Which Switch/Resistor setting produces the Maximum Power Output of the solar cell? Fill-in the answer at the bottom of Table 1 in your Worksheet.
   e. Complete the measurements and calculations in Table 1 before starting Task 2.
Task 2. Measure the Power Output of Solar Cell A under Different Light Conditions

Task 2 will show how different light conditions will affect the performance of the solar cell. When completing this task, consider the reasons why solar intensity is a factor in the use of solar cells.

1. Make sure the modular (+5V) power supply is also plugged into the 120V power strip.

2. Turn on the lamp. Adjust the vertical position of the lamp directly over the Solar Meter breadboard Light Sensor and adjust the height of the lamp so the Solar Meter displays the binary code representing a bright sky (a sunlight intensity of 1,000 watts/m$^2$).

   The binary code that represents a bright sky is "1100xxxx". (Note the digits marked with an 'x' can be any combination of 1s and 0s). Record the actual binary reading in Table 2.

3. Remove the Solar Meter breadboard from under the lamp and replace it with solar cell A. On the resistor board, switch the resistance to the value where you achieved maximum power in Task 1. Refer to Figure 23 for guidance on the assembly needed for Task 2. Find the location on the table that gives maximum light intensity. Maximum light intensity will correspond to the maximum voltage reading on the DMM. Record the voltage output of Solar Cell A for the maximum light intensity (1,000 watts/m$^2$) on the cell at the lamp’s current height in Table 2. Also, record the vertical distance from the top of the Solar Cell A to the front face of the light source in Table 2.

4. Repeat this procedure for a cloudy sky condition (a sunlight intensity of 250 watts/m$^2$). A cloudy sky corresponds to a binary output of "0011xxxx". Record the binary reading and the corresponding voltage in Table 2.

5. Turn off the lamp. Do not disconnect the setup as you will need it for Task 3.

6. Fill in Table 2 completely before moving to Task 3.

7. Save your Worksheet.
Task 3. Power Output of Solar Cell A as a Function of the Incident Angle of Sunlight

As the incident angle of sunlight moves away from true vertical, the power output of the solar cell will decrease. The power output as a function of the incident angle of sunlight should be a cosine function between sunrise and sunset. The Incident angle at noon (sunlight is perpendicular to the face of the solar panel) is 0° and at sunrise/sunset is ± 90°. The power calculations in Task 3 can be done at the end of lab if time permits, or they can be done later.

1. Set the resistance on the resistor board to the Maximum Power Output switch setting, which was found in the Excel Worksheet Table 1.
2. Adjust the lamp height to the "Cloudy Sky Condition".
3. Place the Solar Meter breadboard under the light source and adjust its position on the table for maximum light intensity. Maximum light intensity corresponds to the maximum binary output value. Convert the binary reading to a decimal number and record it in the Excel Worksheet Table 5, second line.
4. Complete the Excel Worksheet Table 3 by measuring the Power Output (watts) of Solar Cell A at all four incident light angle settings.
5. Save your Worksheet.
6. Proceed to Task 4.

Task 4. Measure the Angular Response of Solar Cell B

The surface of Solar Cell B is designed with a "fisheye" lens structure so that it is less sensitive to the variation of incident sunlight angle. In Task 4 you will measure this effect and compare it to the angular response of Solar Cell A. The calculations for Task 4 can be done at the end of lab if time permits, or they can be done later.

1. Connect Solar Cell B to the DMM and resistor board with the same circuit setup that was used in Tasks 1 through 3.
2. Set the resistance on the resistor board to 20 ohms. Adjust the height of the lamp to the "Cloudy Sky Condition".
3. Place Solar Cell B directly under the light source.
4. Measure the Voltage Output and calculate the Power Output and at all four Sunlight Incident Angle Positions.
5. Save your Worksheet.
6. Turn off the lamp, disconnect the solar cell circuit, and unplug Solar Meter Breadboard.
7. DO NOT disassemble the Solar Meter breadboard!
8. Clean up your table and have your lab checkout sheet signed.
9. Continue calculations if time permits.
10. Take a copy of your Solar Cell Lab Worksheet with you.
Task 5. Data Analysis and Calculations

Below are seven sub-tasks involving data reduction, calculations, and graphing. You may work on these items in lab as time permits. Otherwise, they may be completed out of class. At times, you will be asked to describe or explain the values in these calculations. These descriptions are to be addressed in the Results section of your lab memo.

1. Complete Table 5
   a. One active area on solar cell A is 22mm by 13mm. There are 8 active areas on the cell. Calculate the total active area of solar cell A in square meters.

   b. Use the total active area to determine the watts supplied to the solar cell under the bright sky condition, which is also known as the incident power. To find the total incident power:

   \[ \text{Total Incident Power} = \text{incident watt per square meter} \times \text{area of solar cell A} \]

   Recall incident watts per square meter for a bright sky condition is 1000 w/m².

   c. Calculate the Solar Cell A power conversion efficiency by dividing the power produced by the solar cell by the power input to the solar cell. The power produced is found in the Excel Worksheet Table 2 at the zero degree incident angle.

   d. Update the Excel Worksheet Table 5 with the new calculations.

2. Complete Table 6
   a. Convert the decimal value of the light meter reading to watts per square meter by using the calibration curve supplied in Figure 25. To do this, locate the decimal value along the x-axis of the graph and use the line of the graph to find the associated incident solar intensity.

   b. Calculate Incident Power by multiplying Solar Intensity by the Active Area of Solar Cell A (in m²).

   c. Calculate the solar cell efficiency for Task 3 and check to see if it is close to the efficiency calculated in Task 2. To calculate solar cell efficiency for Task 3, Power Output at 0° divided by Incident Power which is found in the Excel Worksheet Table 3.

   d. Update the Excel Worksheet Table 6 with the new calculations.
3. Complete Table 7
   a. The active area of Solar Cell B is approximately 5.6 cm x 7.7 cm. Convert this area to square meters as you proceed with your calculations.

   b. Calculate the Solar Cell B conversion efficiency. Use the Incident Power from Table 6 and Power Output at 0° for the efficiency calculation.

4. Create and Analyze Plot 1
   a. Using the data from the Excel Worksheet Table 1, plot Power Output vs. Resistance. This is Plot 1.

   b. Determine the resistive load where the power is maximized and Power Output (in Watts) produced by the Solar Cell. Describe how the maximum power output point might affect the design of a solar cell system.

5. Create and Analyze Plot 2
   a. Using the data from the Excel Worksheet Table 2, plot Intensity vs. Power. This is Plot 2.

   b. Explain why the use of solar cells might be more appropriate in some regions of the country. Note the impact of the solar cell output efficiency for bright sky conditions.
6. Create and Analyze Plot 3
   a. Using the data from the Excel Worksheet Table 3, plot the incident angle of the light source on the x-axis and the produced power on the y-axis. This is Plot 3.

   b. For an incident angle $\Phi$, resolve the incident light into $a$ and $b$ components, where $a$ is parallel to the solar cell surface and $b$ is perpendicular to the solar cell surface (maximum absorption). Do this by calculating the $b$-component

   \[ b = P(0) \cdot \cos(\varphi) \]  

   for each of the inclination angles, where $P(0) = \text{power at } 0^\circ \text{ angle of incidence}$. Place these values into the Excel Worksheet Table 8.

   c. Determine how accurately the calculation in step b (above) predicts the produced power by comparing the values for the $b$-component in the Excel Worksheet Table 8 to the values of $P$ in the Excel Worksheet Table 3.

   d. What are the implications of this angle data on solar cell/panel placement in different geographic locations? How could automatic controls be used to address this effect?

   e. For Solar Cell A output efficiency for "Cloudy Sky Conditions", how does this value compare to solar cell output efficiency for "Bright Sky Conditions" Task 2?

7. Create and Analyze Plot 4
   a. Using the data in the Excel Worksheet Table 4, plot the incident angle of the light source on the x-axis and the produced power on the y-axis. This is Plot 4.

   b. As with Step 6b above, calculate the value of $b$ using $b = \text{power} \times \cos \Phi$ for each of the inclination angles. Place these values in the Excel Worksheet Table 9. Determine how accurately the calculation predicts the produced power by comparing the values of $b$ in Table 9 to the values of $P$ in the Excel Worksheet Table 4.
c. What function was performed by the irregular surface on Solar Cell B?

8. Local Application
   a. Calculate the size required to provide enough energy to power a single person home in Columbus.

Task 6. Clean-up Procedure
   1. Put items in the appropriate plastic storage box.
   2. The work-area should be clean after you are done with your lab.

<table>
<thead>
<tr>
<th>Item Description</th>
<th>Qty.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar Cell Energy Meter and Stand</td>
<td>1</td>
</tr>
<tr>
<td>5 Volt Modular Power Supply</td>
<td>1</td>
</tr>
<tr>
<td>Solar Cells A &amp; B</td>
<td>1</td>
</tr>
<tr>
<td>Solar Cell Stand</td>
<td>1</td>
</tr>
<tr>
<td>Resistor Board</td>
<td>1</td>
</tr>
<tr>
<td>Lamp Setup (Clamp, Stand, and Lamp)</td>
<td>1</td>
</tr>
<tr>
<td>Meter Stick</td>
<td>1</td>
</tr>
<tr>
<td>Electrical Box Equipment (banana leads, DMM)</td>
<td>1</td>
</tr>
</tbody>
</table>

Task 7. Check-Out Policy
After you have finished the lab and the clean-up procedure, have your instructor or GTA sign the “End-of-Lab Signoff” line at the end of the rubric. You will lose 5 points if this is not signed by your Instructor/TA.
Report Guidelines (Labs 04 & 05: Solar Energy Labs)
Write a Lab Memo

For details on content and formatting, see the Technical Communications Guide on Lab Memo specifications.

Lab Specific Directions

Introduction

- Clearly define the purpose of the project. First, address the overall goals and then the objectives. Briefly introduce the contents of the memo.

Results

- Briefly explain what you did to collect data.
- Provide both quantitative and qualitative data. Provide all summary tables, graphs and calculations with brief observations of the data.
  - Solar Meter (accompanying data/graphs and observations):
    - Table A: Decimal Value of Voltage vs. Voltage Input and Graph
    - Table B: Light Intensity vs. Distance and Graph
    - Solar Meter Final Questions (page 16)
  - Solar Cell: Answer questions under Calculation and Analysis. Embed all the required tables and figures in the section of results.
- Discuss any inaccurate measurements/results and what could have caused them.
- Calculate the size required to provide enough energy to power a single person home.

Discussion

- Address the Solar Meter Lab final questions and the discussion questions found for each section in Data Analysis and Calculations of the Solar Cell lab. Provide sample calculations.
- Answer the discussion questions to demonstrate the learning objectives of the Solar Meter and Solar Cell Labs.

Conclusion and Recommendations

- Develop a comprehensive conclusion from the results obtained in the lab and provide any recommendations for future lab analysis.
- Provide the election committee with specific recommendations about the plausibility of solar cells. Be sure to support your conclusion with a discussion of the significance of the data collected as well as literature from outside resources.