HOW A SOLAR CELL PRODUCES ELECTRICITY

INTRODUCTION
Look at the solar cell your teacher has given you. Hold it in your hand. It does not appear to have much substance; it’s just a thin wafer of solid material, with one side colored dark blue or black and the other colored a silvery gray. On many cells, the dark blue-black side may have thin wires on it. The cell weighs very little, has no moving parts and does not feel warm. In fact, the solar cell does not look like it could do anything, yet it is capable of producing electricity. How does it work?

HOW SOLAR CELLS ARE MADE
Look again at your solar cell. Even though it is very thin, it is made up of two layers of semiconductor material. The semiconductor layers in most solar cells are made of silicon, although solar cells can be made from other materials as well.

Silicon is used to make solar cells because it can be mixed with other substances to change its electrical behavior in

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a certain way. Look at the side that appears dark blue or black. This side is called the “n-layer.” The “n” stands for “negative” because it is made by mixing silicon with substances that have more electrons than it has. Underneath the n-layer is the “p-layer.” The “p” stands for “positive” because it is made by mixing silicon with substances that have fewer electrons than it has. You cannot see the p-layer by looking at the back of the solar cell because it is covered by a silvery-gray material, and may also have a stiff-backing material attached to it. The silvery-gray material helps the cell conduct electricity when it is connected to an electrical circuit. The stiff backing supports the cell and keeps it from breaking.

When the two layers are placed together, a few of the electrons from the n-layer move into the p-layer. When this happens, an electrical barrier is automatically created, keeping the rest of the electrons in the n-layer separated from the p-layer. This barrier, which is only a few millionths of an inch thick, is formed at the boundary of the n- and p-layers when the solar cell is manufactured.

**USING LIGHT TO PRODUCE ELECTRICITY**

What happens when light shines on the solar cell? The light knocks electrons loose in the p-layer and sends them into the n-layer. The barrier, which acts like a one-way door, lets the electrons cross into the n-layer but stops them from going back to the p-layer. This gives the n-layer a negative charge and the p-layer a positive charge. It is as if light were turning the solar cell into a kind of battery.

When the solar cell is connected in a circuit with, for example, a small light bulb, the electrons flow as electric current from the n-layer, through the wire and the bulb, to the p-layer. As electrons arrive at the p-layer of the cell, light sends them back into the n-layer, where they again flow through the circuit. Electric current will continue to flow as long as light is shining on the cell. The current can be used not only to light a small bulb, but also to run a small electric motor or a radio.

Groups of solar cells can also be connected into circuits to produce larger amounts of current than can be produced by a single cell.

When the n-layer and the p-layer are placed together, a few of the electrons from the n-layer move into the p-layer. When this movement happens, an electrical barrier is automatically created, keeping the rest of the electrons in the n-layer separated from the p-layer. This barrier, which is only a few millionths of an inch thick, is formed at the boundary of the n- and p-layers when the solar cell is manufactured.

Look once more at the solar cell, a device that can produce electricity simply by shining light on it. Miraculous, isn’t it?
ELECTRICAL BARRIER FORMED AT THE BOUNDARY OF THE N- AND P-LAYERS OF A SOLAR CELL

Electrons in the n-layer are kept out of the p-layer by the electrical barrier.

SOLAR CELL IN A CIRCUIT
DEMONSTRATING HOW A SOLAR CELL PRODUCES ELECTRICITY

INTRODUCTION
Another way to help students understand how a solar cell produces electricity is to have them play the role of electrons in a solar cell connected to an electrical circuit. Refer to How a Solar Cell Produces Electricity for further background discussion.

SETTING UP THE DEMONSTRATION

Mark off a portion of the classroom floor with two areas connected together. These areas represent the n-layer and the p-layer of the solar cell, with the boundary between them being the p-n junction. Mark the p-layer area with a “+” sign and the n-layer area with a “−” sign. Mark off a path around the classroom from the top of the n-layer to the bottom of the p-layer. This path represents the wire of an electric circuit connected to the solar cell (connecting an electrical device to the circuit is discussed later on).

Choose eight students to be electrons in the solar cell. Have three electrons stand in the area representing the p-layer, and five electrons stand in the area representing the n-layer.

Choose four or five other students to represent the barrier that forms at the p-n junction. Have them stand along the boundary between the two areas to form a barrier. The barrier students’ job is to act like a one-way door by allowing electrons to pass from the p-layer into the n-layer but not from the n-layer into the p-layer.

SETTING UP THE DEMONSTRATION IN THE CLASSROOM

(Diagram 1)
Give an additional student a flashlight to represent the sun. Have the sun stand facing the n-layer so the barrier and the p-layer are directly behind it. The flashlight is not to be turned on until everyone is ready. Select another student to be an electrical device. Have this student hold an electrical device that turns on and off easily. Examples of electrical devices include radios, cassette tape decks, small fans or toys. A flashlight or small desk lamp may be acceptable as long as students do not confuse it with the flashlight that represents the sun. Have the electrical device stand somewhere alongside the circuit, but not too close to the solar cell. He or she is not to turn on the electrical device until electrons start moving through the circuit. Have the remaining students be electrons in the circuit wire and position them evenly along the path that represents the circuit.

**Demonstrating How the Solar Cell Works (Diagram 2)**

When everyone is ready, have the sun shine the flashlight onto the solar cell so the light passes through the n-layer and barrier into the p-layer. When light shines on the electrons in both layers, they should begin moving around. Light shining on the electrons in the p-layer causes them to move one by one toward the n-layer. The barriers allow these electrons to pass into the n-layer momentarily. However, the barriers prevent or block excited electrons in the n-layer and any electrons that just crossed over from the p-layer into the n-layer from moving into the p-layer.
By now the n-layer is getting crowded with electrons who are repelling each other because they all have the same negative charge. Since they can’t get past the barriers, the only place for them to go is into the circuit. Have the first electron enter the circuit. The instant this happens, the electron in the circuit who is nearest to the p-layer should step into the p-layer area. Doing so signals all the electrons in the circuit to begin walking single file (not in clumps) along the circuit path toward the p-layer. After electrons enter the p-layer from the circuit, they should stay there momentarily until it is their turn to enter the n-layer.

At the same time the electrons start to move, the electrical device turns on the device being held. The electrical device should be turned on as long as the sun is shining and electrons are flowing as electrical current in the circuit.

With practice, the electrons should move smoothly (flow as current) from the p-layer, to the n-layer, through the circuit, and back to the p-layer. When electrons have learned to flow as current through the solar cell and the circuit, have them alternately flow and stand still as the flashlight is turned on and off. This corresponds to exposing the solar cell to sunlight and then suddenly covering it, reinforcing the idea that light causes the solar cell to produce electricity. The electrical device should also turn the device on and off accordingly.
EXPERIMENTS WITH SOLAR CELLS

INTRODUCTION
How much electricity can a solar cell produce under different lighting conditions? These four experiments will help you answer this question.

MATERIALS NEEDED FOR ALL FOUR EXPERIMENTS
• Small solar photovoltaic cells with at least a 0.4 volt output
• DC ammeter with a range of approximately 0 to 10 amps
• DC voltmeter with a low rating (1 or 5 volts DC minimum rating is fine)
• Graph paper

CONNECTING THE SOLAR CELL TO AN AMMETER AND A VOLTMETER
In each experiment, you will be measuring the current and voltage produced by the solar cell. The cell’s current is measured using an ammeter, while the voltage is measured using a voltmeter. The diagrams below show how to connect your solar cell to each meter. Your teacher will help you learn how to read the meters.

EXPERIMENT 1: SOLAR CELLS AND LIGHT INTENSITY
This experiment investigates how changes in light intensity affect the amount of current and voltage a solar cell can produce.

ADDITIONAL MATERIALS NEEDED
• A bright, directional light source, such as a shaded desk lamp or a clip-on reading lamp, with a 100-watt bulb

PROCEDURE
1. Place the solar cell 3 inches (7.6 cm) from a bright, directional light source other than the sun. The solar cell should directly face the light source.
2. Measure the current and the voltage of the cell at a distance of 3 inches (7.6 cm). Record results on the Light Intensity Table on next page.
3. Repeat Steps 1 and 2 for distances of 6 inches (15.2 cm), 9 inches (22.9 cm), and 12 inches (30.5 cm).
4. Sketch a graph that shows the relationship between current and the solar cell’s distance from the light source. Label the horizontal (x) axis of the graph “distance from light source” and mark it with the distances shown in the Light Intensity Table. Label the vertical
(y) axis “current” and mark it based on the readings from the Light Intensity Table. Plot the values of current corresponding to each distance on the graph.

5. Sketch another graph that shows the relationship between voltage and the solar cell’s distance from the light source. Label the horizontal (x) axis of the graph “distance from light source” and mark it with the distances shown in the Light Intensity Table. Label the vertical (y) axis “voltage” and mark it based on the readings from the Light Intensity Table. Plot the values of voltage corresponding to each distance on the graph.

**QUESTIONS**

1. Using the Light Intensity Table and graphs, state the relationship between the current produced by the solar cell and the cell’s distance from the light source. Then state the relationship between the voltage produced by the solar cell and the cell’s distance from the light source.

2. Based on your results, would the solar cells produce more electricity on a sunny day or a cloudy day? Why?

3. Predict the time of day when the solar cells will produce the most electricity.

**EXPERIMENT 2: SOLAR CELLS AND THE ANGLE OF THE LIGHT SOURCE**

This experiment investigates how the angle between the sun and the solar cell affects the amount of current and voltage a solar cell can produce.

**ADDITIONAL MATERIAL NEEDED FOR THIS EXPERIMENT**

- Protractor

**PROCEDURE**

1. Point the solar cell directly at the sun or at the light source. Slant the cell so its shadow is directly behind it, with the cell’s face perpendicular to the sun’s rays. (One way to discover the sun’s direction is to insert a stick in the ground and tilt it until it has no shadow.) Measure the current and voltage, and record them under the column of the Angle Table that reads “90°.”
2. Tilt the solar cell back at an angle 15° from the perpendicular or 75° to the sun’s rays. Use the protractor to determine this angle. Measure the current and voltage of the solar cell, and record them under the column of the Angle Table that reads 75°. Continue decreasing the angle of the cell at 15° intervals (60°, 45°, 30°, 15°) and record current and voltage measurements under the appropriate columns of the Angle Table.

3. Sketch a graph that shows the relationship between current and the angle of the solar cell to the sun’s rays. Label the horizontal (x) axis of the graph “angle of solar cell” and mark it with the angles shown in the Angle Table. Label the vertical (y) axis “current” and mark it based on the readings from the Angle Table. Plot the values of current corresponding to each angle on the graph.

**Questions**

1. Describe the relationship between the current produced by the solar cell and the cell’s angle to the light source. Then state the relationship between the voltage produced by the solar cell and the cell’s angle to the light source.

2. The electricity produced by a solar cell held in one position will vary throughout the day due to the change in the position of the sun. What would you need to do to keep the solar cell producing the same amount of electricity throughout most of the day?

**Challenge Question (optional)**

3. The graph showing the current with respect to the angle of the solar cell to the sun is called a sinusoidal curve because it is based on a trigonometric relationship called the sine function. Show how the graph you sketched is related to this function.

<table>
<thead>
<tr>
<th>Angle of Solar Cell to Light Source</th>
<th>90°</th>
<th>75°</th>
<th>60°</th>
<th>45°</th>
<th>30°</th>
<th>15°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current (Amps)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Voltage (Volts)</td>
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</tbody>
</table>
EXPERIMENT 3:
SOLAR CELLS AND
CONCENTRATED LIGHT

This experiment considers how concentrating the light on a solar cell affects the amount of electricity it produces.

ADDITIONAL MATERIALS NEEDED
FOR THIS EXPERIMENT
• Cardboard
• Aluminum foil
• Glue
• Magnifying glass (optional)

PROCEDURE
1. Measure the current and voltage of the solar cell under the sun or a strong light source, and record the results in the Concentrated Light Table. Make sure the angle and distance between the cell and the light source are the same throughout the experiment.
2. Make a cardboard reflector to concentrate light onto the solar cell. Cut out the cardboard shape in the diagram below and glue aluminum foil on the four flaps. Place the solar cell in the base and fold up the four sides to reflect light on the cell. Make sure the angle of the cell and its distance from the light source are the same as they were in Step 1. Measure the current and voltage produced by the cell, and record the results in the Concentrated Light Table.
3. As an option, use a magnifying glass to concentrate light onto the solar cell. To do this, move the magnifying glass around until a bright area appears on the cell. Make sure the angle of the cell and its distance from the light source are the same as in Step 1. Measure the current and voltage produced, and record the results in the Concentrated Light Table.

CONCENTRATED LIGHT TABLE

<table>
<thead>
<tr>
<th>Nature of Light Source</th>
<th>Not Concentrated</th>
<th>Concentrated Using Aluminum Foil Reflector</th>
<th>Concentrated Using Magnifying Glass (optional)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current (Amps)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Voltage (Volts)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
**QUESTIONS**

1. Does concentrating the light on the solar cell increase the current it produces? If so, by how much?
2. Does concentrating the light on the solar cell increase the voltage it produces? If so, by how much?
3. Compare the amount of current and voltage produced by the solar cells using the aluminum foil reflector and the magnifying glass. Which method of concentrating light produces more current and voltage? (Optional)

**EXPERIMENT 4: SOLAR CELLS IN SERIES AND PARALLEL CIRCUITS**

This experiment investigates how much current and voltage is produced when solar cells are connected in series and parallel circuits.

**ADDITIONAL MATERIALS NEEDED FOR THIS EXPERIMENT**

- Two to 4 short wire leads with alligator clips on each end
- One or two additional solar cells

**NOTE:** You may need to share solar cells with other groups if your teacher has not given you additional ones.

**PROCEDURE**

1. Connect two or three solar cells in a series circuit as shown in the diagram. Record how many cells you have connected in the Series and Parallel Circuit Table. Place the series circuit under the sun or a strong light source. Measure the current and voltage produced, and record the results in the Series and Parallel Circuit Table.

2. Connect two or three solar cells in a parallel circuit as shown in the diagram. Record how many cells you have connected in the Series and Parallel Circuit Table. Place the parallel circuit under the sun or a strong light source. Measure the current and voltage produced, and record the results in the Series and Parallel Circuit Table.

**QUESTIONS**

1. Which circuit produced the most current? State a general relationship between the number of cells in this kind of circuit and the amount of current it produces.

2. Which circuit produced the most voltage? State a general relationship between the number of cells in this kind of circuit and the amount of voltage it produces.
3. Suppose you wanted to produce increased amounts of current and voltage using several solar cells connected together. How would you connect them? Draw a circuit diagram below showing the way you would connect the cells.

<table>
<thead>
<tr>
<th>Number of Solar Cells in Circuit</th>
<th>Voltage (Volts)</th>
<th>Current (Amps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Series</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Parallel Circuit</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
B. FROM ENERGY TO ELECTRICITY

INSOLATION GRAPH EXERCISE

BACKGROUND:
When you do an experiment, there are usually two ideas you are working with, such as time of year and the amount of solar energy. The question is, how do you know which side of the graph is used for the time of year versus the amount of solar energy?

The two variables shown on a graph are termed INDEPENDENT and DEPENDENT. When designing an investigation, one of the values will always depend on the value of the other. For example, we could place a cup of room temperature water onto a hot burner and record temperatures and times as it heated up. In this example, time marches on no matter what we do with the experimental setup. It is independent of the experimental design. The independent variable usually has the same interval between each data point. On the other hand, temperature changes produced depend on when we take the data, obviously the water will get hotter the longer it is on the burner. Thus, temperature is the dependent variable as its value is determined by when we take the data. The independent variable is always on the horizontal, or x-axis of the graph. The dependent variable is always placed on the vertical, or y-axis of the graph.

The next step is to determine the SCALE to be used for each variable. The scale is the numbering system used for labeling the axis of a graph so data can easily be determined by looking at the graph. The basic rule is to choose an interval between the labeled lines that will make the data line large enough to fill about two-thirds of the available graph paper.

A graph is a common and useful way to show the results of an experiment because it makes visual the findings of an experiment.

EXTENSIONS
Have students graph data of the daily hour by hour kilowatts collected. Graph with the hours of the day in military time. Second, third and fourth lines can be added to this graph at three-month intervals (March 21, June 21, September 21 and December 21). Lead a discussion on day length and incoming solar radiation and the power output by the panels.

Another graphing assignment is with the same day but with data from different angle panels such as Memorial High School at 45 degrees and West High School at 25 degrees. The students again need to use military time. Ask them to interpolate and extrapolate their graphs. This graph leads to discussion on sun angle.

If you have access to multi-meters and solar panels, build on the question of the sun’s angle. Have students use a multi-meter to measure voltage charged by a solar energy panel. Attach alligator clamps on the panel to the wires on the multi-meter. Connections are color coded. Attach black to black and red to red.
### PROJECT DETAIL: YEARLY INSOLATION GRAPH EXERCISE

<table>
<thead>
<tr>
<th><strong>SUMMARY:</strong></th>
<th><strong>TIME:</strong></th>
<th><strong>MATERIALS:</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>By graphing data students will learn how the time of day and the time of year affect solar energy.</td>
<td>Preparation: 15 minutes</td>
<td>Computer with graphing program and internet connection or graph paper and colored pencils.</td>
</tr>
<tr>
<td><strong>OBJECTIVES:</strong></td>
<td>Activity: 50 minutes</td>
<td></td>
</tr>
<tr>
<td>Students will be able to:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>* Make a graph using correct graphing techniques.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>* Interpolate a graph.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>* Draw conclusions from a graph.</td>
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</tbody>
</table>

### PROCEDURE:

**Orientation:**
Discuss with students the terms INDEPENDENT, DEPENDENT and SCALE. Familiarize students with MGE’s Web site.

**Steps:**
1. Discuss elements of graph procedure:

   - **Rule #1** Graphs must be done neatly if they are to explain experiments clearly.
   - **Rule #2** Always label graph. Label the two variables with the name and units.
   - **Rule #3** If the graph has more than one data line plotted on it, use different colors or symbols in plotting the information and make a key indicating what each color or symbol signifies.

**TIME:**
Preparation: 15 minutes
Activity: 50 minutes

**MATERIALS:**
Computer with graphing program and internet connection or graph paper and colored pencils.

**GETTING READY:**
Retrieve the monthly kilowatt-hours produced by one of the MGE solar schools solar panels from MGE’s Web site. Make a few copies of MGE’s Web site in case you experience technical problems during the class period when retrieving data.

**ASSESSMENT:**

**Formative:**
- Can students accurately describe the elements of a graph?
- Can students interpolate and extrapolate a graph?

**SUMMATIVE:**
Challenge students to find other factors related to the kilowatts produced with the solar panels and graph them.
students place their PV cell in sunlight and read the meter. Assign them to move their panel to various angles (0 degrees, 45 degrees, and 90 degrees). Then have them place aluminum foil around their PV cell and repeat the tests.

Follow this up with a discussion. Which angle gave the best results? Which combination gave the best results? Why?

Based on this experiment, have students make a drawing illustrating the maximum solar input. Include the following: the sun, PV panel, angle, etc.

A final graphing assignment could be to graph the average daily temperature and the amount of energy output in kilowatts produced. Lead a discussion around incoming solar radiation and temperatures.

CREDITS:
Activity adapted from lesson plans designed by:
Tyler Spence, Memorial High School
Tom Palmer, Abundant Life Christian School

PROCEDURE

Orientation:
1. Discuss with the class the characteristics of the best location for a solar energy array. Familiarize students with MGE’s Web site comparing the solar output of various panel arrays. Discuss the impact of location and angle arrangement on photovoltaic output.
2. After deciding on a location, ask what conditions will affect the solar energy output throughout the year.
3. Students should note the seasonal angle of the sun, length of daylight hours and cloudiness.
4. Focus on cloudiness. Discuss exactly how cloud cover affects solar energy output and ask the students how they could know what the cloud cover might be like in the short-term future.
5. Students should identify satellite imagery and weather maps as key predicting tools of cloudiness.
6. Stress the short-term predictability of satellites and maps and ask the stu-
Students if they can think of any way of predicting the cloud cover in the long term.

**STEPS**

1. Prior to beginning the activity, collect "baseline data" for energy output for your location. Take the average energy output for two sunny days, two partly sunny days, and two overcast days. Fill these in on the prediction worksheet for the use of the students.
2. Begin printing off each day, starting Sunday, the surface analysis map for the noontime hour.
3. Each day, Sunday through Tuesday, have a student record the total solar energy output for the day on the surface analysis map so students can analyze the map and note its relation to the solar output.
4. On Wednesday, pass out the prediction worksheet. The students should fill in their solar output predictions for Thursday, Friday and Saturday in pen.
5. Each day, have the students go to MGE’s Web site (www.mge.com) and record the daily solar energy output for the previous day. The students can then compare their predicted value to the actual value and calculate their percent error for the day. Values should be recorded on the prediction worksheet.
6. The following Monday, students can finish their evaluations and calculate their weekly percent error value.
7. On the second Wednesday, the activity starts again with the personal goal to achieve a lower-percent error during the second week.
8. Individual competition may suffice, however class competition may be desirable.

**CLOSURE**

1. Have students investigate the climatic data for the region, focusing on the cloudiness. Have them hypothesize why certain times of the year are typically more cloudy or clear.
**PROJECT DETAIL: PREDICTING PV OUTPUT EXERCISE**

<table>
<thead>
<tr>
<th>SUMMARY</th>
<th>TIME:</th>
<th>MATERIALS:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Students will learn to predict photovoltaic output by analyzing surface weather maps.</td>
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</tbody>
</table>

**OBJECTIVES:**

Students will be able to:

- Predict the movement of weather systems across the United States using meteorology skills and simple mathematical computations.
- Make educated guesses based on patterns within collected data.
- Improve forecasting skills based on analysis of past predictions.

**TIME:**

- Preparation: 20 minutes
- Activity: Four 50-minute class periods

**MATERIALS:**

- Internet access
- A week of daily maps
- Prediction worksheet

**GETTING READY:**

1. One week before the activity is run in class, have the students collect “baseline data” on the effects of cloudiness on solar PV output of one of the MGE Host Schools. Pick an overcast day, a partly sunny day and a clear day and record the solar PV output for these conditions. These values will aid in the PV output predictions the following week.

2. Print daily surface analysis maps starting on Sunday of the week you will begin this activity. Print the analysis at the same time everyday. On Wednesday, give these four maps (Sunday through Wednesday) to the students.

3. Make copies of the PV Prediction worksheet.

**ASSESSMENT:**

**FORMATIVE:**

1. Will the baseline data collected at the beginning of the activity be able to be used year round? Why or why not?
2. Did your estimations become more accurate from the first week to the second week? Try to explain why or why not.
3. What type of pressure system will typically bring sunny skies? Cloudy skies? Use what you know about meteorology to explain this phenomenon.

**SUMMATIVE:**

1. Have students investigate where in the United States would be the best place to have a photovoltaic energy supply. The students should be able to rationalize their answer based on meteorology.

Finally, have students do the same exercise as in number two above but for the world. Where in the world would be the best place for acquiring solar energy through a photovoltaic array?
EXTENSIONS:
CLASSROOM SIMULATION:
SOLAR DAY TRADING

As a twist on the prediction activity, students may like to compete in more of a simulation that uses more strategy. In this simulation, each student is told they have the ability to use 100 solar panels the size of the school’s PV array. The catch is that each array costs a set amount of money to operate for a day of use.

Therefore, students must look at the surface analysis maps and try to predict the amount of sunshine that will be available for the next day. After making this decision, the student will “activate” a certain number of their 100 arrays for the next day. The amount of energy generated by their activated panels will be their school’s value times the number they activated. If they thought it would be a clear day, then all 100 would be put into use (for a sizeable fee). If they thought it to be overcast, then it would be cost efficient to only run a few. The students will need to do a cost/benefit analysis to determine when the generation of electricity through their PV system will be profitable and when it will not. As an added factor in the competition, the teacher may control the price paid for PV electricity over the time period the simulation is run. This will add into the discussion the fact that the price of electricity fluctuates over time and can have an effect on the profitability of solar generated electricity.

GUESS WATT?

If classroom time is limited, or as a means to initiate interest before beginning the lesson, facilitate a class or school-wide competition to Guess Watt the solar panels are producing. Help students by explaining photovoltaic cells, watts, kilowatts, and kilowatt-hours; demonstrate how to access the MGE’s Web site; and develop a basic ‘entry form’ for students to input their predictions. Pick a central location to post PV data about a selected Solar Host School, and post information about output and weather conditions for a week. Then challenge students to predict the next week of daily output. Post winners each day and have an overall Guess Watt scholar selected for the overall winner.
ASSESSMENT

FORMATIVE:

1. Will the baseline data collected at the beginning of the activity be able to be used year round? Why or why not?

2. Did your estimations become more accurate from the first week to the second week? Try to explain why or why not.

3. What type of pressure system will typically bring sunny skies? Cloudy skies? Use what you know about meteorology to explain this phenomenon.

SUMMATIVE:

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PREDICTING PHOTOVOLTAIC OUTPUT WITH METEOROLOGY

STUDENT PREDICTION WORKSHEET

NAME ______________________________ PERIOD___________

<table>
<thead>
<tr>
<th>Baseline Data</th>
<th>Sunny Day</th>
<th>Partly Sunny Day</th>
<th>Overcast Day</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day 1 Output (kWh)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Day 2 Output (kWh)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average Output (kWh)</td>
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<td></td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Week One Predictions</th>
<th>SUN</th>
<th>MON</th>
<th>TUES</th>
<th>WED</th>
<th>THUR</th>
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EQUATIONS NEEDED:

\[
\text{Percent Error} = \left( \frac{\text{Predicted Output} - \text{Actual Output}}{\text{Actual Output}} \right) \times 100\%
\]
SUMMARY

Through a laboratory exercise, students utilize photovoltaic panels to challenge the misconception that Earth’s seasons are the result of variations in the distance between the Earth and the sun.

BACKGROUND

Earth is a nearly perfect sphere that orbits the sun over the period of a year. During that time, Earth’s tilt points to the same place in space. Thus, at one place in Earth’s orbit the tilt of the North Pole is as much “toward” the sun as it will ever be. On this day, the Earth is at its northern hemisphere summer solstice. For the next three months, the North Pole is less and less tilted toward the sun until the tilt is neither toward nor away from the sun. On this day the Earth is at the northern hemisphere autumnal equinox. For the next three months, the North Pole is tilted more and more away from the sun until it reaches a point in its orbit at which it is as tilted as much “away” from the sun as it will ever be. On this day, the Earth is at its northern hemispheric winter solstice. Over the next six months, the Earth completes the second half of its orbit during which time the tilt goes from away, to neither toward nor away, to as toward as it will ever be.

Over the course of the unit, students will come to recognize the pattern described above is the cause for the Earth’s seasons. In this lab, students gather data to demonstrate how latitudinal location on Earth impacts the average energy flow due to changes in angle of insolation.

OBJECTIVES

Students will be able to...
• Explain the cause of Earth’s seasons.
• Measure the electrical energy produced by a solar cell.
• Calibrate solar cell sensitivity
• Define insolation.

TIME

Preparation: Two hours
Pre-Activity: 50 minutes
Activity: Two 50-minute class periods

MATERIALS

• 14” globes on ring stands
• Velcro, self-adhesive
• Four solar cells per globe
• Multi-meters (one per solar cell)
• Bright light source: 300 watt bulbs

CREDITS:

Activity adapted from lesson plans designed by: Benjamin Senson, Memorial High School
GETTING READY:

DETAILED PREPARATION OF GLOBES AND SOLAR CELLS:

A fairly large globe must be obtained, 14’ diameter or larger is preferable. For the summer solstice, it is required that you use globes that rest in a ring rather than those mounted in a bracket that connects the north pole to the south pole. This bracket obstructs the mounting of the polar photocell and blocks rotation of the other photocells into the noontime position required to collect accurate data.

On the globe, select the meridian (north/south line) that passes from pole to pole through the location at which your students live. On this line, you should place the fuzzy side of self-adhesive Velcro so that it runs from pole to equator. Use the fuzzy side so that dirt does not collect on the globe over time.

Three or four identical photocells are required for this lab. If possible, use photocells that are small enough to allow all of them to be placed lengthwise (their longest dimension), end-to-end from the equator to the pole without any overlap of any kind. For each cell, place a square of the bristled side of self-adhesive Velcro to the backside of each photocell. Use extra-strength Velcro to eliminate shifting of the cell during the lab procedure.

Using only Velcro®, there is a significant risk the photocell will shift enough, with changes in the globes position, to adversely impact the value of the data collected. Preventing this shift requires one more preparation step. Place one of the photocells flat against the globe and adjust the photocell so that both of the ends are equally raised from the surface of the globe. Place a pencil or small piece of dowel under each raised end until it fills the gap between the photocell and the globe. Mark the location of the dowels. Remove the photocell and attach the dowels to the backside of the cell either permanently (hot melt glue, superglue, duco cement, etc.) or temporarily with tape. These wedges will prevent the photocells from shifting during the lab procedures.

Photocells must also be calibrated against each other. This procedure is described below under the “Procedures” section. However, prior to starting the lab, you should label one electrical lead from each photocell with a number so that you have one cell per each number 1, 2, 3, etc.

To set up this lab, set up one very bright incandescent light source (200 to 300 watts) in a location where a student can place their globe fairly close to the light source, but far enough away that there is not a significant change in the angle of insolation due to the distance from the bulb (>10’ or as far as is practical).
PROCEDURE

Orientation:
Reinforce the persistence of the Earth’s tilt as it moves through its orbit. Model or demonstrate the equivalence of maintaining the tilt in the same direction as the Earth orbits. Describe the lab procedures with emphasis that the rotation of the globe in place, from tilt toward, to neither toward nor away, to tilt away from the sun, is equivalent to gathering data at the summer solstice, equinoxes and winter solstice.

Demonstrate how to set up the globe and photocells and demonstrate use of the multi-meters.

Attach the Photocells to the Globe:
1. At the equator, place the center of photocell number one so it lies directly over the point at which the equator and the Velcro meridian meet. Orient the photocell so that its longest dimension runs north-south on the globe (parallel to the Velcro).
2. At 30 degrees north latitude, place photocell number two. Match the orientation of photocell number one for this and all subsequent photocells.
3. At 60 degrees north latitude, place photocell number three.
4. At 90 degrees north latitude, or the north pole, place photocell number four.

Attach the Multi-meters to the Photocells:
For each photocell, connect the multi-meters positive lead to the red wire coming from the photocell. Connect the black lead to the ground, common or negative lead of the multi-meter. Adjust the multi-meter to read out current in amps.

Steps:
1. Have student set up their globes.
2. Have students calibrate their photocells.
3. Have students attach the photocells to their globe.
4. Have students attach the multi-meters to the photocells.

Summer Solstice:
1. Rotate the globe in its stand so the North Pole is tilted toward the bright light source in the room. The Arctic Circle should cross over the top of the globe.
2. Turn off all room lights other than the single, bright light source.
3. For each photocell, read the current produced as measured on the multi-meter.
4. Multiply each value by its calibration ratio and record the result.

Equinoxes:
Repeat the Summer Solstice procedures but with the globe oriented with the polar axis straight up and down.

Winter Solstice:
Repeat the Summer Solstice procedures but with the North Pole tilted away from the bright light source in the room. The Arctic Circle should cross over the top of the globe.

Analysis:
1. Calculate the change in noontime calibrated current produced by each photocell, summer to winter.
2. Students should graph the following:
Calibrated noontime current versus time of year (Summer, Equinox, Winter), all photocells on one.
Change in calibrated current versus Latitude.
3. Respond to lab questions below.

ASSESSMENT
FORMATIVE:
Pre-conception quiz and/or discussion
SUMMATIVE:
Grading of lab questions
LAB QUESTIONS:
1. At what location on the globe is the greatest insolation absorbed during the summer solstice?
2. At what location on the globe is the greatest insolation absorbed during the equinoxes? Can you prove your answer?
3. No matter what time of year it is, what location absorbs the greatest insolation?
4. Average the current readings for each photocell across all four seasons. What happens to the average insolation absorbed as you move from the equator to the pole?
5. Based on your answer to question 4, what should happen to the average temperature as you move from the equator toward the pole?
6. Compare the change in insolation from summer to winter, what happens to the range in the current produced by the photocell as you move from the equator toward the pole?
7. Based on your answer to question 6, what should happen to the temperature range (difference in the seasons) experienced as you move from the equator toward the pole?

EXTENSIONS

PRE-LAB DISCUSSION:
Conduct a pre-lab discussion to reinforce the distance misconception. This approach is used to demonstrate the reasonableness of the belief based on first-hand, casual observations of the nature. Every student knows that the closer one gets to a heat source, the warmer one feels and vice versa.

THREE STRIKES DISCUSSION:
The misconception of distance causing seasons is the result of three impossibilities which would have to occur for this belief to be true. This includes mathematical analysis of the percentage change in energy due to distance (too small of a variation to represent seasonality), hemispheric separation (north winter during south’s summer) and mismatch to orbital position (Earth is closest to the sun on Jan. 4th and farthest from the sun on July 4th). Discuss misconceptions.

POST-LAB DISCUSSION:
Conduct a post-lab discussion to compare and contrast the predictions made by both the distance model and tilt-revolution models of Earth’s seasons. Form a class consensus regarding the more appropriate explanation for Earth’s seasons.

PLANETARIUM VISIT:
Bring students to a local planetarium. Planetariums provide visual representation and temporal experience (albeit highly accelerated) of both the change in angle of insolation and length of day throughout the year.

COMPUTER LAB:
Collect data for variations in sunrise/set positions, noontime elevations of the sun, and Day length. Have students graph and analyze this data to recognize the correlation between these different sets of information and one cause, Earth’s tilt and its orbit around the sun.