Irradiance, Temperature & PV Output

Student Objective

The student:
- will be able to predict how the irradiance level will affect the power output of a photovoltaic module
- will be able to predict how changes in temperature will affect the power output of a photovoltaic module
- will use technology to access, manage, integrate and evaluate solar information
- will demonstrate the ability to work effectively with team members.

Materials:
- laboratory manual
- key word list
- photovoltaic module (mono or poly-crystalline)
- insolation meter
- multipurpose meter
- technical specifications for the module being used
- (4) wires with alligator clips
- variable resistor (rheostat)
- protractor
- piece of window screen approximately 1 ½ feet square
- graph paper
- self-sealing plastic baggies or plastic bags with ties
- ice
- thermometer
- tape
- calculator

Key Words:
ohms
peak irradiance
standard test conditions (STC)

Time:
1 - 2 class periods for the investigation and application
1 class period to prepare group news report

Procedure

1. **Engage:** Lead a discussion on findings from the *Photovoltaic Orientation & Power Output* activity and answer any questions that the students have from the problem set. Review previous terminology such as short circuit current, open circuit voltage, irradiance level, and maximum power point. General questions may be assigned to a student to be researched and presented later to the class. Points that may be brought up that will be covered more thoroughly during this investigation, and thus could be given a "you will find out today" response:
   - how clouds and weather have an affect on the power output of a module.
2. Students should work in groups of 3 - 5 per team. Students should be developing interpersonal and problem-solving skills as they work in their groups. Remind students to set high standards and to deliver quality work, maintain a positive work ethic, and recognize the strength and skills of their tem members. Pass out materials.
3. **Explore:** Students should read, follow all procedures, and complete the activities in the Laboratory Manual up to the Summary section. This is an exploratory activity. Students are expected to explain the results they collect and elaborate as they apply the concepts learned from the data.
4. The Problem set is optional and may be used at your own discretion. This phase of the activity checks for understanding using an open-ended format.

Procedure - Group Report

1. Explain to the students that they will be writing a news report in their groups, that is to target home buyers with information concerning photovoltaics.
2. Have the students read the Summary section and work on their news report. Allow the students to get creative; they may wish to include graphs or photos in their article.
3. After completing their news article, the individuals in each group should analyze their own group by answering the group analysis questions. These are not to be graded, instead, use these answers to help assess how well each person is integrating into the group. You may wish to have the each group share an idea for improvement.
4. You may wish to have a few of the groups present their news article, or disseminate them to the school or community.

Evaluation and Student Assessment

In their news report, students should restate that the irradiance level directly affects the power output of photovoltaics. The photovoltaic array's position is a very important factor and home buyers should entrust the placement of PV arrays to certified installers. Buyers should also be aware that seasonal and daily temperature do have an affect on the power output of their solar cells but residential buyers need not worry because manufacturers have designed the array to compensate for these regional energy fluctuations.

Use a holistic scale for scoring:

5 - clearly stated and terms used correctly
4 - complete ideas with minor errors
3 - needs more work

2 - little or no effort
0 - not completed

Related Reading

- ***Photovoltaics: Design and Installation Manual*** by Solar Energy International (New Society Publishers, 2004)
  Solar Energy International (SEI) is a non-profit that trains adults and youth in renewable energy and environmental building technologies. This manual is well-suited for those who have some electrical experience, and students in high school tech prep-level courses. The book contains an overview of photovoltaic electricity and a detailed description of PV system components, including PV modules, batteries, controllers and inverters. It also includes chapters on sizing photovoltaic systems, analyzing sites and installing PV systems.

Internet Sites

http://www.fsec.ucf.edu/en/consumer/solar_electricity/basics/index.htm
Florida Solar Energy Center's photovoltaic fundamentals page explains the basics of photovoltaic cells including their manufacture, the components of systems, as well as the pros and cons of photovoltaic power.

http://www.mathconnect.com/ENGINEERING-Formula.htm
Common electrical formulas and conversions

http://solar.anu.edu.au/level_1/Sun/PVPanel/PVPanel.html
Centre for Sustainable Energy Systems (CSES) interactive page calculates the power output of an array based on a variety of parameters including location, date and time, temperature, and array tilt angle.

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Answers - Laboratory Exercises

1. Data readings will vary, but should show consistency between groups who are collecting data at the same time.
2. I-V curves should show similarity between groups, and be labeled and titled correctly. The x- axis is voltage, y-axis is current, and graph intervals should be even. The two separate curves should be labeled with their respective irradiation level, and the maximum power points should be indicated. The title of the graph should include the temperature.
3. Answers may vary slightly, but should come from the appropriate points on the graph. Students should be able to find the maximum power point from their graphs.
4. With a decrease in irradiance, the current also decreases proportionally. Students may also notice that the curve shape remains the same.
5. Students may hypothesize that a decrease in the amount of light causes fewer electrons to be released.
6. Answers will vary, but students should see the same trend in their graph as the one in the diagram.
7. 2.89 amps
8. (a) Answers will vary depending on the module used, however the students should show proper use of the formula and a knowledge of the standard test condition (1kW/m^2). If you are using the small 3V modules, the answer will be close to 1.24 amps

   2. Answers will vary depending on the module used, however the students should show proper use of the formula and the final result should be ½ of the correct answer to (a). If you are using the small 3V modules, the answer will be close to .6 amps.
9. Data readings will vary, but should show consistency between groups.
10. I-V curves should show similarity between groups, and be labeled and titled correctly. The x- axis is voltage, y-axis is current, and graph intervals should be even. The two separate curves should be labeled with their respective average temperature, and the maximum power points should be indicated. The title of the graph should include the average irradiance.
11. Answers may vary slightly, but should come from the appropriate points on the graph. Students should be able to find the maximum power point from their graphs.
12. With a decrease in temperature, the voltage increases; colder panels produce more power. Students may also mention that the curve shape remains the same.
13. Students will have a harder time with this question, and it is included strictly to get them thinking. The main reasons have to do with the properties of the semi-conductor materials, the fact that higher temperatures cause more molecular activity, and that there

is a higher resistance in electric circuits with higher temperatures. Advanced students may wish to investigate this further.

14. Answers will vary, but students should see the same trend in their graph as the one in the diagram.
15. The device in North Carolina should produce more power because of the colder temperatures with the same irradiance levels. Also, the more northern device is focused more directly towards the sun's angle of incidence for the winter months than the southern device.
16. 74.63 watts
17. Students should notice that the calculations agree with their real world observations, that with a lowered temperature, the calculated output of the module is increased.

Answers - Problem Set

1. 30 watts
2. Approximately half
3. a. module - module 1 will have 3.36 amps, module 2 will have 3.23 amps.
4. 15.38 volts
5. 4.35 amps, 66.9 watts
6. Irradiance level, temperature
7. Changes in the irradiance level affect the current output. Lower irradiance levels will cause a decrease in current and power outputs.
8. Changes in cell temperature affect the voltage level. Higher temperatures will cause a decrease in voltage and power outputs.

Irradiance, Temperature & PV Output

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Nature of Science																					
Standard 1	**SC.912.N.1.**	**X**																			
Earth and Space																					
Standard 5	**SC.912.E.5.**				**X**																
Physical Science																					
Standard 10	**SC.912.P.10.**	**X**													**X**	**X**					
Language Arts Standards		**LA.910.3.5.1, LA.910.3.5.3, LA.4.2.1, LA.1112.3.5.1, LA.1112.3.5.3, LA1112.4.2.1**																			
Mathematics Standards		**MA.912.A.1.4, MA.912.A.2.1, MA.912.A.2.2, MA.912.A.2.7, MA.912.A.2.8, MA.912.A.2.12, MA.912.A.2.13, MA.912.A.10.1**																			

Science Standards
Standard 1: The Practice of Science

- SC.912.N.1.1- Define a problem based on a specific body of knowledge, for example: biology, chemistry, physics, and earth/space science, and do the following:
  1. pose questions about the natural world
  2. conduct systematic observations
  6. use tools to gather, analyze, and interpret data (this includes the use of measurement in metric and other systems, and also the generation and interpretation of graphical representations of data, including data tables and graphs)
  7. pose answers, explanations, or descriptions of events
  8. generate explanations that explicate or describe natural phenomena (inferences)
  9. use appropriate evidence and reasoning to justify these explanations to others
  10. communicate results of scientific investigations, and
  11. evaluate the merits of the explanations produced by others.

Standard 5: Earth in Space and Time

- SC.912.E.5.4 - Explain the physical properties of the Sun and its dynamic nature and connect them to conditions and events on Earth.

Standard 10: Energy

- SC.912.P.10.1 - Differentiate among the various forms of energy and recognize that they can be transformed from one form to others.
- SC912.P.10.14 - Differentiate among conductors, semiconductors, and insulators.

- SC912.P.10.15 - Investigate and explain the relationships among current, voltage, resistance and power.

Language Arts Standards
Writing Process - Standard 5: Publishing

- LA910.3.5.1 and LA.1112.3.5.1 - The student will prepare writing using technology in a format appropriate to the purpose.
- LA.910.3.5.3 and LA.1112.3.5.3 - The student will share with others or submit for publication.

Writing Applications - Standard 2: Informative

- LA.910.4.2.1 - The student will write in a variety of informational/expository forms, including a variety of technical documents.
- LA.1112.4.2.1 - The student will write in a variety of informational/expository forms, including documents using precise technical and scientific vocabulary.

Mathematics Standards
Algebra - Standard 1: Real and Complex Numbers

- MA.912.A.1.4 - Perform operations on real numbers (including integer exponents, radicals, percent, scientific notation, absolute value, rational numbers, irrational numbers) using multi-step and real-world problems.

Algebra - Standard 2: Relations and Functions

- MA.912.A.2.1 - Create a graph to represent a real-world problem.
- MA.912.A.2.2 - Interpret a graph representing a real-world situation.
- MA.912.A.2.7 - Perform operations (addition, subtraction, division, and multiplication) of functions algebraically, numerically, and graphically.
- MA.912.A.2.8 - Determine the composition of functions.
- MA.912.A.2.12 - Solve problems using direct, inverse, and joint variations.
- MA.912.A.1.13 - Solve real-world problems involving relations and functions.

Algebra - Standard 10: Mathematical Reasoning and Problem Solving

- MA.912.A.10.1 - Use a variety of problem-solving strategies, such as drawing a diagram, making a chart, guess-and-check, solving a simpler problem, writing an equation, and working backwards.

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Ohm's Law - the current in a circuit is directly proportional to the voltage across the circuit, and inversely proportional to the total resistance of the circuit

$$V = I \times R$$
$$I = V / R$$
$$R = V / I$$

By substituting the equation for power (**$P = V \times I$**), variations in Ohm's law can also be expressed as follows:

$$P = I^2 \times R$$
$$P = V^2/R$$

peak irradiance - standard peak sunlight condition, $1kW/m^2$.

standard test conditions (STC) - the standard reference environment for photovoltaic cell operation is an environment of 1000W/m2 irradiance, 1.5 air mass, and cell temperature of 20° C

Irradiance, Temperature & PV Output

If your weather conditions have been anything except perfectly clear for the past two investigations, you have probably noticed that the amount of solar irradiance affects the power output of your module. In this investigation we are going to look at this further and investigate the effect that temperature has on photovoltaic devices.

Array Tilt Angle & Solar Azimuth

Date ________________ Time ____________ Daylight Savings Time? ___ yes ___ no

Latitude ________________________________

Fill in below the solar azimuth and optimum tilt angle from the previous activity, unless it is a different time of day or more than two weeks since you calculated these angles. If so, you will need to find the new angles for the current day and time, and fill them in below.

Optimum Array Tilt Angle ________________ Azimuth ______________________________

Irradiance Level

1. In this investigation you are going to determine how irradiance level affects the power output of a photovoltaic device. As before, for best results, data for I-V curves should be collected under clear skies within two hours of solar noon. Solar cell temperature should be allowed to stabilize before being measured. Remember, during these types of tests, the I-V curve data points should be taken quickly to minimize the effect of a change in irradiance level.
    - Using your module, variable resistor and wires with alligator clips, assemble the test circuit as you did for the *Photovoltaic Power Output & I-V Curves* activity. It is important that you leave the positive lead to the PV module disconnected. As before, ask your instructor to check your circuit before continuing.
    - To determine the amount of solar irradiance at your location, use the insolation meter to read and record this value in the data chart.
    - Using the information you learned in previous solar activities, set your module in its optimum position. Consider both the tilt angle and the solar azimuth. Tape a thermometer on the edge of the module (without covering any of the PV cells) and record the beginning temperature in the data sheet.
    - Connect the positive lead from the PV module to the multimeter. Adjust the variable resistor (rheostat) to zero ohms (voltage reading should also be zero), and record the short-circuit current I_{sc}, in the data table.
    - Increase the resistance until the voltage reading is approximately 1/4 of the V_{oc}. Record the current and voltage readings in the data table.

- Increase the resistance to 1/2 and then 2/3 of the V_{oc}, and record the current and voltage readings.
- From this point on, make much smaller increases in the resistance each time so that you will have enough data points to plot the I-V curve accurately. Continue to record the current and voltage readings (adding more lines to the table if necessary), until the maximum resistance setting is reached, meaning the current is zero.
- Disconnect the resister from the test circuit (current becomes zero). Record the open-circuit voltage, V_{oc}.
- Record the ending irradiance level
- Next, collect data for your module with a simulated cloud cover. Hold a piece of screen approximately three feet from your module, in the direct line of the sunlight, so that the screen casts an even shadow across the whole module. Record the beginning irradiance reading by measuring the irradiance through your screen 'cloud cover'.
- Repeat the data collection procedures listed above using the cardboard to mimic cloud cover.
- Again, record the ending irradiance and temperature reading for this cloud cover test.

	'As Is' Irradiance (W/m^2)	**Simulated Cloud Cover Irradiance**	**Cell Temperature (^oC)**
Initial Measurement			
Final Measurement			
Average			

'As Is' Conditions			**Simulated Cloud Cover**		
Voltage (Volts)	**Current (Amps)**	**Power (Watts)**	**Voltage (Volts)**	**Current (Amps)**	**Power (Watts)**
0	**I_{sc} =**		**0**	**I_{sc} =**	

V_{oc} =	**0**		**V_{oc} =**	**0**	

Application and Analysis

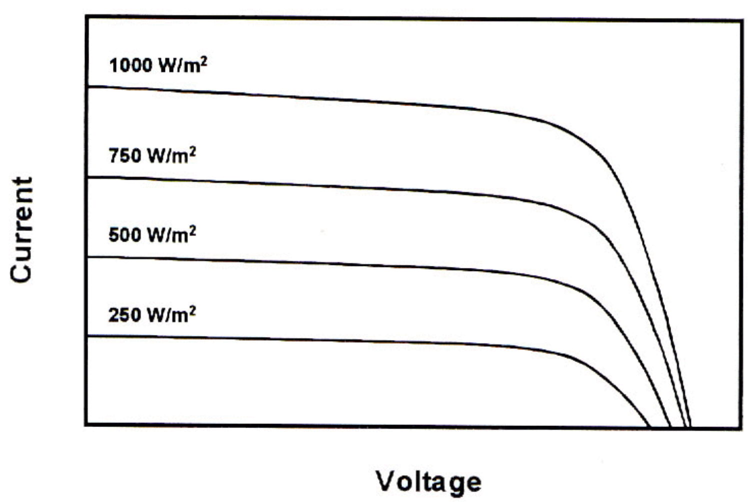
2. Using the data you collected:
   - Graph the I-V curves for full sunlight and simulated cloud cover on graph paper.
   - Graph the power curves as you did in the *PV Power and IV Curves* activity (remember, voltage is the x-axis, and power is the y-axia)
   - Use the power curves to find the x-coordinates for the maximum power points (P_{mp}) on the I-V curves. Make sure to label all of your curves, indicate the respective average irradiance readings, label the axis, and title your graph. Your title should include your average temperature reading.
3. Use your graphs to determine the power, voltage, and current at the maximum power point for both curves.

   'As Is' Curve: P_{mp} = ____________ V_{mp} = ____________ I_{mp} = ____________
   Simulated Curve: P_{mp} = ____________ V_{mp} = ____________ I_{mp} = ____________

4. What difference(s) did you notice in the two I-V curves?

5. What do you think caused these differences?

Below is a graph showing a typical effect of the change in irradiance levels on a photovoltaic device.



6. How did your graph compare with the one above?

Scientists often use **standard test conditions (STC)** to set or define variables in a standard reference environment to allow comparison in a wide variety of conditions. The standard test condition for irradiance is set at 1000 watts of solar energy per square meter ($1kW/m^2$). This is called the *peak irradiance*, and is used to compare different systems under differing conditions. This is possible because the I_{sc} is directly proportional to the light intensity (the V_{oc} varies more slowly). In other words, the ratio of the I_{sc} to the irradiance will be the same; for example, if the irradiance is halved, the I_{sc} will drop to half also.

$$\frac{I_{sc1}}{\text{irradiance}_1} = \frac{I_{sc2}}{\text{irradiance}_2}$$

7. A module has a rated I_{sc} of 3.4 amps at $1000W/m^2$. Using the formula above, what would the actual I_{sc} value be if the irradiance had a measurement of 850 W/m^2?

Because the current is proportional to light intensity, power is also essentially proportional to the irradiance level.

8. What would be the approximate maximum power of the module you have used in your investigations for an irradiance of
   (a) standard test condition for irradiance?
   (b) 500 W/m^2?

Temperature

9. Determine how temperature affects the power output of a photovoltaic device.
   - Use the same procedure as in #1 above for the 'as is' condition and record your new data in the chart below.
   - Record the ending 'as is' temperature reading.
   - Next, collect data for your module with a simulated colder temperature. To do this, fill plastic baggies with ice and place them underneath and around the sides of your module. Allow the module to remain in this condition for five minutes and then begin record the simulated cold temperatures the same way as before by increasing resistence and recording the changes in current and voltage.
   - Collect and record your data for the simulated cold temperature in the data table below.
   - Record the ending irradiance reading and the ending colder temperature reading.

	Irradiance (W/m2)	'As Is' Cell Temperature (ºC)	Simulated Cold Cell Temperature (ºC)
Initial Measurement			
Final Measurement			
Average			

'As Is' Condition			Simulated Cold Temperature		
Voltage (Volts)	**Current (Amps)**	**Power (Watts)**	**Voltage (Volts)**	**Current (Amps)**	**Power (Watts)**
0	I_{sc} =		**0**	I_{sc} =	
V_{oc} =	**0**		V_{oc} =	**0**	

Application and Analysis

10. Using the data you collected:
    - Graph the I-V curves for the as-is temperature and simulated cold temperature on graph paper.
    - Graph the power curves as you did previously in the Irradiance activity
    - Use the power curves to find the x-coordinates for the maximum power points (P_{mp}) on the IV curves. Make sure to label all curves indicate the respective average temperature of each, label the axis, and title your graph. Your title should include the average irradiance reading.

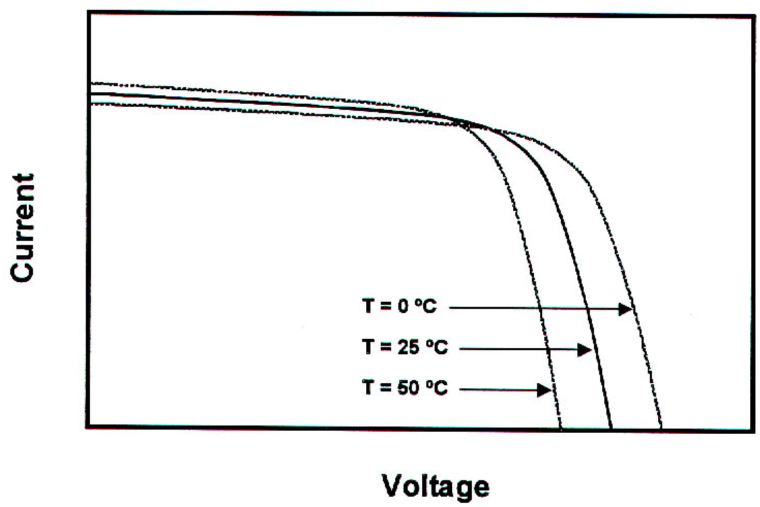
11. Determine the power, voltage, and current at the maximum power point for both curves.

    'As Is' Curve: P_{mp} = ____________ V_{mp} = ____________ I_{mp} = ____________
    Simulated Curve: P_{mp} = ____________ V_{mp} = ____________ I_{mp} = ____________

12. What difference(s) did you notice in the two I-V curves?

13. What do you think caused these differences?

Below is a graph showing a typical effect of the change in temperature on a photovoltaic device.



14. How did your graph compare with the one above?

15. Given two photovoltaic devices on a day with the same total insolation, one in Florida in the summer, and one in North Carolina in the winter, which device would you predict would produce the most power? Why?

The standard test condition for temperature is 25°C. Obviously, temperature can vary quite a bit depending on location and season. As shown in the graph above, as the cell temperature rises, the main effect is to reduce the voltage and power output available at most currents. There is also a slight rise in current at very low voltages. The change in voltage is directly proportional to the rise in temperature. The formulas to translate the current and voltage based on cell temperature are:

$$\text{Actual voltage} = Vmp_{rated} + [C_v \times (T_{new} - 25)]$$
$$\text{Actual amperage} = Imp_{rated} + [C_i \times (T_{new} - 25)]$$

C in these formulas represents a temperature coefficient. Different manufacturer's cells have slightly different temperature coefficients, so in real world applications or in analyzing your school's system, you will need to use your manufacturer's specifications. However, for the following examples and problems, use the temperature coefficients for a typical single crystal silicon PV cell, the Siemens SP75:

C_V (voltage) = -0.077 V/ºC $\qquad$ C_i (current) = +.00206 A/ºC

Example: If the temperature is actually 60ºC, and the voltage rating for your Siemen's SP75 module is 17 volts at 25ºC. What would you expect the voltage reading to be at 60ºC?

$$\text{Actual voltage} = 17 + [-0.077 \times (60 - 25)]$$
$$= 14.3 \text{ volts}$$

If your maximum current rating for the module is 4.4 amps, what is the actual current and power output of your module at 60º C?

$$\text{Actual current} = 4.4 + [.00206 \times (60 - 25)]$$
$$= 4.47 \text{ amps}$$

$$\text{Power} = 14.3 \text{ volts} \times 4.47 \text{ amps}$$
$$= 63.9 \text{ watts}$$

16. If the temperature dips to 15º C, what will the actual power output of your Siemen's SP75 module be? Use the temperature coefficients and the voltage and current ratings from the example above.

17. Is this result consistent with what you observed in your investigation and I-V curves?

Summary

When the irradiance level of light changes, the number of photons and energy entering the PV device changes, and the number of electrons released transferring to electrical energy also changes. Changes in irradiance significantly affect output current, but have a much smaller effect on voltage. The current is directly proportional to light intensity, and the voltage varies more slowly in a logarithmic relationship.

The operating temperatures of solar cells are important in that higher operating temperatures typically result in lower power outputs and efficiencies; they also decrease cell lifetime slightly. As temperature increases, current increases slightly. Voltage, however, decreases significantly with increases in cell temperature, resulting in a net reduction in power. Manufacturers of modules anticipate the loss of voltage in real world hot conditions, and compensate by building modules with enough cells in series so that even when very hot, the module has enough voltage to charge batteries or operate the system's load.

Evaluation

What evidence do you and your team members now have to support the claims stated in this summary? In your group, write this up as a news report with the home buyer as the target audience.

Evaluate your own group by answering the questions below:

1. How would you describe the effectiveness of your group completing the task?

2. What went well with completing this task?

3. Did all group members share in the responsibility of completing this task?

4. Regardless of your answer, how could the sharing of team responsibility be improved?

Irradiance, Temperature & PV Output

1. What would the approximate maximum power output be under 600 W/m^2 irradiance for a PV module producing 50 watts maximum power at 1000 W/m^2?

2. If the irradiance level is half of what you measured for your as-is I - V curve, at what current and power would your module operate?

3. Two modules are measured on different days. Module 1 measured 2.5 amps for I_{sc} on a day with an irradiation of 745 W/m^2. Module 2 was measured on a day with an irradiation of 650 W/m^2, and had a measure I_{sc} of 2.1 amps. Which module has the larger I_{sc} measured at the standard insolation?
   a. module 1
   b. module 2
   c. they have the same I_{sc} at 1000 W/m^2
   d. not enough information given

4. The Siemen's SP75 module has a V_{mp} of 17.3 volts at 25°C. In real world conditions, the cells will easily heat up to 50°C. What would the voltage at 50°C be? (Temperature coefficient for this module: Voltage = -0.077 V/°C)

5. The module above has a current rating of 4.3 amps at standard operating conditions for temperature. At 50°C, what would the current and power output of the module be? (Temperature coefficient for this module: Voltage = -0.077 V/°C; Current = +.00206/°C amps)

6. Based on your investigations, what variables affect the I-V characteristics of a module?

7. How do changes in irradiance affect the I-V curve?

8. How do changes in cell temperature affect the I-V curve?