Photovoltaic Power Output & I-V Curves

Student Objective

The student:
- will be able to determine the voltage, current and power using Ohm's formula of a given PV module
- given the efficiency, irradiance and the power (watt) rating of a module, will be able to determine the size of the array necessary to produce given amounts of power
- given an I-V curve, will be able to determine the module's maximum power point
- will be able to explain how an I-V curve is generated.

Materials:
- laboratory manual
- key word list
- photovoltaic module, any size (3V, .3A panel is used in examples)
- insolation meter (solar meter)
- multimeter (2 per group)
- technical specifications for module being used including voltage, amperage, open circuit voltage, short circuit amperage and maximum power rating
- variable resistor (rheostat), with current rating greater than short circuit current for module
- wires with alligator clips (4 per group)
- thermometer
- tape
- graph paper
- ruler

Key Words:

active area efficiency
ampere (amp)
circuit
current
direct current (DC)
efficiency
insolation meter
I-V curve
load
maximum power current (I_{mp})
maximum power point (P_{mp})
maximum power voltage (V_{mp})
module
multipurpose meter
ohms
Ohm's Law
open circuit voltage (V_{oc})
power (DC)
short circuit current (I_{sc})
solar irradiance
solar noon
total area efficiency
variable resistor (rheostat)
voltage

Time:
1- 2 class periods

Procedure (prior to class)

1. Look up your local latitude if you are unfamiliar with it.
2. Familiarize yourself with the multimeter that the students will be using. When measuring amperage a load must be used unless you are using a fused multimeter.
3. Make sure that the power rating of the variable resistor (rheostat) exceeds the maximum power rating of the module and that the resistance (ohms) falls withing 20% of the maximum power point resistance (R = V/I). For the 3V panel use a 3 watt, 100 ohm rheostat.

Procedure (during class time)

1. Lead a discussion on what the students may already know about solar energy in general and photovoltaics in particular. Points to cover should include:
   - the distinction between solar thermal (using solar energy to heat something) and photovoltaics (turning solar energy directly into electricity)
   - current uses of photovoltaics that the students might be familiar with (i.e. highway call boxes, road signs and billboards, signal buoys, satellites, as well as calculators, watches and radios).
2. If this is the first time the class has worked with electricity, lead a discussion of what they already know about basic electrical circuits. Points to cover should include:
   - the circular nature of a circuit
   - DC electricity is a ‘flow’ of electrons from the positive to the negative
   - difference between AC (alternating current) which is the standard electrical current carried through utility lines in the U.S., and DC (direct current) which is produced by photovoltaic devices and batteries
   - amperage (amp) is the measure of the rate of flow
   - voltage (volt) is the measure of the force of the ‘push’ through the circuit.
3. Students should work in teams of 3 - 5 per team. Pass out materials. If you are using the 3V PV panels, remind students that the panels are fragile and may be broken if bent
4. If this if the first time the class has used a multimeter, explain its basic function and use.
5. Students should complete the activities in the Laboratory Manual.

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 photovoltiac 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://www1.eere.energy.gov/solar/animations.html

Energy Efficiency and Renewable Energy Network (ERIN) page sponsored by the Department of Energy. Animation of how a photovoltaic cell works.

http://www.nmsea.org/Curriculum/Primer/from_oil_wells_to_solar_cells.htm

New Mexico Solar Energy Association's *From Oil Wells to Solar Cells: A Renewable Energy Primer*. Contains an overview of renewable energy including benefits, costs and obstacles to implementation. Also includes a good introduction to solar energy technology.

http://www.nmsea.org/Curriculum/7_12/PV/explore_pv.htm

New Mexico Solar Energy Association**.** A basic explanation of how a photovoltaic cell produces electricity.

Photovoltaic Power Output & I-V Curves

Laboratory Exercises

1. Answers will vary, but should be fairly consistent between groups.
2. Answers will vary, but students should show a knowledge of how to apply Ohm's law to calculate the power values.
3. Student's readings will probably be lower than published module specifications. This is mainly due to environmental factors and not using the optimum tilt angle.
4. Answers will vary, but students should show evidence that they are considering real world conditions (such as weather) to be mitigating factors.
5. Data readings will vary, but should show some consistency between groups. There still will probably be a variance between groups however, since the students haven't yet learned about tilt angles, and may not be using the optimum angle.
6. Answers will vary, but student's I-V curves should follow the typical shape, and be labeled and titled correctly. The x- axis is voltage, y-axis is current, and graph intervals should be even. The title of the graph should include the irradiance level and temperature.
7. Answers will vary but should come from the appropriate points on the graph. Students should be able to find the maximum power point from their graphs.
8. Student's readings will probably be lower than published module specifications.
9. Answers will vary, but students should show evidence that they are considering real world conditions (such as weather) to be mitigating factors.
10. Students should mention weather and the intensity of sunlight. They may also realize that tilt angle can cause discrepancies in the data. More data points could also increase the reliability of the data.
11. Answers will vary, but students should show proper use of the formula for efficiency.
12. Students readings will probably be lower than published module efficiency.
13. Students should realize that an increase in values for either the irradience level or the power output in the equation will mean a higher efficiency value.
14. With an efficiency rating, insolation data for a given area and a desired power output, the size of the array necessary for that load can be determined. Conversely, if the size of the array, the irradiance and the efficiency are known, the maximum power point can be determined.
15. Answers should include loss to heat. They may also include loss in the transmission of the electricity (resistance in the circuit), reflection off the module, as well as light hitting areas that do not have photovoltaic materials.

Problem Set

1. Insolation meter
2. 1000 watts
3. 5 amps
4. Answers b (current at open circuit), and c (voltage at short circuit) will both have a value of zero.
5. d (20 m^2)
6. No
7. There are an infinite number of operating (load) points along an I-V curve.

Photovoltaic Power Output & I-V Curves

Benchmark MA.B.1.4.2 - The student uses concrete and graphic models to derive formulas for finding rate.

Benchmark MA.B.2.4.2 - The student solves real-world problems involving rated measures.

Benchmark MA.B.4.4.2 - The student selects and uses appropriate instruments, technology and techniques to measure quantities in order to achieve specified degrees of accuracy in a problem situation.

Benchmark MA.D.1.4.1 - The students describes, analyzes, and generalizes relationships, patterns, and functions using words, symbols, variables, tables, and graphs.

Benchmark MA.D.1.4.2 - The student determines the impact when changing parameters of given functions.

Benchmark MA.E.1.4.1 - The student interprets data that has been collected, organized and displayed in charts, tables, and plots.

Benchmark SC.B.1.4.4 - The student knows that as electrical charges oscillate, they create time-varying electric and magnetic fields that propagate away from the source as an electromagnetic wave.

Benchmark SC.B.1.4.5 - The student knows that each source of energy presents advantages and disadvantages to its use in society.

Benchmark SC.B.1.4.6 - The student knows that the first law of thermodynamics relates the transfer of energy to the work done and the heat transferred.

Benchmark SC.B.1.4.7 - The student knows that the total amount of usable energy always decreases, even though the total amount of energy is conserved in any transfer.

Benchmark SC.H.1.4.1 - The student knows that investigations are conducted to explore new phenomena, to check on previous results, to test how well a theory predicts, and to compare different theories.

Photovoltaic Power Output & I-V Curves

active area efficiency - the ratio of maximum electrical power output compared to the light power incident on only the area of the device that is exposed or 'active' semiconductor material

ampere (amp) - a unit of electrical current or rate of flow of electrons. One volt across one ohm of resistance causes a current flow of one ampere. One ampere is equal to 6.25×10^{18} electrons per second passing a given point in a circuit.

circuit - the circular path of an electrical current, including the source and any loads or devices powered by it

direct current (DC) - a one way flow of electric current - from positive to negative

efficiency - the ratio of output of a device compared to the input to the device

insolation meter - a device to measure the amount of solar irradiance. Also called a ***pyranometer***.

I-V curve - the plot of electrical output (voltage and current) characteristics of a photovoltaic cell or module at a particular temperature and irradiance

load - any device or appliance that is using power in an electrical circuit

maximum power current (I_{mp}) - the amount of current of a given device at its maximum power point

maximum power point (P_{mp}) - the point where the product of current and voltage is at maximum power

maximum power voltage (V_{mp}) - the voltage value of a given device at its maximum power point

module - a number of photovoltaic cells electrically wired together, usually in a sealed unit for handling and assembling into panels and arrays

multipurpose meter - an instrument to measure electrical output in amps and volts and resistance in ohms

ohms - the unit of electrical resistance of a circuit in which a potential difference of one volt produces a current of one ampere

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

$$\mathbf{V = I \times R}$$
$$\mathbf{I = V / R}$$
$$\mathbf{R = V / I}$$

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

$$\mathbf{P = I^2 \times R}$$
$$\mathbf{P = V^2/R}$$

open circuit voltage (V_{oc}) - the maximum voltage produced from a device, corresponding to zero current flow

power (DC) - in DC circuits, power is given by the product of the voltage and current

$$\mathbf{P = V \times I} \qquad \text{(where P is the power in watts)}$$

short circuit current (I_{sc}) - the maximum current produced by a device, corresponding to zero voltage

solar irradiance - the measure of the power density of sunlight. Expressed in watts per square meter. The solar constant for earth is the irradiance received by the earth from the sun, 1367 W/m^2, at the top of the atmosphere and $\approx$1000 w/m^2 after passing perpendicularly through the atmosphere.

solar noon - the time of day when the sun is at its highest point in the sky. At this time in the northern hemisphere, the sun's shadow will point directly north.

total area efficiency - the ratio of maximum electrical power output compared to the total light power incident on the entire device

variable resistor - a device that provides a variable amount of resistance (impedance to flow) in a circuit, thereby acting as a load in the circuit

voltage - a measure of the force or 'push' given the electrons in an electrical circuit; a measure of electric potential. One volt produces one amp of current when acting against a resistance of one ohm.

Photovoltaic Power Output & I-V Curves

In this investigation we are going to look at some of the general characteristics of a photovoltaic module, and learn how to plot and read a current-voltage (I-V) curve, the most important performance descriptor for a photovoltaic device.

Solar Irradiance

1. Determine the amount of solar irradiance (W/m^2) using an insolation meter (also called a pyranometer). Make sure you face the meter directly at the sun, and move it around slightly to find the direction that gives you the highest reading. Record this below.

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

Location (latitude) ________________________ Irradiance reading ________________ W/m^2

Power Output

2. Determine the DC voltage and current of your solar module. Connect the multipurpose meter to your module and record your readings in the chart below, taking three sets of data and calculating the average of the readings.

	Irradiance (W/m^2)	**Voltage (V)**	**Current (Amps)**	**Power (Watts)**
Trial 1				
Trial 2				
Trial 3				
Average				

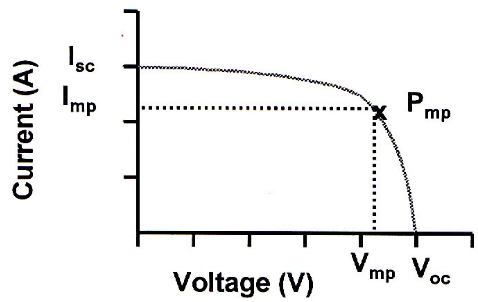
To find the power output of the module, calculate the power (measured in watts), using a variation of Ohm's Law:

Power (w) = **Volts** (v) x **Amps** (a)

3. Analyze your results. How did your results for volts, amps and power compare to the module's specifications?

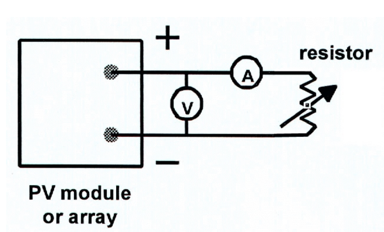
4. What do you think could have accounted for this difference?

I-V Curve
The current-voltage (I-V) characteristic is the basic descriptor of photovoltaic device performance. This is plotted on a graph with voltage on the x axis and current on the y axis, while keeping irradiance and temperature levels constant. A typical I-V curve is shown below.



The I-V curve represents an infinite number of current-voltage operating points, the specific operating point being determined by the electrical load (device or appliance) connected to the PV system. These current-voltage operating points are plotted between the *short-circuit current* point (I_{sc}) where the device produces maximum current and zero voltage and the *open-circuit voltage* point (V_{oc}) where the device produces maximum voltage and zero current. The point at which a PV device delivers its maximum power output and operates at its highest efficiency is referred to as its *maximum power point* (P_{mp}). The voltage and current values at the maximum power point are referred to as the *maximum power voltage* (V_{mp}) and the *maximum power current* (I_{mp}), respectively.

5. **Collect I-V curve data for your module**.
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; allow five minutes between taking your panel outside and data collection During the test, the I-V curve data points should be taken as quickly as practical to minimize the effect of a change in irradiance level.
   - Using the small PV module, variable resistor (rheostat) and wires with alligator clips, assemble the test circuit as shown on the top of the next page, leaving the positive lead to the PV module disconnected. Be sure your multimeter is set correctly for the measurement you wish to obtain. Ask your instructor to check your circuit before continuing.

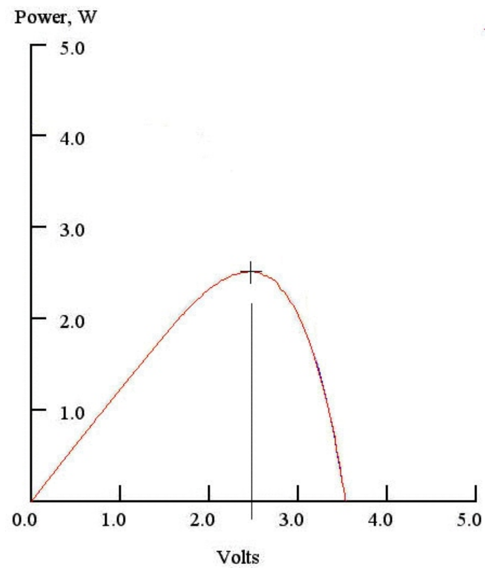


- Determine the beginning amount of solar irradiance using an insolation meter and record this below.
- Face the PV module toward the sun. Tape a thermometer on the edge of the module, being careful not to cover any of the photovoltaic cells, and record the beginning module temperature.
- Connect the positive lead from the module to the multimeter.
- Adjust the variable resistor to zero ohms (voltage reading should be zero), and record the short-circuit current, I_{sc}, in the data table.
- Locate V_{oc} for your module and calculate the value that is 1/4 of it. Increase the resistance until you obtain approximately this voltage reading. Record the current and voltage readings.
- Increase the resistance to approximately 1/2 and then 2/3 of the V_{oc}, recording the current and voltage readings for each.
- From this point on (2/3 of V_{oc}), make much smaller increases in the resistance each time so that you will have enough data points to plot the curve accurately (Hint: When the voltage drops rapidly, take smaller incremental measurements). Continue to record the current and voltage readings (adding more lines to the table as needed), until the maximum resistance setting or zero current is reached.
- Disconnect the resistor from the test circuit (current becomes zero). Record the open-circuit voltage, V_{oc}.
- Record the ending irradiance reading and the ending temperature reading.

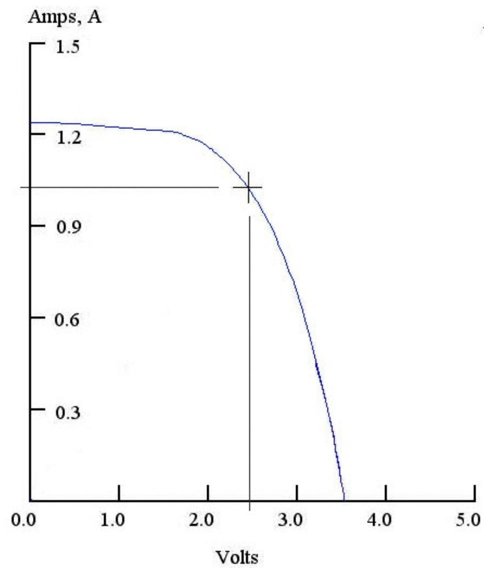
	Irradiance (W/m^2)	**Cell Temperature (ºC)**
Initial Measurement		
Final Measurement		
Average		

Voltage (Volts)	**Current (Amps)**	**Power (Watts)**
0	**I_{sc} =**	
V_{oc} =	**0**	

6. Using the data you collected, plot a power curve which shows power as a function of voltage. Make sure to label both axis. Then plot your I-V curve on graph paper. Make sure to label both axis, and title your graph. Your title should include your average irradiance and temperature readings. Typical graphs for a 3V panel are illustrated below:



Power curve



I-V curve

Label the maximum power point, the point on the I-V curve where the power (the product of current and voltage) is the highest. An easy way to find the maximum power point is to first locate the V_{mp} (maximum power point) on the power curve. This will be the x-axis value of the maximum power point on your I-V curve.

7. Determine the power, voltage, and current at the maximum power point.

P_{mp} = ______________ V_{mp} = ______________ I_{mp} = ______________

8. Analyze your results. How did your I-V curve compare to the module's I-V curve supplied by the manufacturer? If you don't have an I-V curve for your module, how did your I-V curve compare to the I_{sc}, V_{oc}, I_{sc}, V_{mp} and P_{mp} of your module's specifications?

9. What do you think could have accounted for this difference?

10. How could you improve the reliability of this experiment?

Efficiency

One common measure of the quality of a solar cell or module is its efficiency. In general, efficiency is defined as the ratio of output from a device compared to the input to the device. However, two different efficiencies are often quoted in photovoltaic literature. *Total area efficiency* is the ratio of maximum electrical power output compared to the total solar energy incident on the entire cell or module (area x irradiance); whereas *aperture or active area efficiency* usually refers to a single cell and only includes the active semiconductor area of the cell. Light incident on shaded areas like interconnect wires, gridlines and frame area are not included. Obviously, for a device with interconnected cells the active area efficiency is higher than the total area efficiency.

11. Calculate the total area efficiency for your module for the specific trial above:
   - Measure your module. Figure area in square meters
   - Calculate the efficiency using the formula:

$$\text{efficiency} = \frac{P_{mp}\ \text{(maximum power point)}}{\text{area} \times \text{average irradience}}$$

Efficiency of module = ____________________________

12. Analyze your results. How did your efficiency compare to the module's rated efficiency?

13. What conditions would increase the observed efficiency of the module?

14. What are the benefits of knowing the efficiency of your solar panel or module?

15. What do you think happens to the solar energy that is not directly converted to electricity? (Remember, according to the law of conservation of energy, all of the energy can be accounted for). List all the possible ways that energy could be lost or never utilized in this transfer.

Photovoltaic Power Output & I-V Curves

1. Name a device that is used to measure solar irradiance.

2. A photovoltaic array produces 50 volts and 20 amps. What is its power output in watts?

3. A photovoltaic panel produces 200 watts at 40 volts. What is its current (amperage) output?

4. Circle the letter of all the terms that will always have a value of zero.
   a. voltage at open circuit
   b. current at open circuit
   c. voltage at short circuit
   d. current at short circuit

5. You are planning a photovoltaic system installation with typical modules that convert sunlight to DC electrical energy at 10% efficiency. Assuming that losses from interconnecting wires, gridlines and frames are negligible, approximately how much roof surface area will be required for a PV array rated at 2000 watts DC under peak sunlight conditions (1000 W/m^2 irradiance)?
   a. 1 m^2
   b. 5 m^2
   c. 10 m^2
   d. 20 m^2
   e. 50 m^2

6. Can I_{mp} ever be greater than I_{sc}?

7. For a given current-voltage (I-V) characteristic, how many possible operating points (loads) are there?