ENGR 1181 | Labs 4 and 5: Solar Energy Labs 1 and 2

- Preparation Material Part 1 (Lab 4)
- Lab Procedure Part 1 (Lab 4)
- Preparation Material Part 2 (Lab 5)
- Lab Procedure Part 2 (Lab 5)
- Report Guidelines (Combined)
Preparation Material Part 1:

Lab 4 – Solar Energy Lab 1
Overview of Solar Energy Lab 1

In Solar Energy Lab 1 (Solar Meter Lab) you will build a solar energy meter to measure the energy intensity from an overhead floodlight (simulating the energy intensity of sun light).

Learning Objectives – students will be able to:

1. Describe, build and calibrate a solar energy meter circuit.
2. Convert binary bits to decimal numbers.
3. Explain how a potentiometer works.
4. Explain how a photodiode light sensor works.
5. Use a schematic diagram to build a working electronic circuit.
6. Use a Photodiode Light Sensor and a Binary Voltmeter circuit to measure the intensity of simulated sun light (in Watts/m²).

Figure 1: 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 can be collected by solar cell arrays to generate electricity (renewable energy).
What is a Binary Voltmeter Calibration Circuit?

The Binary Voltmeter measures the voltage at V Input and converts that voltage into an 8-Bit Binary Number. That Binary Number is shown on the output LED indicator lights marked "D7 D6 D5 D4 D3 D2 D1 D0 (Figure 2). If an LED is "ON", it is a binary "1". If the LED is "OFF", it is a binary "0".

The function of the DMM is to measure and record Voltage values in the calibration process.
Binary numbers are used in computers because computers are made from transistors which are either "ON" (Binary 1) or "OFF" (Binary 0). All numbers in computers (and program instructions) are written and stored as binary bits – a combination of 1’s and 0’s.

An 8-Bit Binary Number is a combination of 1’s and 0’s:

$$N_{binary} = d_7 \cdot d_6 \cdot d_5 \cdot d_4 \cdot d_3 \cdot d_2 \cdot d_1 \cdot d_0$$  \hspace{1cm} (1)

The Decimal Equivalent of the Binary Number can be calculated by:

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

or

$$N_{decimal} = d_7 \cdot 128 + d_6 \cdot 64 + d_5 \cdot 32 + d_4 \cdot 16 + d_3 \cdot 8 + d_2 \cdot 4 + d_1 \cdot 2 + d_0 \cdot 1$$  \hspace{1cm} (2)

Counting in binary works the same as counting in decimal. Instead of using the numbers 0-9, binary uses only ones and zeroes. Counting up from 0 in binary is shown in Table 1. From the Table, it can be seen that the largest Decimal Number that can be represented by an 8-Bit Binary Number is 2^8-1 = 255. A 16-Bit Binary Number can represent numbers from 0 to 2^{16}-1 (0 to 65,535). Most computers use either 32-Bit or 64-Bit binary numbers.

### Table 1: 8-Bit Binary Numbers and their Decimal Values

<table>
<thead>
<tr>
<th>8-Bit Binary Number</th>
<th>Decimal Equivalent</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 0 0 0 0 0 0</td>
<td>0</td>
</tr>
<tr>
<td>0 0 0 0 0 0 1</td>
<td>1</td>
</tr>
<tr>
<td>0 0 0 0 0 1 0</td>
<td>2</td>
</tr>
<tr>
<td>0 0 0 0 0 1 1</td>
<td>3</td>
</tr>
<tr>
<td>0 0 0 0 1 0 0</td>
<td>4</td>
</tr>
<tr>
<td>0 0 0 0 1 0 1</td>
<td>5</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>1 1 1 1 1 1 0</td>
<td>254</td>
</tr>
<tr>
<td>1 1 1 1 1 1 1</td>
<td>255</td>
</tr>
</tbody>
</table>

Look again at Figure 2 (previous page) 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 binary numbers "1" and "0"
3. D7 is the Most Significant Bit (MSB). D0 is the Least Significant Bit (LSB)
4. Equation 2 can be used to convert any 8-bit binary number to a decimal number
• **Example for converting a Binary Number to its equivalent Decimal Number**

For example, convert the Binary Number 0 0 0 0 0 1 0 1 into a Decimal Number:

\[
N_{\text{decimal}} = 0 \cdot 128 + 1 \cdot 64 + 0 \cdot 32 + 0 \cdot 16 + 0 \cdot 8 + 1 \cdot 4 + 1 \cdot 2 + 0 \cdot 1 = 70
\]

![Binary Number Example](image)

Figure 3: Given a Binary Number, calculate its Decimal Value

• **How is the Binary Voltmeter Circuit calibrated?**

To calibrate the Binary Voltmeter circuit, we will use a Trimpot (an abbreviated name for Trimming Potentiometer – Figure 4). Trimpots are used in electronic circuits to make adjustable resistors.

Turning the knob on the Trimpot causes a slider to vary the resistance between terminals 1 and 2 and between terminals 2 and 3. The total resistance between terminals 1 and 3 is a constant – that is the resistance value of the Trimpot (in this case 10 kOhms).

In the Trimpot circuit shown in Figure 4, notice that bottom end of the Trimpot (Pin 1) is connected to Ground, the top end (Pin 3) is connected to +5 Volts, and the Slider (Pin 2) is the Trimpot Output (called \(V_{\text{adj}}\) for "Adjustable Voltage Output").

![Trimpot Circuit](image)

Figure 4: Schematic of the Trimpot (left above) and a picture of the Trimpot Circuit Board

The Calibration Procedure is as follows:

• Set the Voltage Output of the Trimpot to values between 0 and +5 Volts in 0.5 Volt steps.
• Read and record the 8-Bit Binary Number output displayed on the LEDs
• Convert that Binary Number to its Decimal Equivalent
• Plot the Binary Voltmeter Calibration values in an Excel Spreadsheet (a plot of Decimal Number output vs Voltage input)
The Solar Energy Meter Circuit

Figure 5: Schematic of the Solar Energy Meter Circuit

Figure 5 shows the schematic of the 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 to +5 Volts

- **Binary Voltmeter Board**
  - Changes the input voltage signal (V Input) to 8 binary Bits (the LEDs)

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

- **Wires**
  - Are shown as the lines between components that connect the parts together electrically and are used to connect the circuit boards to +5 Volts and ground. The symbol for "Ground" is the four small horizontal lines that form an inverted triangle pointing down.
• **How does the Light Sensor work?**

The Figure 6 shows the Light Sensor circuit board.

![Image of Light Sensor circuit board](image)

The Photodiode contains a silicon chip that converts light photons to electrical current. The current generated is proportional to the light intensity falling on the Photodiode. The Amplifier converts that current to a voltage. The Voltage Output of the Light Sensor is proportional to the intensity of sunlight on it \((I_{solar} \text{ in Watts/m}^2)\). The calibration equation for the Solar Light Meter is:

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

In order to use the Solar Energy Meter:

• Place it at the location where you want to measure light intensity
• Read the binary digits indicated by the LEDs
• Convert the 8-Bit Binary Number to its Decimal Value (using Equation 2)
• Multiply the Decimal value by 5 (Equation 3) and that equals \(I_{solar}\) in Watts/m²

• **Lab Preparation Assignment**

In order to finish your preparation for the Solar Energy Lab 1:

• Take the Solar Energy Lab 1 quiz (on Carmen)
• Preview the following Solar Energy Lab 1 Procedure
Lab Procedure Part 1:

Lab 4 – Solar Energy Lab 1
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 a house in Columbus, Ohio using the incident values from the results.
2. Is installing solar panels on the roofs of newly constructed homes feasible?

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

1. The average energy use per person in an Ohio 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.
Solar Energy Lab 1 Setup

Figure 7: Solar Energy Lab 1 Setup
Task 1. Build the Calibration Circuit and measure the Power Supply Voltage

1. Build the Binary Voltmeter Calibration Circuit shown in Figure 8.
2. The short wire on the LEDs goes to Ground.
3. Plug the +5 Volt Modular Power Supply into an AC outlet.
4. Plug the positive DMM Probe wire into +5 Volts and plug its negative wire into Ground.
5. From the DMM verify that the Power Supply voltage is close to +5V. If it is significantly different from +5V, notify a member of the instructional team.

![Binary Voltmeter Calibration Circuit](image1)

Figure 8: The Binary Voltmeter Calibration Circuit for Task 1
ENGR 1181 Labs 04 & 05: Solar Energy Labs
Lab 04: Solar Energy Lab 1 Procedure

Task 2. Calibrate the Binary Voltmeter Circuit using the "Trimpot" as a variable voltage

In the Trimpot circuit shown in Figure 9, notice that bottom end of the Trimpot (Pin 1) is connected to Ground, the top end (Pin 3) is connected to +5 Volts, and the Slider (Pin 2) is the Trimpot Output (called $V_{adj}$ for "Adjustable Voltage Output").

1. Go to the course website on the Lab 4 webpage and download and open the Solar Energy Lab Worksheet.
2. Plug the positive DMM Probe wire into V Input on the Binary Voltmeter Board and plug the negative wire into Ground exactly as shown in Figure 8.
3. Turn the Knob on the Trimpot fully counter-clockwise (CCW) until the DMM reads 0 Volts.
4. Read and record the LED Binary Output reading in the Task 2 part of the worksheet (it should be 0 0 0 0 0 0 0 0).
5. Turn the Knob on the Trimpot a bit Clockwise (CW) until the DMM voltage is close to 0.5 Volts. Close is anywhere between 0.4 and 0.6 Volts.
6. Record the value of V Input (on the DMM) and the LED Binary Output reading in the worksheet.
7. Repeat step 5 and 6 above, in 0.5 Volt increments, until all DMM voltages and LED Binary output numbers have been recorded in the worksheet.
8. The last reading should be taken with the Trimpot turned fully clockwise.

Converting from Binary to Decimal:

An 8-Bit Binary Number is a combination of 1's and 0's:

$$N_{binary} = d_7 \cdot d_6 \cdot d_5 \cdot d_4 \cdot d_3 \cdot d_2 \cdot d_1 \cdot d_0$$

The Decimal Equivalent of any Binary Number can be calculated by:

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

or $$N_{decimal} = d_7 \cdot 128 + d_6 \cdot 64 + d_5 \cdot 32 + d_4 \cdot 16 + d_3 \cdot 8 + d_2 \cdot 4 + d_1 \cdot 2 + d_0 \cdot 1$$
Light Sensor Board for Tasks 3 & 4

The Silicon Photodiode on the Light Sensor board is sensitive to light. Look at 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 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 and turns it into a voltage, V Out, which you measure using the Binary Voltmeter.

The Solar Energy Meter is designed so that the intensity of light measured ($I_{solar}$, in Watts/m$^2$) is related to the output of the Binary Voltmeter ($N_{decimal}$) by the equation:

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

Figure 10: Light Sensor board with Photodiode
Task 3. Build the Solar Energy Meter Circuit

1. Remove the TrimPot and its wires from the Breadboard.
2. Plug the Light Sensor board into the breadboard exactly as shown in Figure 11.
3. Add wires exactly as shown in Figure 11.
4. Notice how the Light Sensor is placed far to the left. This will make it easier to read the LED’s when they are under the bright light source in Task 4.

Figure 11: The Solar Energy 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 Solar Energy Meter 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 see the LEDs better (Some LEDs will keep blinking make your best guess as to call it on or off).
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. The Excel Worksheet Table B is located under the “Part 1: Solar Meter” tab in the Excel Worksheet.

**Before continuing to Task 5, complete 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!

**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 Final Questions located at end of lab with your group. 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. If your lab is the final lab of the week, please leave your breadboard assembled.
2. Put items in the appropriate plastic storage box.
3. The work-area should be clean after you are done with your lab.
Final Questions for Solar Energy Lab 1:

1. What function did the potentiometer perform in this circuit?

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

3. What is the decimal value for the following binary values?

   100 =
   1001=
   10000=
   010101=

<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 Energy Lab 1 Memo is not due at the beginning of the Solar Energy Lab 2. The Solar Labs are a combined lab memo due after Solar Energy Lab 2 is completed. The *Report Guidelines* covers both labs and is at the end of this document.

**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 of grading guideline (rubric).** You will lose 5 points if this is not signed by your Instructor/TA.
Preparation Material Part 2:

Lab 5 – Solar Energy Lab 2
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 13 shows how these two layers form a solar cell.

![Figure 13: A Solar Cell](image)

The two layers have a concentration difference of electrons, one with excess and the other with deficiency of 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.

Figure 14 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 (environmentally 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 a phone 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 15).
The solar cell generates power from sunlight and delivers that power to the resistor, where it ends up being dissipated as heat, or:

\[
P_{\text{output from the Solar Cell}} = P_{\text{out}} = I \cdot V = I^2 R = \frac{V^2}{R} \text{ in Watts}
\]  

(4)

The power conversion efficiency of the Solar Cell is:

\[
\text{Efficiency} = \eta = \frac{P_{\text{out}}}{P_{\text{in}}}
\]

(5)

\[
\text{Power Conversion Efficiency} = P_{\text{out}} \cdot 100
\]

(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**

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 Energy 2 (Solar Cell) quiz on Carmen
- Preview the following Solar Energy Lab 2 Procedure
Lab Procedure Part 2:

Lab 5 – Solar Energy Lab 2
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.
Solar Energy Lab 2 Setup

Figure 17a: Lab Equipment

Figure 17b: Laboratory Equipment (Solar Cells)

* Solar Cell A: 5.1 cm x 2.05 cm
* Solar Cell B: 5.6 x 7.7 cm
Figure 18: Lamp Stand Setup

Figure 19: Breadboard and its support platform
Task 1. Investigate Power Output as a Function of Resistance

1. Set up Solar Cell A according to the Figures 20 and 21 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 20: Solar Cell A - connection diagram](image1)

![Figure 21: Solar Cell A connected to the Resistor Board and the DMM](image2)
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 22. 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.
**ENGR 1181 Labs 04 & 05: Solar Energy Labs**  
**Lab 05: Solar Energy Part 2 Lab Procedure**

**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/m²).

   The binary code that represents a bright sky is "1 1 0 0 x x x x", so that the left 4 LEDs should be "ON ON OFF OFF" in order. (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/m²) 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/m²). A cloudy sky corresponds to a binary output of "0 0 1 1 x x x x". 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 and 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 is directly related to the cosine function of the incident angle of sunlight varying during the day, 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. Use the lamp height for the "Cloudy Sky Condition". Place Solar Cell A directly under the light source.
2. Set the resistance on the resistor board to the Maximum Power Output switch setting which was found in the Excel Worksheet Table 1.
3. Find the location on the table that gives maximum light intensity. Maximum light intensity will correspond to the maximum voltage reading on the DMM. Complete the Excel Worksheet Table 3 by measuring the Voltage Output and calculating the Power Output for Solar Cell A at all four Sunlight Incident Angle Positions.
4. Save your Worksheet.

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 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 Energy Lab 2 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.

   \[
   \text{Total Active Area of Solar Cell A} = 22 \text{mm} \times 13 \text{mm} \times 8 = 2288 \text{mm}^2 = 0.2288 \text{m}^2
   \]

   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 active area:

   \[
   P_{\text{total active area}} = \text{Incident Watts per square meter} \times \text{area of solar cell A}
   \]

   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 23. 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 (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 (measured data) and Table 8 (theoretical data), 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 Φ, 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

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

for each of the inclination angles, where \( P(0) \) = power at 0° 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.

   ![Figure 24: Incident Light on Solar Cell](image)

   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 (measured data) and Table 9 (theoretical data), 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 \( b = \text{power}(P) \cdot \cos(\Phi) \) 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 grading guideline (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

As a team, write the introduction, results, and discussion parts of this lab memo according to the instructions below and grading guideline. **The conclusion part must be prepared individually.** 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 Energy Lab 1 (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 Energy Lab 2: Answer questions under Calculation and Analysis

Discussion

- Discuss any inaccurate measurements/results and what could have caused them.
- Calculate active area (in square meters) of solar panels required to provide enough energy to power a single home in Ohio. Is installing solar panels on roofs of newly constructed homes feasible?
- Address the Solar Energy Lab 1 final questions and the discussion questions found for each section in Data Analysis and Calculations of the Solar Energy Lab 2. Provide sample calculations.
- Answer the discussion questions to demonstrate the learning objectives of the two Solar Energy Labs.

Conclusion and Recommendations (Individual part)

- 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.