

Maximum Power Point¹ (Lesson Plan)

(The Principles of Optimizing Photovoltaic Cell Power Output)

Suggested Grade Level 9-12

Overview

In this lesson, students will investigate how to optimize the power output of a photovoltaic cell using a home-made gnomon stand. Data collected from students' investigations will be used to create current-voltage and power-voltage curves to determine the "maximum power point," (MPP) at which their PV cell operates. The suggested time frame for this lesson is two to three (2-3) 50-minute class periods.

Standard Statements

- 3.1.10 A Discriminate among the concepts of systems, subsystems, feedback and control in solving technological problems
- 3.2.10 B Apply process knowledge and organize scientific and technological phenomena in varied ways
- 3.2.10 C Apply the elements of scientific inquiry to solve problems.
- 3.4.10 B Analyze energy sources and transfers of heat.
- 3.8.10 C Evaluate possibilities consequences and impacts of scientific and technological solutions.

Content Objectives

Students will know that

1. Photovoltaic (PV) systems have unique advantages over conventional power-generating technologies. PV systems can be designed for a variety of applications and operational requirements.
2. The high cost of PV modules and equipment (as compared to conventional energy sources) is the primary limiting factor for the technology.
3. Voltage is the measure of the force by which an electron is pushed through a circuit; its unit is the volt (V). Current (I) is defined as the flow of electrons, and its unit is the ampere (A). Power is the product of voltage times current; its unit is the watt (W).
4. Ohm's Law describes the relationship between current, voltage and resistance.
5. The angle at which a solar cell is positioned in relation to the sun affects its power output.
6. The amount of current produced by a PV cell is proportional to the amount of the light hitting the cell; therefore, increasing light intensity or increasing the size of the cell itself will increase the power output of the cell.
7. In order to construct a solar-powered system that will work at maximum efficiency, numerous factors pertaining to the design must be considered.

¹ Adapted from PSU's GREATT lesson, "Solar Power: The History, Chemistry and Application of Photovoltaics."

Process Objectives

Students will be able to

1. Identify the main parts of a PV system.
2. Wire a solar cell, resistor, and multimeter in series.
3. Determine the optimal conditions for operating a PV panel in a circuit with known resistance.
4. Graphically illustrate the relationship between power and voltage to describe a PV cell's "maximum power point" (MPP).

Assessment Strategies

1. Evaluation of the completed student handouts and the student's participation in class discussions.
2. Observation of student's participation and performance during an inquiry-based activity.

Materials

Part 1:

- Teacher computer with internet access
- Student computers with internet access—small groups
- Projection equipment
- Video Clips (see multimedia resources below)

Part 2, Per Group:

- Photovoltaic panel
- 2 Multimeters (or an ammeter and a voltmeter) (capable of reading at least 200mA of current)
- 2 insulated wires with alligator clips
- Several resistors of varying capacity (different for each group, if possible)
- 1 "gnomon stand" (construction directions included in Teacher Notes)
- Compass
- Computer
- Microsoft Excel or comparable graphing software (optional)

Notes on Materials

- Most materials should be available in a physics lab. However, RadioShack and other electronics stores will carry inexpensive multimeters and circuit building equipment. A great compendium of suppliers for various science materials can be found at the following website:
<http://www.exploratorium.edu/snacks/snacksupplies.html>.
- A great resource for solar panels and solar car kits is Sun Wind:
http://www.sunwind.ca/kits/sunnyside_instruct.html.

Multimedia Resources

- Video:
 - Part 1**
 - Energy from the Sun (4:15) [QuickTime movie]
 - Part 2**
 - Pv4 (1:11) [QuickTime movie]
 - Optional**
 - Inverter (:44) [QuickTime movie]
 - Solar Water Heater(1:37) [QuickTime movie]
 - Passive Solar (1:01) [QuickTime movie]

Procedures

Part 1: Investigate solar energy and how a PV cell works (30 minutes)

1. Introduce the investigation of solar power with a discussion of the major source of energy in the system—the sun. The supplemental video segment from Penn State Public Broadcasting’s *PA Energy’s*, “Energy from the Sun” may be used to introduce the array of solar applications in Pennsylvania. [Optional: The following series of movies filmed at Penn State’s Center for Sustainability may be used to highlight components of the photovoltaic system including the inverter and two different types of solar applications: “Inverter,” “Solar Water Heater,” and “Passive Solar.”]
2. Allow students to work in small groups to manipulate the PV system animation (<http://www.greenspec.co.uk/html/design/materials/pvcells.html>) and complete Part 1 of the student handout. To take a look at the micro-scale of what happens in a solar cell, allow students to access and view the short video, "Pv4" from individual computers.

Part 2: Build and test a PV system (1-50 minute Class Period)

1. Distribute “Part 2” materials to pairs or trios of students.
2. You may wish to demonstrate how to wire the solar panel, resistor, and multimeter in series (described in the Maximum Power Point student handout) before taking your class outside. Utilizing two multimeters perfects the circuit science in this lesson. Realizing that access to such materials is limiting, the multimeter can be wired parallel to the solar cell and one lead moved to the resistor to proceed with the experiment.
3. Circulate among student groups as they work together to wire their solar panel circuits and turn on the multimeters. [They should obtain a current reading of about 120-150mA. If not, make sure that they have their multimeters set to the 200mA, 20VDC setting.] Students should obtain a gnomon stand and attach their solar panel to the stand with duct tape.
4. Students should now head outside and follow the instructions for Part 2 in the Maximum Power Point student handout. In this section, students should experiment with the PV cell to investigate solar orientation and angle of incidence. Once they determine the angle producing the highest power output, they should investigate how varying the direction at which the panel is facing affects power.

5. Once students have completed the outdoor portion, return to the classroom to discuss what conditions optimized the power output of the PV cell in students' explorations and allow students to complete questions b-g of the student handout.

Part 3: Construct current-voltage and power curves (1, 50 minute Class Period)

1. Create Table 2 (in Part 3 of the student handout) by compiling each group's data for the resistance, angle of incidence, current, and voltage that produced the most power in Part 2.
2. Allow student groups to work through Part 3 of the student handout to calculate the power output for each resistance and create an I-V Curve and Power Curve for their solar panels by hand or using spreadsheet software like Microsoft Excel.
3. Lead students through question 6 in the student handout to analyze their graphs to determine the maximum power point for their solar panels.
4. Discuss the importance of operating at Maximum Power Point (MPP) to be able to get the most power out of the solar panel. A good example discussed briefly in the teacher notes is the use of PV panels in transportation.

Maximum Power Point (Teacher Notes)

(The Principles of Optimizing Photovoltaic Cell Power Output)

Notes on Part I:

Basic Electricity Review²

To understand photovoltaics, it is necessary to know something about electricity. There are three very important concepts, Voltage, Current, and Power.

- **Voltage**, measured in volts, is a measure of the electrical force between two points. Voltage is the cost in energy required to move a unit of positive charge from a more negative point (low potential) to the more positive point (higher potential).
 - A voltage potential can be thought of as the potential energy released when a unit charge moves “downhill” from the higher to lower potential. It is important to think of a voltage potential between or across two points in a circuit. Often a voltage potential is measured in reference to a single common point referred to as “ground,” located on the “-“ side of the voltage source.
- **Current**, measured in amperes or amps, is a measure of the number of electrons flowing through a wire in a particular time. It is analogous to gallons of water per second flowing in a hose.

*Note that voltage and current are totally different concepts. In an electrical circuit, the number of electrons that are moving is called the **amperage** or the **current**, and it is measured in **amps**. The "pressure" pushing the electrons along is called the **voltage** and is measured in **volts**. So you might hear someone say, "If you spin this generator at 1,000 rpm, it can produce 1 amp at 6 volts." One amp is the number of electrons moving (1 amp physically means that 6.24×10^{18} electrons move through a wire every second), and the voltage is the amount of pressure behind those electrons.

- The third concept is that of **power**. Power is simply voltage times current. It is also the amount of energy that is delivered in a unit of time.

*Electric current always travels in a closed loop, a "circuit".

Circuits: a synopsis from *howstuffworks.com*

Whether you are using a battery, a fuel cell or a solar cell to produce electricity, there are three things that are always the same:

² The following review materials on electricity and the nature of PV panels used in the Junior Solar Sprint were obtained from: <http://chuck-wright.com/SolarSprintPV/SolarSprintPV.html>, where Chuck Wright, renewable energy expert and consultant for the Texas State Energy Conservation Office's Renewable Energy Demonstration Program, "Infinite Power," shares his wisdom and PV panel testing results for the panels recommended for use with the Solar Sprint cars.² (If you are utilizing smaller PV panels, the included information will still be of great value.)

- The source of electricity will have **two terminals**: a positive terminal (typically represented in red) and a negative (typically represented in black) terminal.
- The source of electricity (whether it is a generator, battery, etc.) will want to push electrons out of its negative terminal **at a certain voltage**. For example, an AA battery typically wants to push electrons out at 1.5 volts.
- The electrons will need to flow from the negative terminal to the positive terminal through a copper wire or some other conductor. When there is a path that goes from the negative to the positive terminal, you have a **circuit**, and electrons can flow through the wire.
- You can attach a **load** of any type (a [light bulb](#), a [motor](#), a [TV](#), etc.) in the middle of the circuit. The source of electricity will power the load, and the load will do its thing (create light, spin a shaft, generate moving pictures, etc.).

The basic circuit of solar panel and motor is shown below. For the purposes of the investigation in this lesson, the resistor would represent the motor or load.

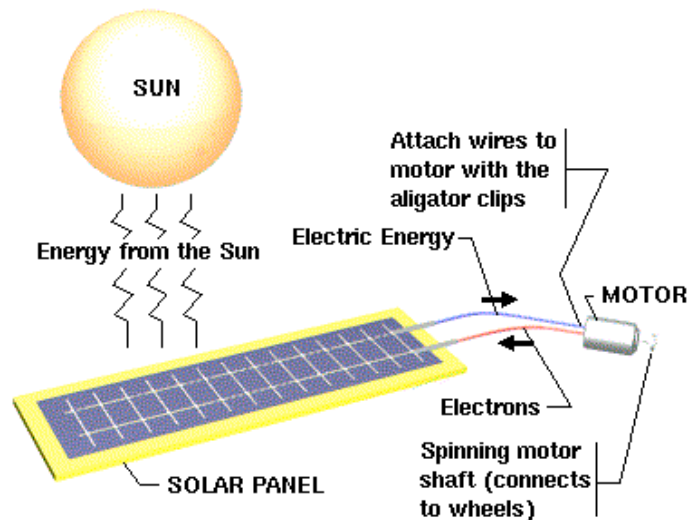


Figure 2: Solar Panel motor configuration

Source: http://eagle.chimacum.wednet.edu/middle/jss/Course_SolarPanel.htm

How Does A Solar Panel Work?³

When you look at the diagram above, you might ask, "How does the solar panel turn the sun's energy into electric energy?" The solar panel is made of a sandwich of two materials called *semiconductors*. Each material is made of millions of atoms. As you might already know, atoms have a positively charged *nucleus*, and negatively charged *electrons* which spin around the nucleus. When these two materials are put together in a sandwich, an interesting thing happens: electrons become pulled from the bottom half. But there's a problem. The electrons are all attached to atoms, and the atoms won't let go very easily. This is where the sun's energy helps out. If we shine sunlight on these

³ Chimacum School District Junior Solar Sprint Course.
http://eagle.chimacum.wednet.edu/middle/jss/Course_SolarPanel.htm, accessed 11 January 2006.

materials, the sunlight has enough energy to knock the electrons off of the atoms. The electrons will then be free to be pulled to the top of the sandwich.

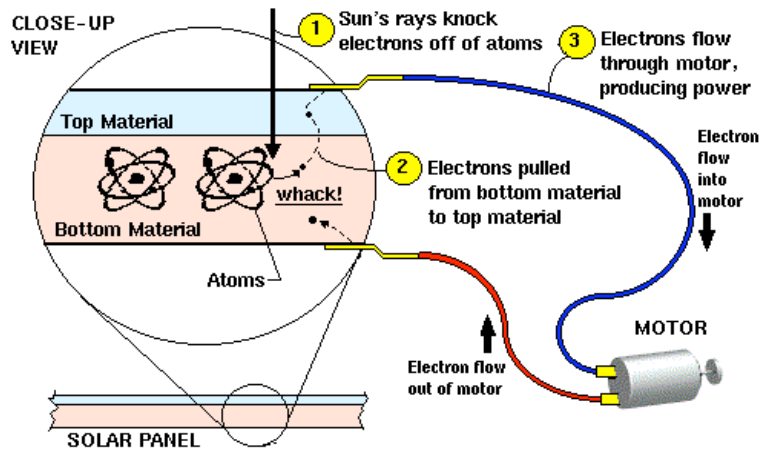


Figure 3: How a solar panel works

Notes on Part 2:

To be able to complete Part 2, students need to wire the circuit shown here:

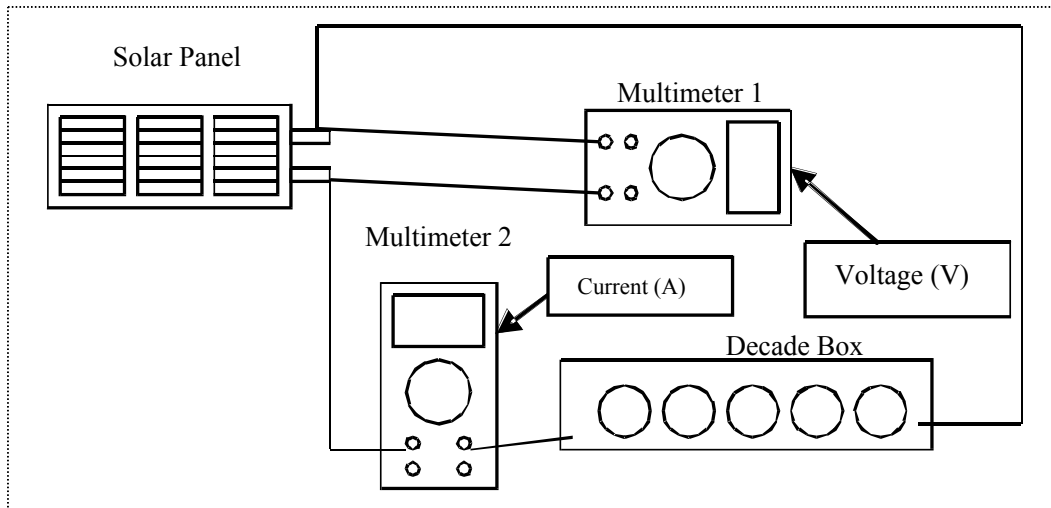


Figure 4. Solar cell circuit for use in Part 2.⁴

In Figure 1, the resistor (labeled decade box) is in series with the solar cell but the multimeter is in parallel with the resistor. In this condition the multimeter can measure V , but not I . You cannot use one multimeter and measure both V and I at the same time.

⁴ Graphic created by Professor Andy Lau of Penn State University's College of Engineering.

Construction of the Gnomon Stand

To allow students to experiment with solar orientation and angle of incidence without the hassle of trigonometry, Penn State Professor Andy Lau has devised the following set-up that is easy to make and reusable from year-to-year. A piece of 2' X 3' cardboard and a nail are all that you need to get going.

1. Attach a 2" gnomon of your choice to the cardboard.
2. Trace 8 circles onto the cardboard with the radii listed in the table below (The radii listed are for a 2" gnomon.)
3. Label the circles for each angle of incidence beginning with 10 at the smallest circle.

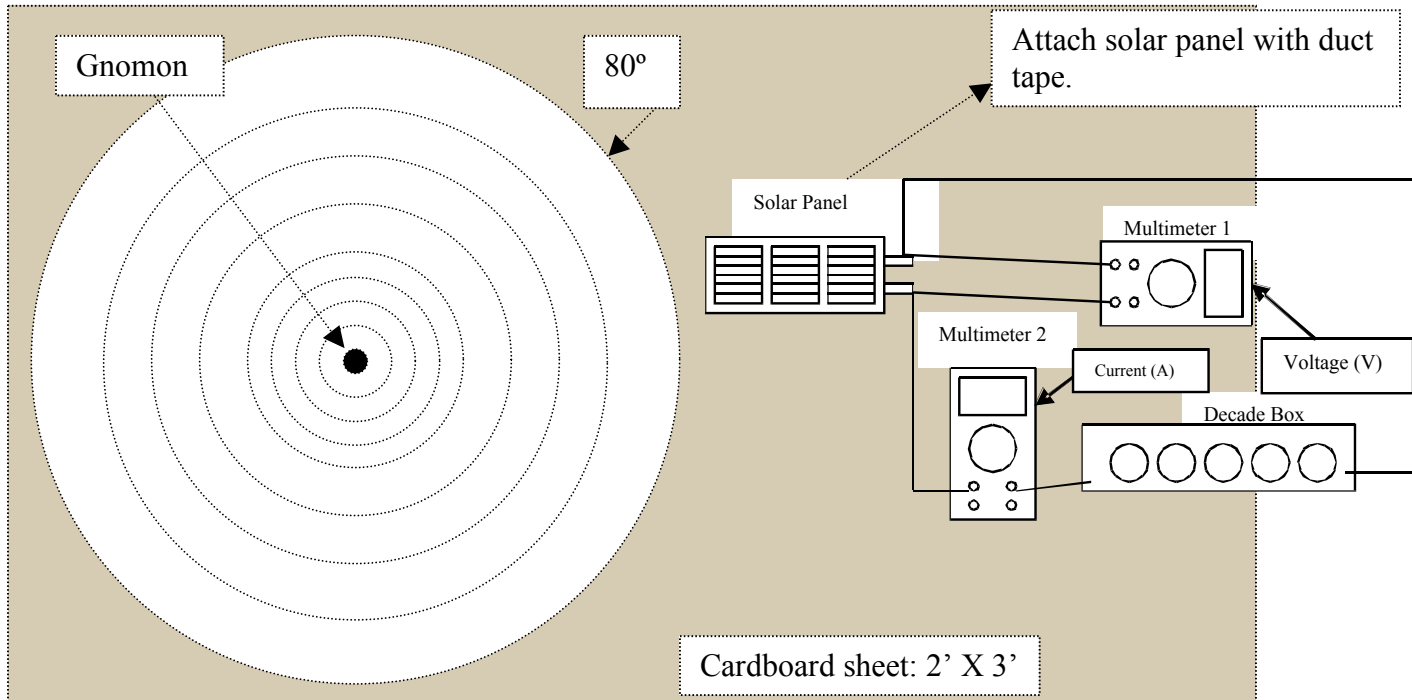


Figure 5. Gnomon Stand Diagram.

Table 1. Derived Circle Radii for a Two-Inch Gnomon

Angle of Incidence	tan of angle	Approximate Radius (inches)
10	0.176	0.325
20	0.364	0.728
30	0.577	1.154
40	0.839	1.678
50	1.192	2.4
60	1.732	3.5
70	2.747	5.5
80	5.671	11.4

This strategy works with the help of a little trigonometry. The gnomon acts like a normal that we would draw to the solar panel. Therefore, the length of the shadow cast by the gnomon can be our indicator of the angle of incidence as the attached panel is tilted. When the tip of the shadow created by the gnomon is on one of the circles, sunlight is

striking the panel at the corresponding angle of incidence. See Figure 6 below for the visualization of the relationship, $\tan(\text{angle } A) = X/h$.

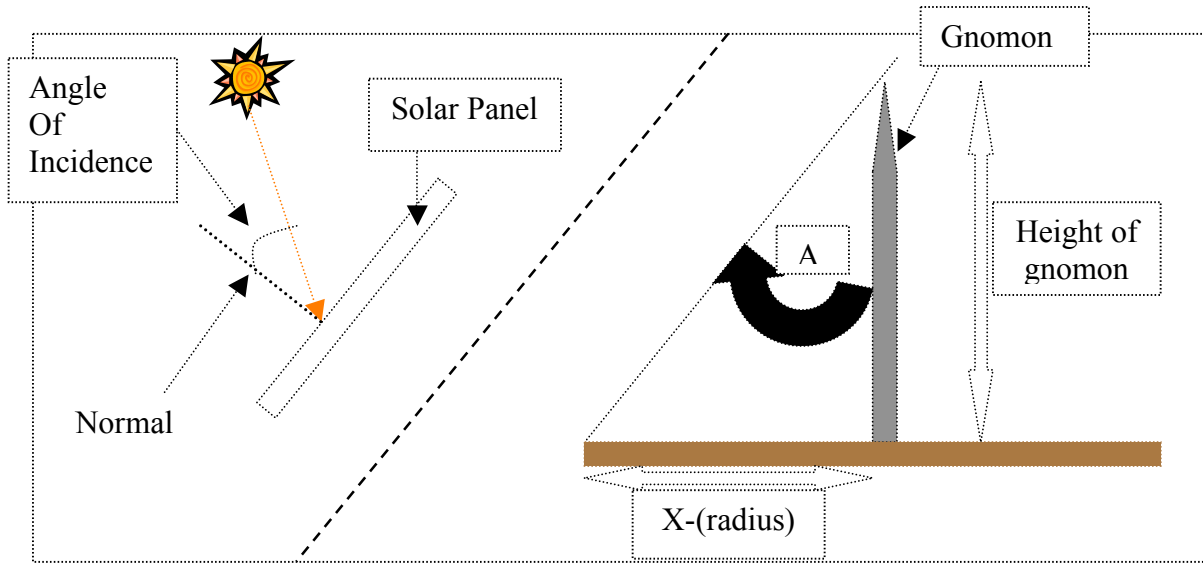
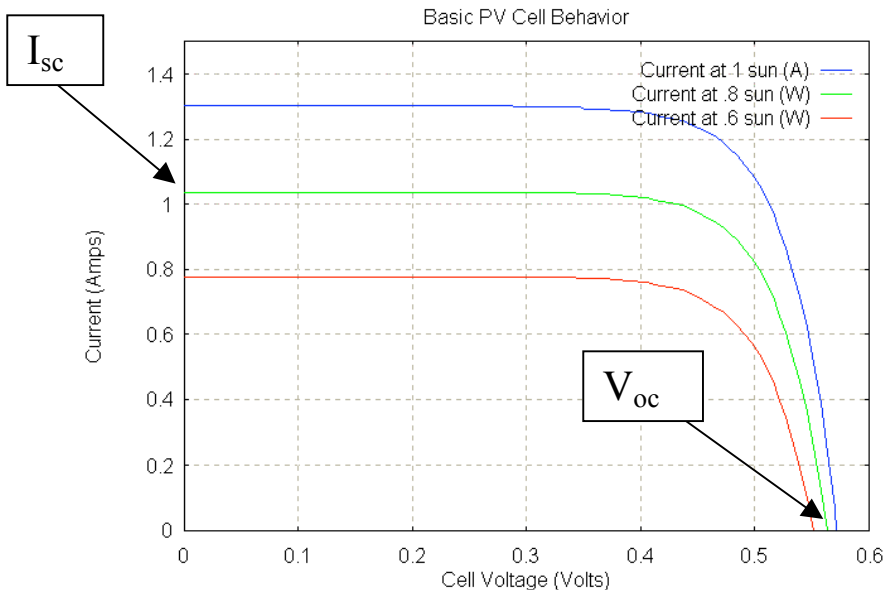


Figure 6. Diagram supporting the relationship used to derive circle radii.

Data Collection and Analysis: A suggested way for students to analyze their data is to plot two curves from the data collected in Part 2. The idea that orienting the panel towards the sun is intuitive for the most part; however, an important point to make, especially if students are trying to maximize the power output from the solar cell, is that there is a “Maximum Power Point” at which the cell operates.

The following graph from Chuck Wright’s Solar Panel exploration represents the behavior of a solar cell at particular intensities of solar radiation. Students will be creating one of these curves using data from Table 1. The explanations of short circuit and open circuit are included below the graph.

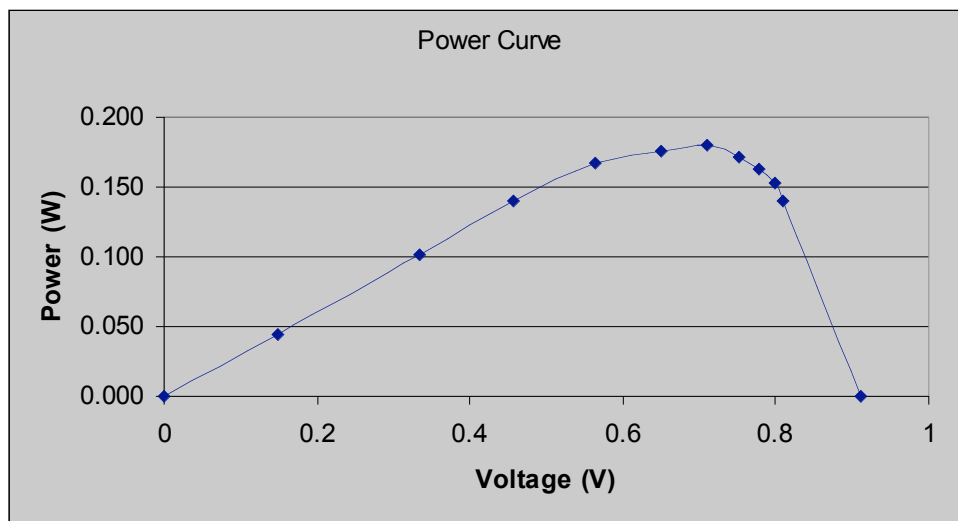
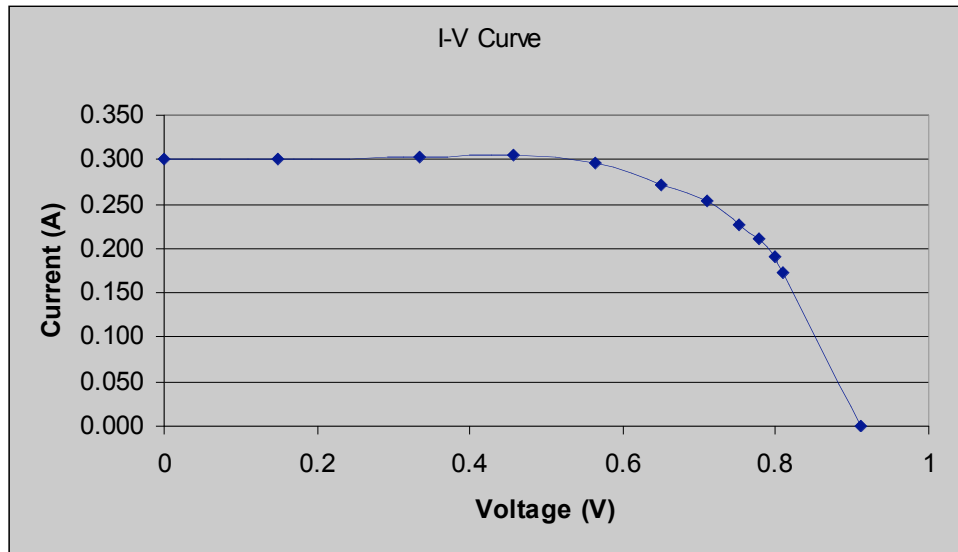


Note the point at which a curve intersects the vertical axis. This is known as the short circuit condition, and it defines how the cell operates if a wire is connected between its terminals, shorting it out. The current flow here is known as I_{sc} . Because there is no voltage, the cell delivers no power.

Now note the point at

which a curve intersects the horizontal axis. This is where the cell operates if it is unconnected. This is known as the open circuit condition, and the voltage produced is denoted V_{oc} . Because the current is zero, no power is delivered.

These following sample graphs were obtained from a mini-solar panel rated for 1V, 400 mA illuminated by a 150 watt floodlight positioned 16 cm above the solar panel.⁵

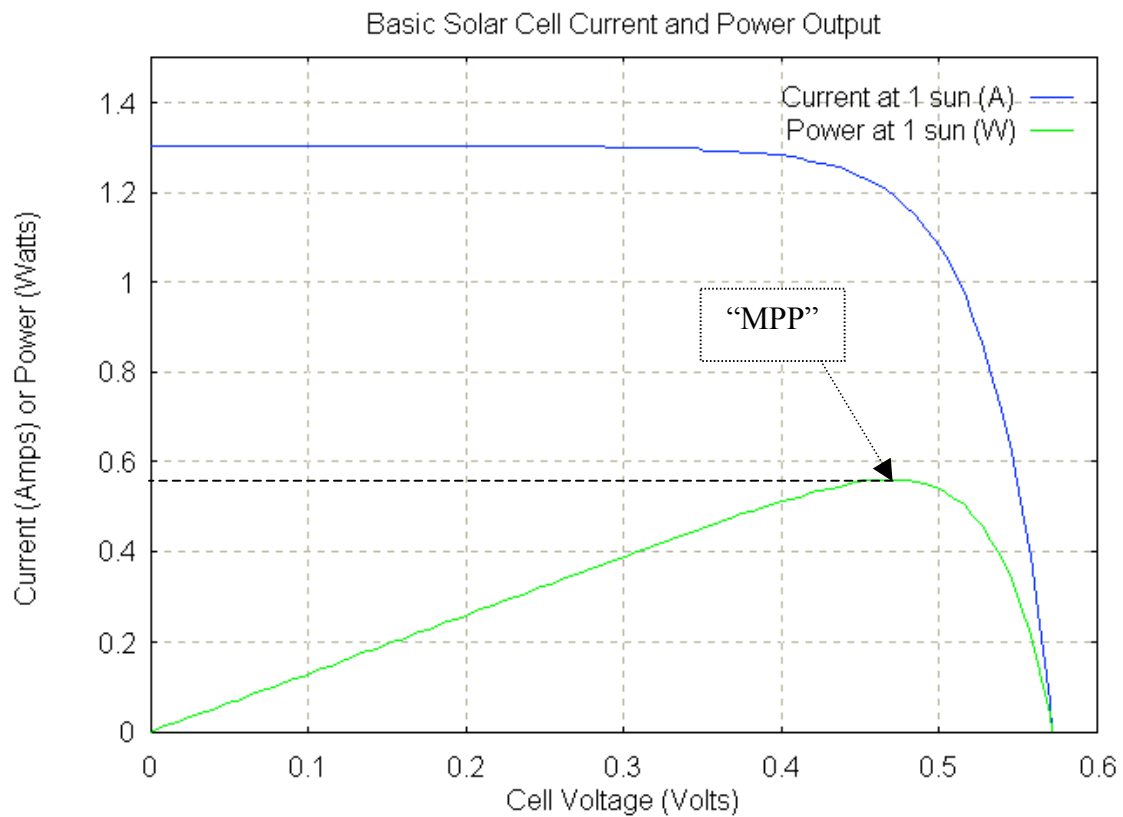


Source:

http://www.powernaturally.org/Programs/SchoolPowerNaturally/InTheClassroom/kitlessonsdocs/Solar_Kit_Lesson_11_Measpowermax.doc

⁵ School Power Naturally. "Solar Kit Lesson 11." Accessed 5 January 2006, http://www.powernaturally.org/Programs/SchoolPowerNaturally/InTheClassroom/kitlessonsdocs/Solar_Kit_Lesson_11_Measpowermax.doc

Note that the power is maximum at a single operating point. This is known as the "Maximum Power Point", or MPP. An important point to remind students is that, "If one is to get the most out of their solar cells, it is essential to operate around the MPP".⁶ This is particularly of interest if students may be utilizing a solar panel them to build a solar-powered car as a next step.



⁶ Wright, Chuck. "Solar Sprint PV." Accessed 7 January 2006, <http://chuck-wright.com/SolarSprintPV/SolarSprintPV.html>.

Name(s): _____

Maximum Power Point (Student Handout)
(The Principles of Optimizing Photovoltaic Cell Power Output)

Part 1: Investigating How a Photovoltaic (PV) System Works

Take a look at the animation of a PV system with your partner(s) at:

<http://www.greenspec.co.uk/html/design/materials/pvcells.html>

Work all the way through and answer the questions below together when you are finished.

Part 1

1. Name the major parts of the photovoltaic system? (Also include the job of each part you list).

2. What does the energy output of a solar (PV) cell depend upon?

3. Experiment with the “Energy Output” segment of the animation? Which direction and tilt combinations produce the highest output for the PV cell?

4. Why is it important to find out the highest power output for a PV cell?

Part 2 (Experimenting with a Photovoltaic Cell: How Can We Obtain Maximum Power?)

In this part of the activity you will be measuring the voltage and current produced by a photovoltaic cell under various conditions. While conducting these experiments, think about which conditions help the cell produce the most power! (Power=Current x Voltage)

STEP 1: Set up your model PV system:

- 1) Lay the solar panel on a clean surface, silicon side down. Wire the panel to the multimeter as shown in Figure 1 below.

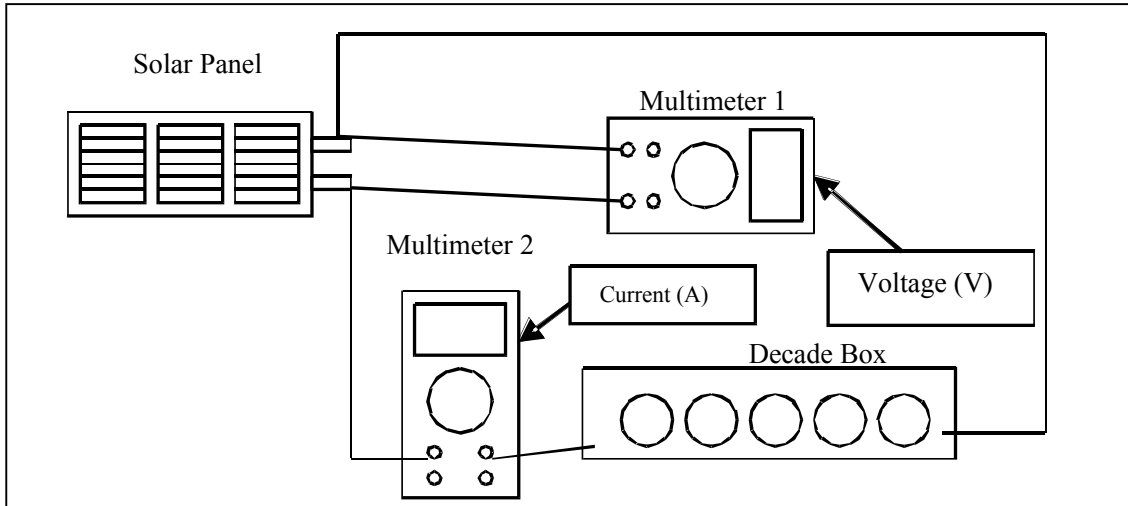


Figure 1. Diagram of a PV panel wired in series with a multimeter.

- a) Clip one end of a wire with alligator clips to one of the metal tabs on the back of the solar panel. Connect the other end of the wire to the red lead of the multimeter and to one arm of a 100 ohm (Ω) resistor at the same time. Take a second wire with alligator clips and clip one end to the second arm of the same resistor and to the black lead of the multimeter. Attach the other clip to the second metal arm on the solar panel.



Great job! Take a look at the following question and get ready to collect some data!

What purpose do you think the resistor serves?

- b) Turn the solar panel over and turn on the multimeter. (To get a proper reading you should be using the 200mA DC setting for current and the 20V DC setting for voltage). Measure the current (I). What is it?

- c) Measure the voltage (V). What is it? _____

STEP 2: Find out how the “tilt” (angle) and direction of a PV panel affect its power output:

1. Obtain a gnomon stand from your teacher, attach your solar panel, and face it towards the sun. Use a compass to find the direction in which you are facing and record that in Table 1.

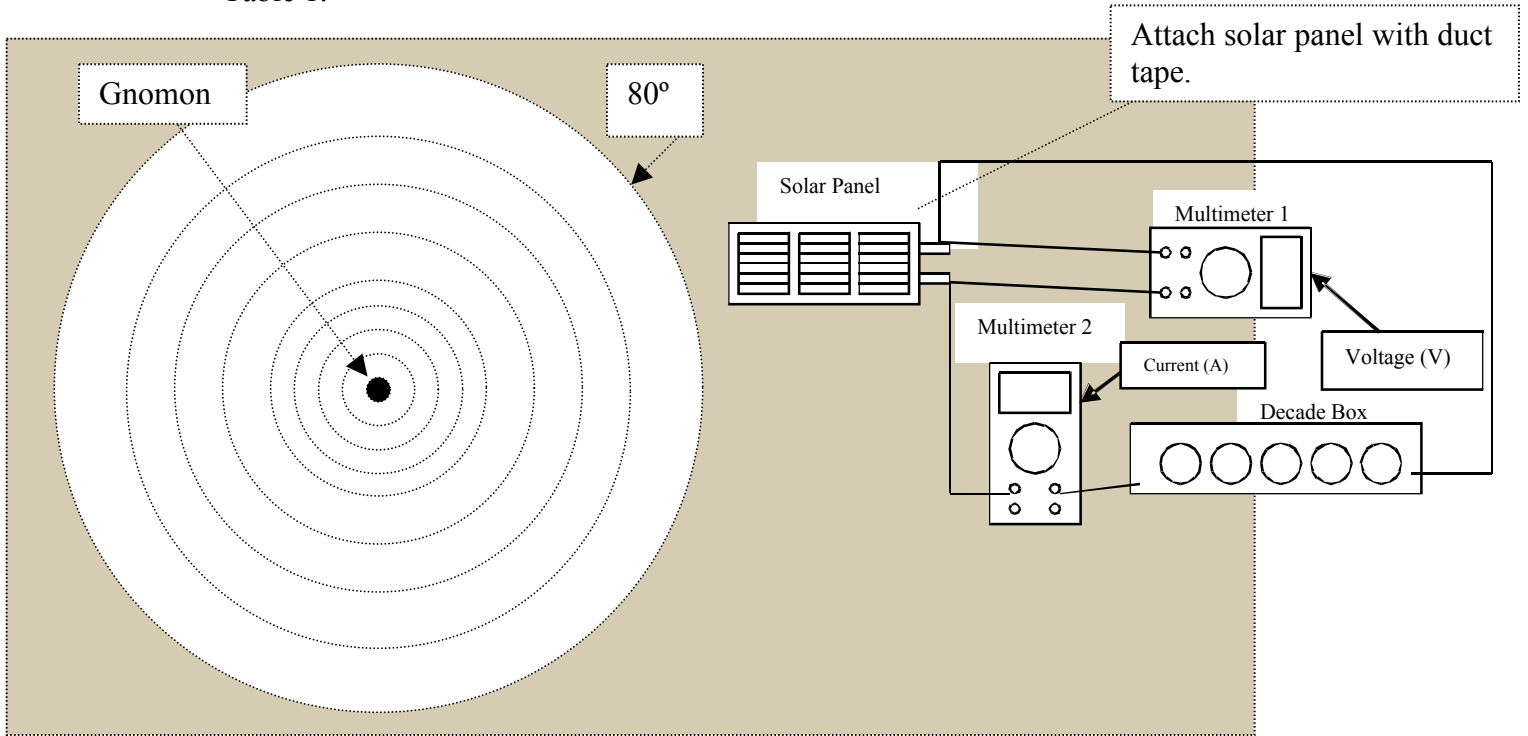


Figure 2. Gnomon Stand with Solar Panel Attached.

- a) Tilt the gnomon stand so that the tip of the gnomon’s shadow falls upon the circle for each angle and measure the current and voltage. Record your data in Table 1 below and calculate the power output of the cell for each angle. (Don’t forget to record the resistance used in your system and time of day in Table 1 below.)

Table 1.

Direction (N, S, E, W)	Time:	Resistance:	
Angle of Incidence (in degrees)	Current (amps)	Voltage (V)	Power (watts)
10			
20			
30			
40			
50			
60			
70			
80			

- b) At what angle and direction does the cell produce the most power? Why do you think this is so?

- c) Do you think that conducting this experiment at a different time during the day would affect your results? If so, why?

- d) How do you think that conducting this experiment during the different seasons would affect your results?

STEP 3: Questions to Consider

- e) Based upon your observations and evidence, what are the **best conditions** for gaining the most power from a PV cell?

- f) What are some of the **limits** of using PV panels to make electricity?



- g) What are some **obstacles** to using PV panels to do work like powering automobiles?

Part 3 (Graphing and Analyzing Your Class's PV Panel Data)⁷

In this section, you will use the data that your class has gathered in the previous pages to create two graphs. The graphs will be your tools to find the “Maximum Power Point” (MPP) for your PV panel!

- 1) Remember Ohm’s law as you are working through this section:

$\text{Ohm's law: Voltage (V) = Resistance } (\Omega) \times \text{Current (A)}$
--

 Remember that electric power is measured in watts (W) where: 
$\text{Power (W) = Voltage (V) } \times \text{Current (A)}$

- 2) Calculate and record the output power for each resistance value in Table 2 below.

Table 2. Class Data for Current & Voltage with Different Resistances in Series

Resistance (Ω)	Angle of Incidence (degrees)	Voltage (V) “volts”	Current (A) “amperes”	Power (W) “watts”

- 3) Create the I-V Curve for your solar panel.


On a separate sheet of paper or using Microsoft Excel, plot the class data from Table 2 for current versus voltage to obtain the panel’s **I-V curve**. Plot current (A) on the y-axis and voltage (V) on the x-axis. Label and show the scale of each axis.

⁷ Adapted from Solar Kit Lesson #11, “Power Maximum: An Electrical Determination” of School Power Naturally’s Solar Education for NY.

- 4) Next, create the Power Curve for your solar panel.

On a separate sheet of paper or using Microsoft Excel, plot power (that you calculated and entered into Table 2) versus voltage to obtain the panel's **power curve**. Plot power (W) on the y -axis and voltage (V) on the x -axis. Label and show the scale of each axis.

- 5) From the power-voltage graph, what is the value of maximum power and what is the voltage at maximum power?



- 6) From both graphs, what is the current at maximum power? (From the maximum power point on the power curve, trace upward parallel to the y -axis until you intersect the I-V curve. Trace left parallel to the x -axis until you reach the y -axis.)



- 7) Attach copies of your graphs to this handout for full credit.