Solar Angles and Geometry—Determining the Effect of Angle Orientation on PV Module Output
Grades 9–12

Noninquiry

Category: E = Environmental factors; S = Fuel/energy source; G = Power Generation

National Standards:

Math Curriculum Standard (from *National Council for Teachers of Mathematics*):

ALGEBRA

- Understand patterns—represent, analyze, and generalize a variety of pattern with tables, graphs, words, and, when possible, symbolic rules.
- Use mathematical models to model and solve contextualized problems using various representations, such as graphs, table, and equations.

DATA ANALYSIS AND PROBABILITY STANDARD

- Formulate questions, design studies, and collect data about a characteristic shared by two populations or different characteristics within one population
- Use observations about differences between two or more samples to make conjectures about the populations from which the samples were taken

Science Curriculum Standard (from *National Academy of Science and National Research Council*):

TRANSFER OF ENERGY

- Energy is a property of many substances and is associated with heat, light, electricity, mechanical motion, sound, nuclei, and the nature of a chemical. Energy is transferred in many ways.
- Electrical circuits provide a means of transferring electrical energy when heat, light, sound, and chemical changes are produced.

EARTH IN THE SOLAR SYSTEM

- The sun is the major source of energy for phenomena on the earth's surface, such as growth of plants, winds, ocean currents, and the water cycle. Seasons result from variations in the amount of the sun's energy hitting the surface, due to the tilt of the earth's rotation on its axis and the length of the day.

Technology Curriculum Standard (from *International Society for Technology in Education*):

TECHNOLOGY PRODUCTIVITY TOOLS

- Students use technology tools to enhance learning, increase productivity, and promote creativity.

TECHNOLOGY RESEARCH TOOLS

- Students use technology to locate, evaluate, and collect information from

a variety of sources.
- Students use technology tools to process data and report results.

DATA ANALYSIS AND PROBABILITY STANDARD

- Formulate questions, design studies, and collect data about a characteristic shared by two populations or different characteristics within one population

Materials: (Items listed should be provided for each group) PV Module, protractor, graph paper, paper towel roll, multimeter, compass, ruler, 30 foot string, calculators, pencils and markers.

Summary: In this noninquiry-based activity, students will explore and learn how to orient a PV module for maximum electricity production through data gathering and analysis. They will record the current and voltage measurements of a PV module using a multimeter, and they will determine the effect of angle orientation on PV module output. See the materials section above.

Curriculum Integration: This activity integrates science, math and technology as students learn how to use a compass for orientation, how to determine and calculate various solar angles, how to take voltage and current measurements with a multimeter, and test the effects of altered angles of orientation.

Time: 4 days

Grouping: Groups of 3–5 students

Developer: Robi Robichaud, National Renewable Energy Laboratory.

ACTIVITY

Solar Angles and Geometry—
Determining the Effect of Angle of Orientation on PV Module Output

Grade Level—Subject

9–12th Grade—Science, Math, and Technology Education (with minor adjustments all materials can be quite appropriate for 6–8th grade).

Overview

In this lesson students will explore and learn:

- How to orient a PV module for maximum electricity production through data gathering and analysis
- How to take current and voltage measurements of a PV module using a multimeter
- How to determine the effect of angle of orientation on PV module output

Purpose

The purpose of this lesson is to introduce students to the concept of how to maximize the solar resource, how to take measurements of the electrical output of a PV module and put the measurements into a more useful, graphical form.

Learning Objectives

After completing this lesson, students will be able to:

- Identify "normal" orientation for a PV module
- Be able to take current and voltage measurements and calculate power from them
- Use a multimeter to take a series of sequential measurements for performance analysis
- Understand how to interpret a graph for determining optimum angle of orientation

Vocabulary

maximum
voltage
power
angle of orientation
current
volt
watt
photovoltaic module
amp
multimeter
normal

Resources & Materials

Groups of 3–5, each group should have:

PV module (2–20 Watts)
protractor
graph paper
paper towel roll
multimeter
compass
ruler
one 30-foot string
calculators
pencils/markers

Preparatory Activities & Prerequisite Knowledge

Students should already know or be familiar with the following:

protractor
angles

independent variable (x)
dependent variable (y)
current
power
how to read a graph (x and y axes)
how to plot/construct a graph (x and y axes)
voltage

Before the first day of this lesson, students should have some familiarity with photovoltaic modules and systems, how they work, and why we use them. They should also have completed the unit on Appliance Power and Energy and the unit of Power and Energy Basics so they will be able to attach meaning to the DC electrical power output of the PV module.
Teacher should have some familiarity with a multimeter and taking current and voltage readings with it. Students should also be comfortable with the safe use of a multimeter.
NOTE: A small module of 5–20 Watts is preferred for these exercises. There is no need for a 50–100 watt module, no need for a high-voltage or high-current module. Safety is paramount, and the smaller the power source, the less need to worry even if a student is not taking working with electricity very seriously.

Discussion and Analysis of Orienting PV Panel

Teacher leads students through introduction and discussion of maximizing the available sunlight (solar resource) through orienting the panel so that it faces the sun directly.

Day 1

Solar Geometry and Its Effects on Electric Power

In order to measure the power produced by a solar electric or photovoltaic (PV) module, students need some background information on the sun, its rotation, its intensity, the photoelectric process, and the importance of module orientation for producing maximum electricity. Students then take measurements of the current and voltage produced by the PV module. With this information, they can calculate the power.

Angle of Orientation

For maximum solar electricity production, solar panel orientation is important. Students will be able to determine exactly how important orientation is through testing the PV power production at various angles of orientation.

Group Work—Outside

Students should be in groups of 3-5 and most of what follows should take place outside (except for the data analysis done on a computer) preferably on a reasonably sunny day. After students are comfortable working with the multimeter and taking measurements, doing similar testing on a cloudy, partly cloudy, rainy or snowy day may provide students greater insight as to the effects of these meteorological conditions on PV output. It is preferable that each group has a full set of supplies to do this activity.

Teacher-led Questions, Answers, and Discussion

Ask students for information about the path of the sun during the day and during the year. It should be agreed that the sun moves (appears to move) from east to west across the sky daily and is higher in the sky at noon on June 21st than on December 21st. The explanation for the yearly change in the sun's path across the sky has to do with the earth's axis tilt and how it affects the relative position of the sun in our sky view.

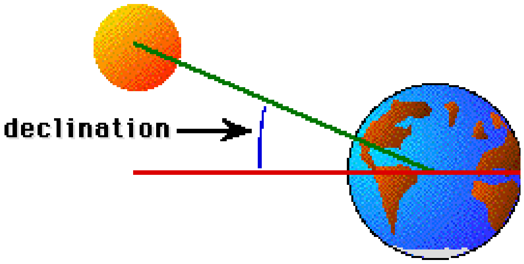
Introduce the idea that sun's daily highest point in the sky—the sun's **altitude angle—occurs at solar noon each day**. The altitude angle is measured from the **horizon up to the sun**. The sun does not honor Daylight Savings Time and solar noon is relatively constant (varies by a few minutes seasonally, but not by an hour as we change it with Daylight Savings and Standard Time).

During the Winter Solstice at solar noon, the sun will be at its lowest solar noon point in the sky for the entire year. The sun's altitude angle will be **23° less during the Winter Solstice than at the Equinox** (it is at about 55° at solar noon on the Equinox). So, 55° - 23° = 32°. The sun will be 32° above the horizon at noon on the Winter Solstice. During the Summer Solstice at solar noon, the sun will be at its highest solar noon point in the sky for the entire year. The sun's altitude angle will be 23° more than at the Equinox. So, 55° + 23° = 78°. The sun will be 78° above the horizon at noon on the Summer Solstice.

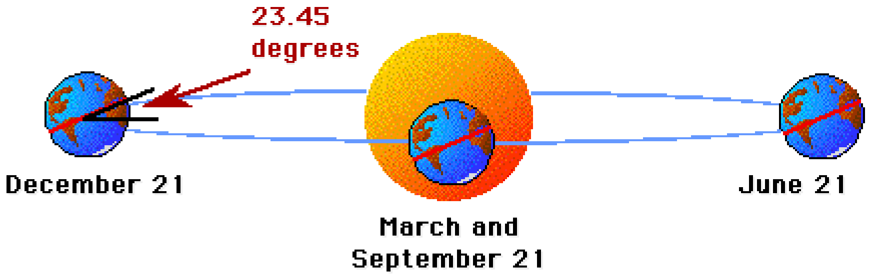
The following links that help explain and calculate solar angles and geometry were developed by Christopher Gronbeck, Sustainable By Design, christopher@susdesign.com
http://www.susdesign.com/
His is an interesting web site that will do all of your solar angle calculations for you

What follows below are brief descriptions of the angle and how it is calculated manually.

Declination Angle



Declination angle is the angular distance of the sun's position north or south of the earth's equator. The earth's axis is tilted 23.34° from the plane of the earth's orbit around the sun. Where the earth is in its annual path around the sun causes the declination angle to vary from 23.45° north on December 21st (Winter Solstice) to 23.45° south on June 21st (Summer Solstice). The tilted earth axis is what causes our seasons and is why we have opposite seasons in the northern and southern hemispheres.



The declination angle is calculated with the following formula:

$d = 23.45 * \sin [360 / 365 * (284 + N)]$

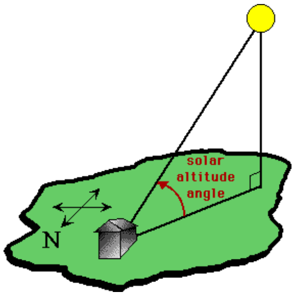
Where:

d = declination angle (degrees)

N = day number, January 1 = day 1 and day number is counted continuously to 365 (Julian calendar)

Altitude Angle

The altitude angle (sometimes referred to as the "solar elevation angle") describes how high the sun appears in the sky. The angle is measured between an imaginary line between the observer and the sun and the horizontal plane the observer is standing on. The altitude angle is negative when the sun drops below the horizon. In this graphic, replace "N" with "S" for observers in the Southern Hemisphere.



The altitude angle is calculated as follows:

$$\sin (Al) = [\cos (L) * \cos (D) * \cos (H)] + [\sin (L) * \sin (D)]$$

where:

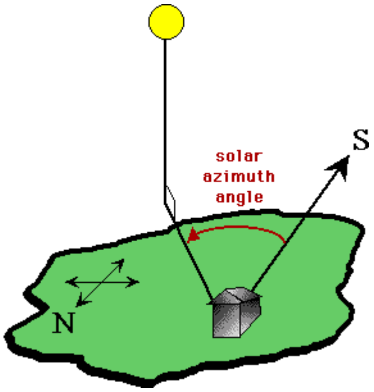
Al = Solar altitude angle

L = Latitude (negative for Southern Hemisphere)

D = Declination (negative for Southern Hemisphere)
H = Hour angle
Source: http://susdesign.com/sunangle/

Azimuth Angle

The solar azimuth angle is the angular distance between due South and the projection of the line of sight to the sun on the ground. A positive solar azimuth angle indicates a position East of South, and a negative azimuth angle indicates West of South.



Note that in this calculation, Southern Hemisphere observers will compute azimuth angles around +/- 180 degrees near noon. Comments would be appreciated concerning whether or not this should be modified such that solar noon is associated with an azimuth value of 0.

The azimuth angle is calculated as follows:

$$\cos(Az) = (\sin(Al) * \sin(L) - \sin(D)) / (\cos(Al) * \cos(L))$$

where:
L = Latitude (negative for Southern Hemisphere)
Az = Solar azimuth angle
D = Declination (negative for Southern Hemisphere)
Al = Solar altitude angle

The sign of the azimuth angle also needs to be made equal to the sign of the hour angle when using the above equation.

Source: http://susdesign.com/sunangle/

Magnetic Declination Angle

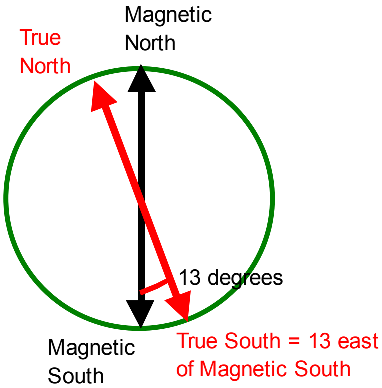
If the sun were at solar noon, it would be in our southern sky at 13° east of magnetic south. We could orient our solar panel to face directly at the sun, 13° east of magnetic south easily.

Students should be asked to find **magnetic south** and **true south** using a compass. The compass will point to **magnetic north**, 180° opposite that will be magnetic south. **13° east of magnetic south** will be **true south**. The PV panels on the roof of your school were mounted facing as close to true south as the support structure of the roof would allow.

Magnetic Declination and Earth Rotation

1. In few places on Earth does magnetic north equal true north.

   In Denver, true north will be 13 degrees west of magnetic north, so true south will be 13 east of magnetic south. When you go outside, use your compass to find magnetic south, then go 13 degrees east to find true south.



2. For maximum output, we like the sun’s rays to be "**normal**" to the PV module. **Normal means perpendicular**, but for 3-D objects, perpendicular is more difficult to determine. We can make something **"normal"** to the sun’s rays by having it face the sun directly **so it casts <u>no shadow</u> (or a minimal shadow).**
3. The earth rotates 360 degrees each day (one full circle), causing the sun to appear to revolve 360 degrees around the earth each day. How many degrees across the sky does the sun move in 1 hour?

Sample Problems Using Magnetic North/South and Sun Rotation

Here are several simple calculation problems to ensure that students understand magnetic declination and the rotation of the earth.

- How many degrees across the sky does the sun move in 1 hour?

  Use a simple proportion: 360 degrees / 24 hours = x degrees / 1 hour == now solve. First multiply both sides by 1 hour, the hours will cancel out on the left, then divide 360 degrees by 24 and you will get:
  X = 15 degrees in one hour, the sun moves across the sky 15 degrees in one hour.

- How many degrees per hour does the earth rotate?

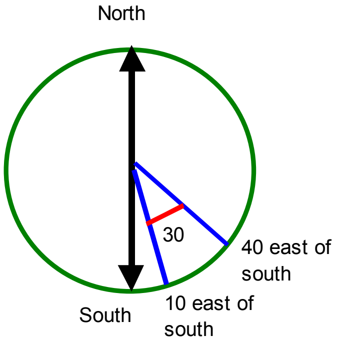
  15 degrees.

- How many degrees does the earth rotate in 3 hours?

  3 x 15 degrees = 45 degrees.

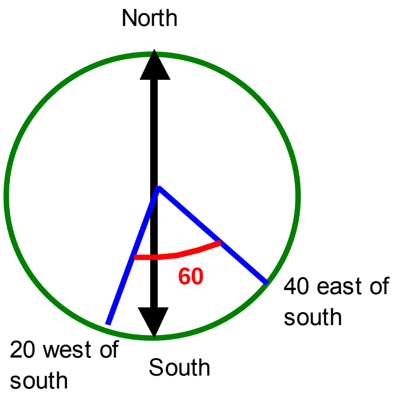
- If the sun is at 40 degrees east of south at 10:00 a.m., where will it be in 2 hours?

2 hours * 15 degrees / hour = 30 degrees
So, sun will be 10 degrees east of south.



- If the sun is at 40 degrees east of south at 10:00 a.m., where will it be in 4 hours?

4 hours * 15 degrees / hour = 60 degrees
So, sun will be 20 degrees west of south



- If the sun is at 95 degrees east of south at 6:30 a.m., where will it be at 5:00 p.m.?

How many hours are we talking from 6:30 am to 5:00 pm**?**
5.5 + 5 = 10.5 hours
How many degrees will the sun rotate in 10.5 hours?
10.5 hours * 15 degrees / hour = 157.5 degrees
The sun will use 95 of those degrees to get to south (157.5 - 95 = 62.5)
So it will continue westward another 62.5 degrees and be 62.5 degrees west of south

Magnetic Declination and Earth Rotation Worksheet

1. In few places on Earth does magnetic north equal true north. **In Denver, true north will be 13 degrees west of magnetic north, so true south will be 13 east of magnetic south. When you go outside, use your compass to find magnetic south, then go 13 degrees east to find true south.**

2. For maximum output, we like the sun's rays to be **"normal"** to the PV module. **Normal means perpendicular**, but for 3-D objects, perpendicular is more difficult to determine. We can make something **"normal"** to the sun's rays by having it face the sun directly **so it casts <u>no shadow</u> (or a minimal shadow).**

3. The earth rotates 360 degrees each day (one full circle), causing the sun to appear to revolve 360 degrees around the earth each day. How many degrees across the sky does the sun move in 1 hour?

4. How many degrees per hour does the earth rotate continuously?

5. How many degrees does the earth rotate in 3 hours?

A sketch may be helpful on the next 3 questions.

6. If the sun is at 40 degrees east of south at 10:00 a.m., where will it be in 2 hours?

7. If the sun is at 40 degrees east of south at 10:00 a.m., where will it be in 4 hours?

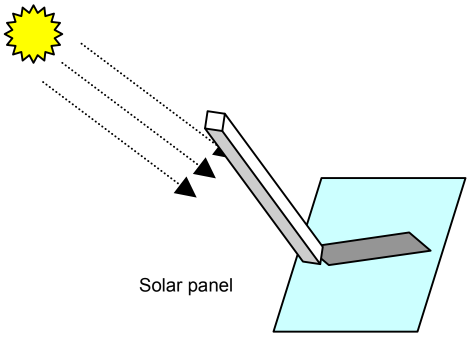
8. If the sun is at 95 degrees east of south at 6:30 a.m., where will it be at 5:00 p.m.?

Day 2
“Normal” to the Sun

Ask students to face the PV module directly at the sun so it will maximize electric power output. It may be difficult for students to tell if they truly are facing **directly** at the sun. To determine if we are facing directly at the sun, we need another form of measurement. We need to determine if the tilt angle of our solar panel is optimized so that it is completely “flat” relative to the sun’s incoming rays.

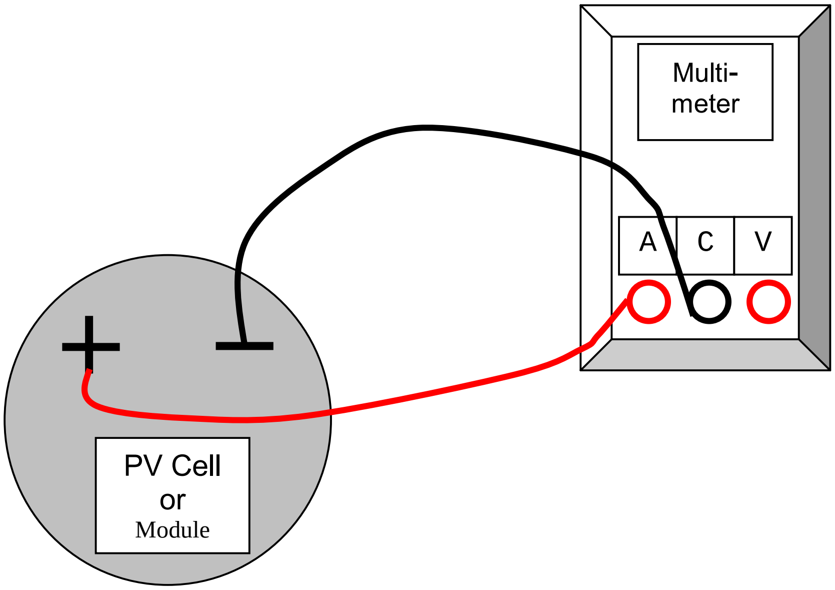
The concept of “normal” or being perpendicular in 3 dimensions, not just perpendicular in 2 dimensions like in plane geometry, should be introduced. The easiest way to get across this somewhat abstract concept is with a hollow tube, e.g.. a cardboard paper towel tube. If you orient the tube so that you have full circle on sun shining through to the ground (with no shadow being cast by the tube), then the tube is “parallel” to the sun’s rays.

On a sunny day, if the PV module is facing “**normal**” to the sun, the maximum amount of **direct beam sunlight** will be striking the surface of the PV module.
A similar way of obtaining “normal”, and one that will help to properly orient the solar panel, is to place a 1 x 1 x 12 piece of wood (or a cardboard paper towel tube) on the panel surface to that one of the small, square ends is flush against the panel. It will probably cast a shadow. Keeping it flush against the panel, adjust the panel so that the wood casts no shadow. At that point, the panel will be “normal” to the sun.



Students should be asked to orient their solar panel “**normal**” to the sun to maximize electrical output. If a cylinder or rectangular prism is placed upright with its base flush on the surface of the module and it casts no shadow, it is “normal.” The module will probably be angled to the east or west of true south and be tilted up to some degree to achieve “normal.” Of course, exactly how will vary depending on your location (latitude), time of year, and time of day. Once students have found the proper orientation, they should try to maintain the exact same “tilt” angle for the module for the rest of the measurements to be taken.

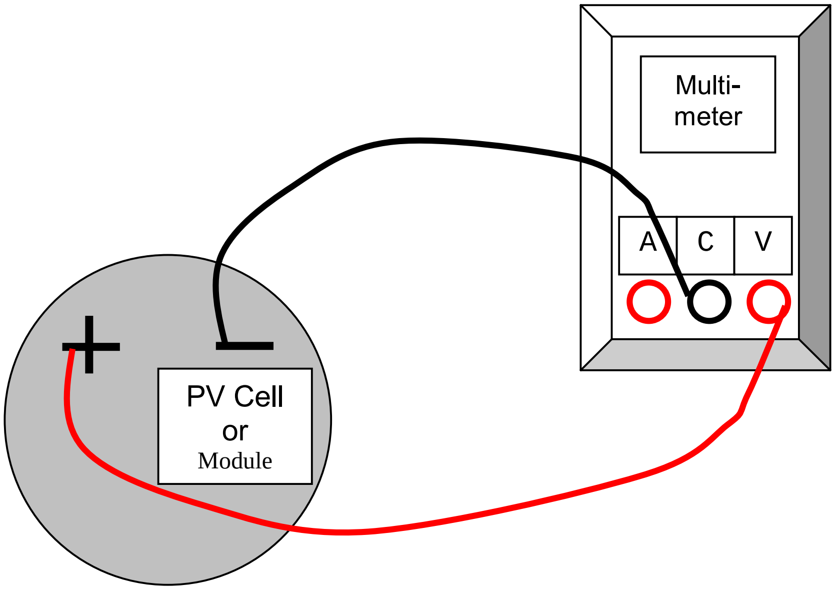
Once “normal to the sun” is found, that direction pointing to the sun will be considered the reference point. Let’s call it **0°.** Using the **multimeter**, students take a current reading (be sure the multi-meter has the black lead in the COM port and the red lead in CURRENT or A for Amp) to determine how much current (in amps) the PV module is producing while facing directly normal to the sun. Have a student record the reading under Current at **0°** in the worksheet (three pages hence).



To measure current, make the PV module or cell part of a complete circuit.

Then, remove the red lead from Current and put it into the VOLTAGE port or V port. Using the multimeter, students take a voltage reading (be sure the multi-meter has the black lead in the COM port and the red lead in VOLTAGE or V port) to determine how much voltage (in volts) the PV module is producing while facing directly normal to the sun. Be sure to change the leads on the multimeter and the type of measurement being made (Voltage). Have a student record the reading under Voltage at 0° in the worksheet (two pages hence).

To measure voltage, measure the potential across the PV cell terminals.

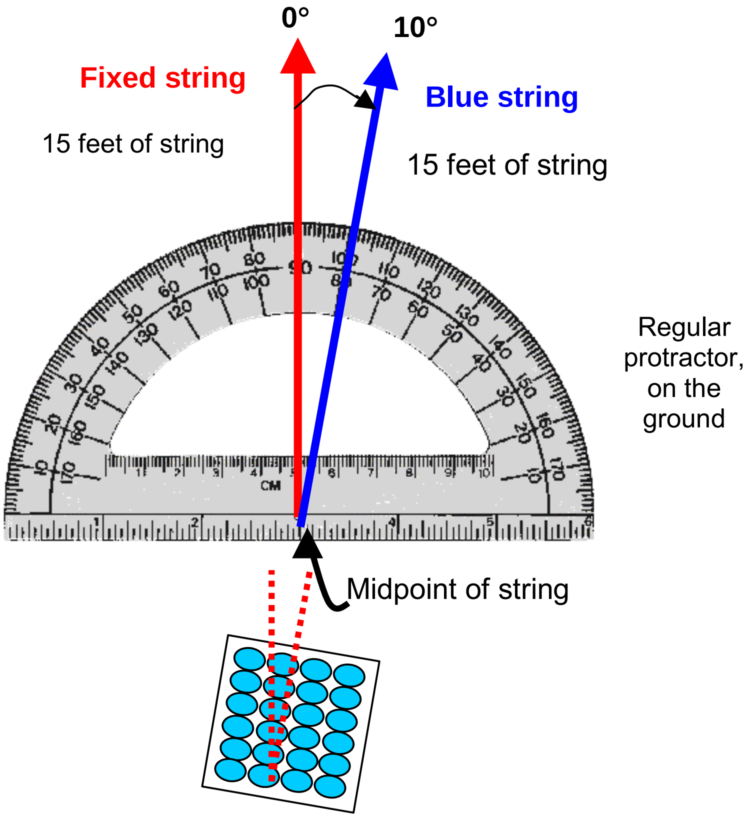


Students have now taken one current and one voltage measurement with the PV module facing “normal” to the sun. Power can be calculated by multiplying current x voltage (I x V = P). See the Power and Energy Unit for a detailed explanation.

To determine the effects of angle of orientation, students will take a series of measurements with the angle of orientation changing by **10°** increments for each measurement (from **0°** to **90°**). Trying to determine exactly how far to turn the PV module to represent a **10°** increment can be challenging. Present the problem and see what your students come up with. Below is one method that works reasonably well.

A protractor is a useful tool for determining angles, however, it seems rather small for determining angles of the PV module relative to the sun. Using a protractor and one 30-foot length of string, we can "enlarge" the protractor as a tool to serve the purpose.
Lay the protractor on the ground as shown on the next page. Have a student hold the middle of the string in place on the center point of the protractor (at the zero point on the horizontal bar). Extend one end of the string along the **90°** axis, which is perpendicular to the horizontal bar—let's call this the "**fixed string**". It is the **red string** in the diagram on the next page. Keep the protractor and this string permanently in this position as this will serve as the reference point for all the other measurements.

Extend the other end (let's call it the **blue string** to be able to tell them apart here) of the string **10°** west of the **90°** axis or along the **100°** line. With the string extending out 15 feet from the protractor, one can more easily see how far to turn the PV module to be **10°** west of "normal" (**10°** east of "normal" would work just as well).

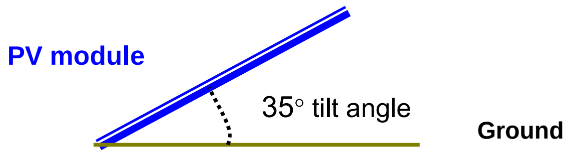


PV module, not drawn to scale, turned or facing **10°** off of **normal**.

Use the blue string to establish "line of sight" to be able to effectively shift the PV module 10° west of the original measurement. With the PV module now 10° west (or east) of normal, have students take current and voltage measurements again with the multimeter (remember to change the ports the red lead is in for current and voltage measurements) and record them on the worksheet on the next page.

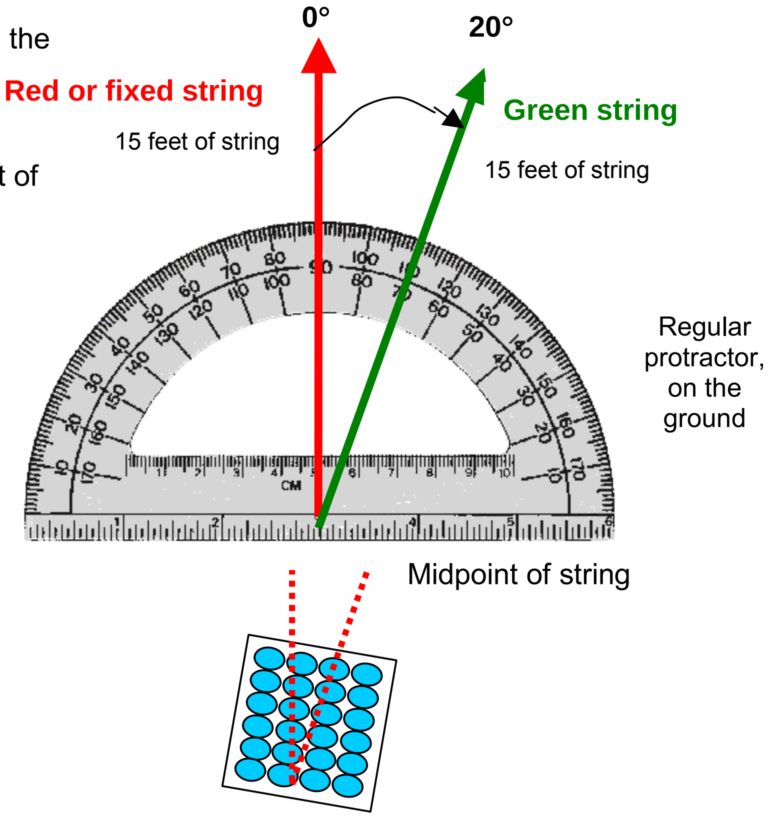
Tilt Angle

It is important to try and maintain the same “tilt” angle (i.e., how much the module is tilted up from the ground) for all of the measurements taken. The tilt angle is called the “Beta” (β) angle in solar engineering applications.



Bear in mind, for the results to be meaningful in terms of the effect of angle of orientation on PV power production, the weather conditions need to be stable. A clear day with steady sun is best. A cloudy day with mixed cloud cover or changing cloud thickness will make it difficult to obtain meaningful or consistent results.

Keeping the protractor in the same place (on the ground), and the **fixed string** on the same line, extend the “blue” half of the string to **70° or 20° off of “normal”.** Re-align the PV module to follow the line of sight of the new line from the “**green”** string. Let’s call it the “green” string so we can differentiate in this text. (First measurement was **10°** and we called it **blue**, 2nd measurement was **20°** and we called it **green**). From this 2nd line of sight, the **green** string, students will again take current and voltage measurements that will show the power output when facing **20°** off of “normal.”



PV module, not drawn to scale, turned or facing **20°** off of normal.

Have students continue this process taking measurements at 30° off of normal, 40°, 50° and so on through to 90°. Students can even continue taking measurements beyond 90° off of normal, in other words, facing “away” from the sun. Measurements can be taken all the way to 180° away from normal—this is facing directly away from the sun. Students can continue to take measurements every 10° or they could simply do 90°, 135°, and 180° for illustrative purposes (as no one would ever orient a PV module 135° away from the sun for power production). Students may be surprised at how much power the PV module can generate while facing away from the sun.

Students can also take measurements with the PV module laying horizontal on the ground (tilt angle of 0°) and with the module vertical (perpendicular to the ground) while facing 0° or directly in the direction of the sun but with a tilt angle of 90°. The results of these measurements can be seen in summary form below.

Reminder on finding power

Do you remember how to find Power? [If not, refer to Power and Energy Concepts]
To find the amount of power the module is producing, we need voltage and current:
Power = Voltage * Current or $P = V * I$
[Watts] = [Volts] * [Amps]

Day 3

Graphing and Analyzing Collected Data

After students have collected all of the voltage and current data from the different angles of orientation, they should construct graphs of Voltage vs. Angle of Orientation, Current vs. Angle of Orientation, calculate power and construct a graph of Power vs. Angle of Orientation. Then compare the graphs to learn about characteristics of PV with regard to sunlight intensity and angle of orientation. The sheets on the following pages will give you an idea of what the graphs might look like and conclusions that can be drawn from the graphs.

NREL

PV in the Classroom

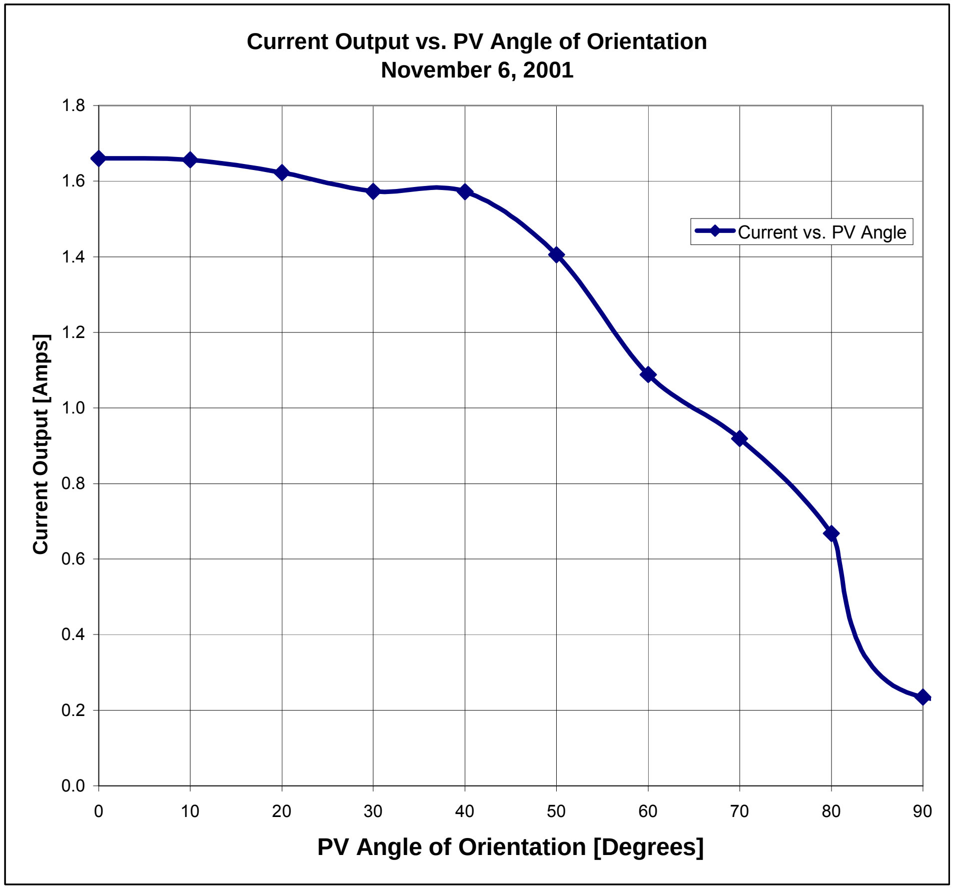
Title ______________________________

Measured Data		
Test #		
	X Axis	**Y Axis**
[Units]	**[Units]**	**[Units]**
[#]		
1		
2		
3		
4		
5		
6		
7		
8		
9		
10		
11		
12		
13		
14		
15		
16		
Total		

Y Axis ______________ **Units** ______________

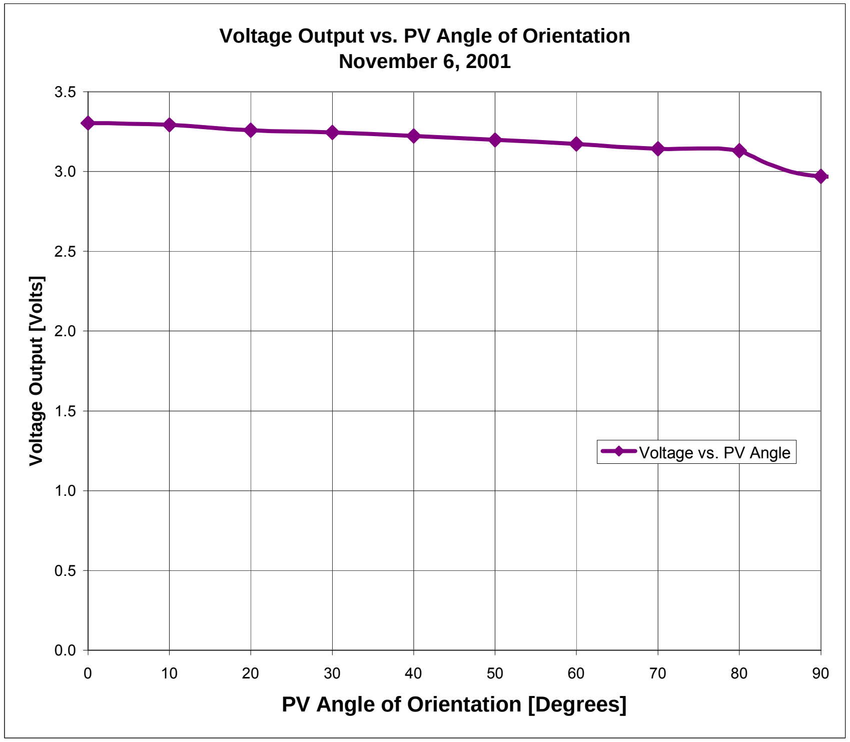
X Axis ______________________ **Units** ____________

Measured Data		
Test #	**X Axis**	**Y Axis**
	PV Orientation Angle	**Current**
[Units]	**[Units]**	**[Units]**
[#]	**[Degrees from "normal"]**	**[Amps]**
1	0	1.660
2	10	1.656
3	20	1.623
4	30	1.573
5	40	1.572
6	50	1.405
7	60	1.088
8	70	0.919
9	80	0.668
10	90	0.235
11	180	0.151
12	horizontal	0.685
13	vertical	1.489
14		
15		
16		
Total		



What your students may notice is that the current appears to vary considerably once the PV cell is pointed 40 or more degrees away from the sun. The current generated is a property of the sun's intensity—the less direct the angle, the less the intensity and, hence, less the current generated.

Measured Data		
Test #	X Axis	Y Axis
	PV Orientation Angle	Voltage
[Units]	[Units]	[Units]
[#]	[Degrees from "normal"]	[Volts]
1	0	3.304
2	10	3.292
3	20	3.258
4	30	3.246
5	40	3.224
6	50	3.198
7	60	3.173
8	70	3.142
9	80	3.131
10	90	2.971
11	180	2.903
12	horizontal	3.203
13	vertical	3.295
14		
15		
16		
Total		



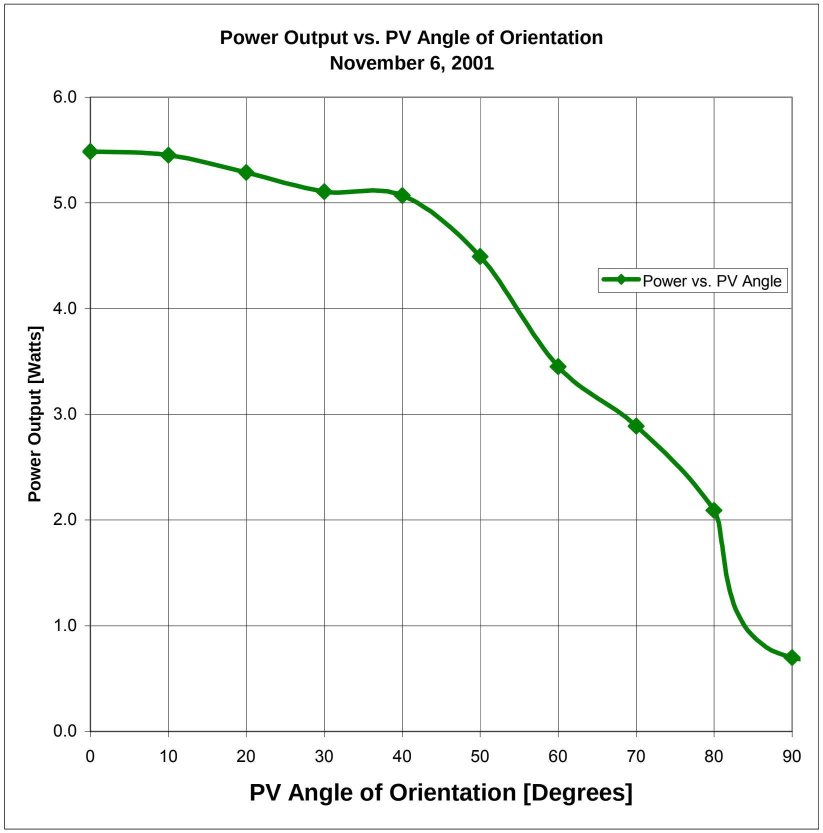
What your students may notice here is that the voltage produced appears to vary little with the angle of orientation. This is due to the voltage capacity being a property of the silicon material, not the sun’s intensity.

Next, students will need to calculate the power produced by the PV cell at different angles of orientation. A sample is provided.

Calculating PV Power Output from Voltage and Current Measurements

Test #	Normal (degrees from true south)	Degrees from "Normal"	Voltage	x	Current	=	**Power out**
	[degrees]	[degrees]	[V]	x	[A]	=	[Watts]
1		0		x		=	
2		10		x		=	
3		20		x		=	
4		30		x		=	
5		40		x		=	
6		50		x		=	
7		60		x		=	
8		70		x		=	
9		80		x		=	
10		90		x		=	
11		135		x		=	
12		180		x		=	

Measured Data				
Test #	X Axis			Y Axis
	PV Orientation Angle	Current x	Voltage =	Power
[Units]	[Units]	[Units]	[Units]	[Units]
[#]	[Degrees from "normal"]	[Amps] x	[Volts] =	[Watts]
1	0	1.660	3.304	5.485
2	10	1.656	3.292	5.452
3	20	1.623	3.258	5.288
4	30	1.573	3.246	5.106
5	40	1.572	3.224	5.068
6	50	1.405	3.198	4.493
7	60	1.088	3.173	3.452
8	70	0.919	3.142	2.887
9	80	0.668	3.131	2.092
10	90	0.235	2.971	0.698
11	180	0.151	2.903	0.438
12	horizontal	0.685	3.203	2.194
13	vertical	1.489	3.295	4.906
14				
15				
16				
Total				


Power Output vs. PV Angle of Orientation
November 6, 2001

When we multiply current times voltage to find the power, the power follows a similar pattern as the current, that is, it varies considerably with the sunlight intensity, especially when the PV cell is angled more than 40 degrees away from the sun.

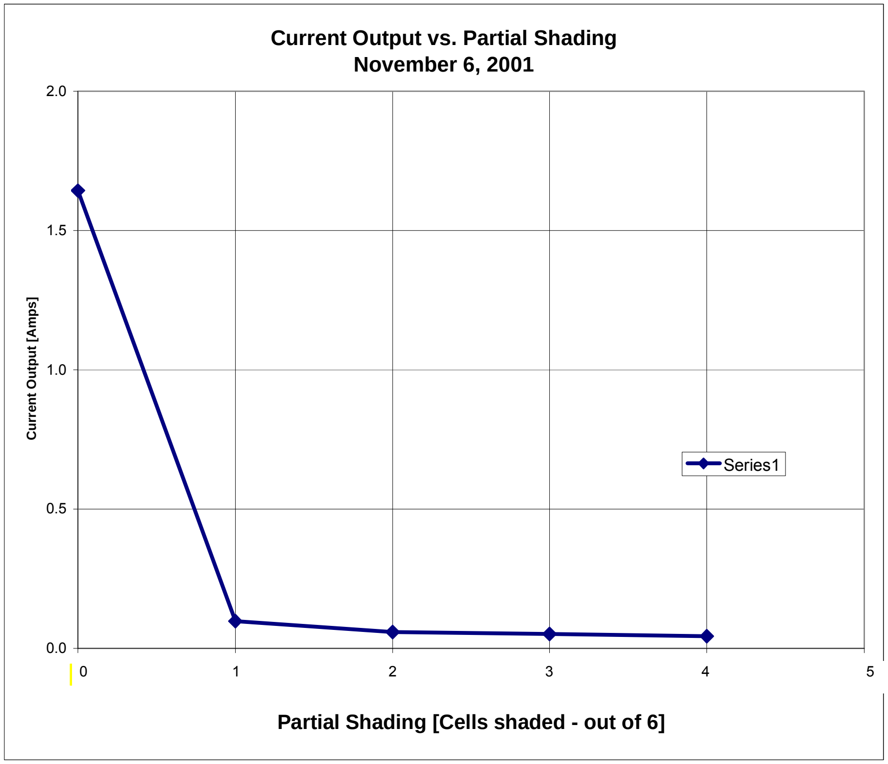
Partial Shading Effects of PV Power

Another activity that students can do to learn more about the behavior of single crystal PV cells is to measure current and voltage while varying the amount of the small module covered (blocking the sun's rays). Using small modules that have discreet cells that can be shaded individually helps make the process more scientific. Some samples follow.

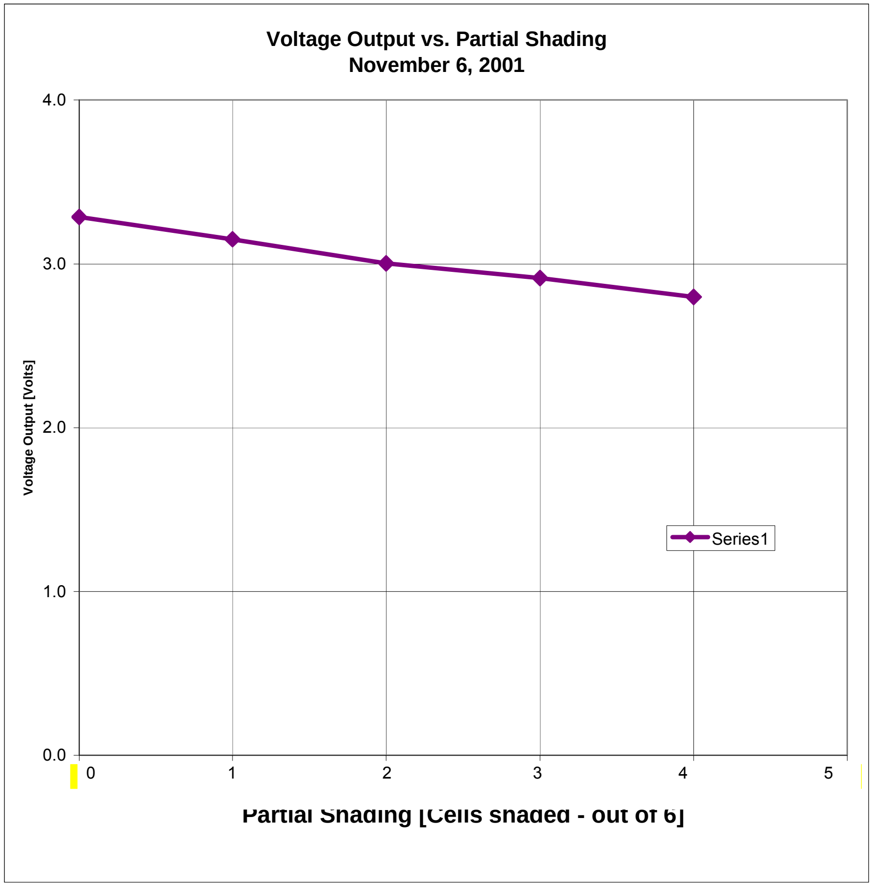
NREL

PV Activities

Measured Data		
Test #	**X Axis**	**Y Axis**
	Partial Shading	**Current**
[Units]	**[Units]**	**[Units]**
[#]	**[# of Shaded Cells - out of 6]**	**[Amps]**
1	0	1.643
2	1	0.097
3	2	0.058
4	3	0.052
5	4	0.043
6		
7		
8		
9		
10		
11		
12		
13		
14		
15		
16		
Total		



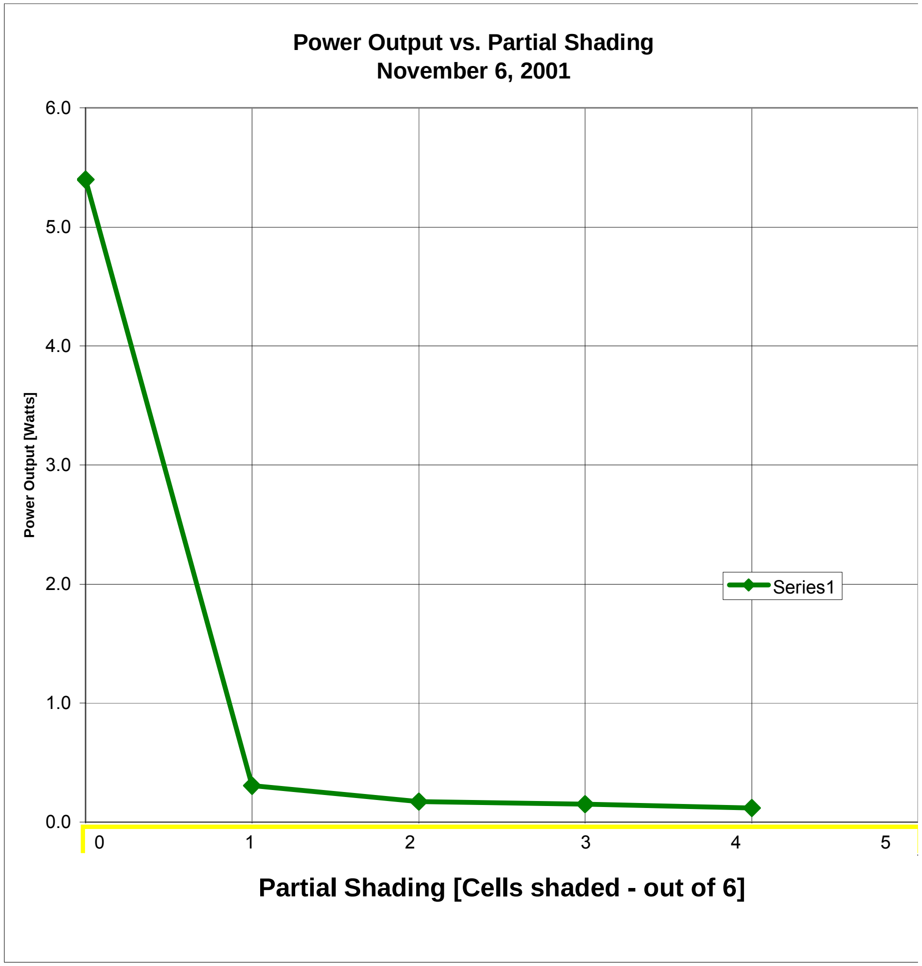
Measured Data		
Test #	**X Axis**	**Y Axis**
	Partial Shading	**Voltage**
[Units]	**[Units]**	**[Units]**
[#]	**[# of Shaded Cells - out of 6]**	**[Volts]**
1	0	3.285
2	1	3.149
3	2	3.003
4	3	2.913
5	4	2.797
6		
7		
8		
9		
10		
11		
12		
13		
14		
15		
16		
Total		



Here again students will see that the voltage does not vary significantly with the number of cells shaded since voltage is a property of the silicon material.

Measured Data

Test #	X Axis			Y Axis
	Partial Shading	Current x	Voltage =	Voltage
[Units]	[Units]	[Units]	[Units]	[Units]
[#]	[# of Shaded Cells - out of 6]	[Amps] x	[Volts] =	[Watts]
1	0	1.643	3.285	5.397
2	1	0.097	3.149	0.305
3	2	0.058	3.003	0.174
4	3	0.052	2.913	0.151
5	4	0.043	2.797	0.120
6				
7				
8				
9				
10				
11				
12				
13				
14				
15				
16				
Total				



When we multiply current times voltage to find the power, the power follows a similar pattern as the current, that is, it varies considerably with partial shading. When siting a real PV system for maximum power output, careful attention ought to be paid to shading as one can see the serious impact in can have on power output.

Day 4

There are many variations that your students can do with PV cells or small PV modules once they know how to get oriented to the sun. All the details won't be provided here, the procedure is quite similar to the previous lessons, but the application varies slightly.

Concentrating Solar Power Activity

Another variation to the PV Power activity is to use additional reflective surfaces to make your solar cell into a concentrating solar cell. Test the effect of adding 1, 2, 3, and 4 concentrators on the current, voltage and power output.

Water Pump Activity

Power an automobile water pump (used to spray water on the windshield) using PV cells or small modules. The water pump may operate at 6-12 Volts DC (check the specifications sheet that comes with it)

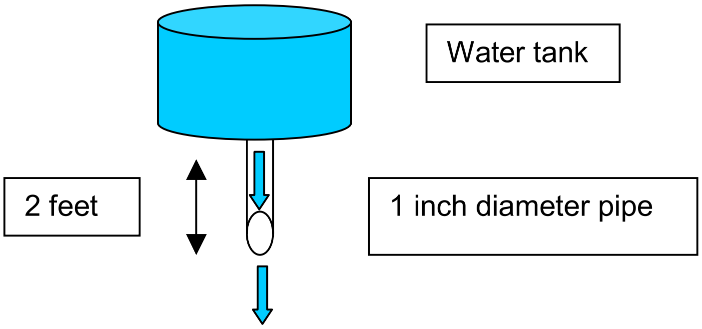
ENERGY FACT SHEETS

Power and Energy Concepts

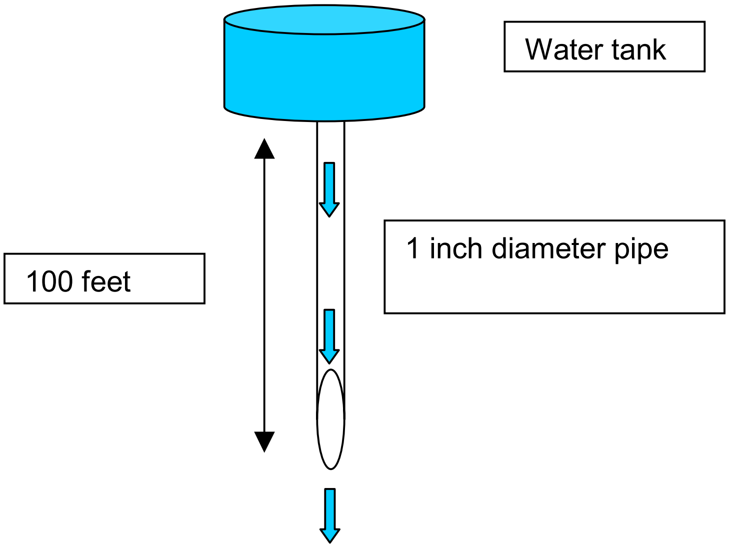
Components of electrical power can be confusing. We will introduce them using water analogies. Voltage, current, resistance, power and energy can be described using common concepts more typically associated with water, but reasonably adapted to electricity terminology (especially as aids to understanding).

Voltage

The concept of voltage can be described using water pressure and water pressure potential. If a tank full of water is suspended 2 feet above the ground with a 1 inch pipe coming out of the bottom, would students feel comfortable putting their head under the water stream? The water coming out would be similar (same order of magnitude) to the force of a shower they take at home.



If the same full water tank was suspended 100 feet above the ground with the same 1-inch pipe coming out of the bottom, the force of the water hitting the ground would be much greater than before. So much greater that the students might have difficulty standing up in the falling stream of water, and even if they could stand up under it, the force of the water would likely hurt them or give them a headache. If you doubt the difference in voltage pressure with this analogy, try another. Imagine yourself on a stool 2 feet above the ground. Now jump off. What is the force of your body hitting the ground, great or small? This should be easily manageable for most of us. Now imagine jumping off a building ledge that is 100 ft. above the ground. The force with which you would hit the ground would be immense and survival unlikely. The same thing is happening to the water in the 100 ft. pipe.



Voltage (V) is a measure of the amount of pressure, or electromotive force, applied to electrons to make them move. **A Volt is the unit of electromotive force that will force a current of one ampere through a resistance of one ohm.** After we learn about current and resistance, this definition will make more sense. **Voltage** is measured in units of **Volts (V).**

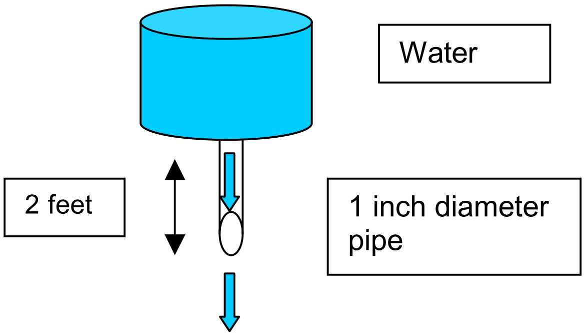
Just as the tank suspended 100 feet would apply a higher water pressure than a tank suspended 2 feet, a power supply at 100 volts would apply a greater electromotive force or voltage pressure than a power supply at 2 volts. For voltage discussions, a more commonly used term is **potential** (i.e., voltage potential), which is reasonably analogous to pressure for our purposes.

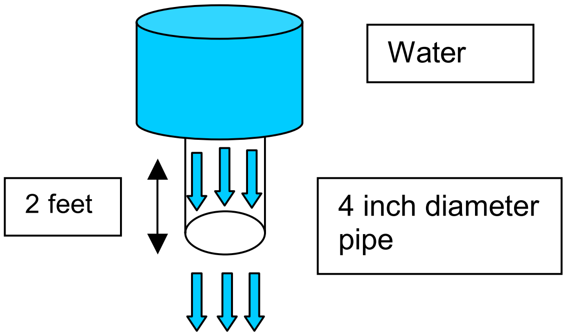
AA batteries are 1.5 Volt—they apply a small amount of voltage or pressure for lighting small flashlight bulbs. Your car has a 12 Volt battery—it applies quite a bit more pressure or voltage to push current through circuits in your car to operate the radio or defroster. At home, we operate with 120 Volts being the standard voltage that comes out of the wall outlets—that is a dangerous amount of voltage! And, your electric clothes dryer is typically wired at 240 volts—again, a very dangerous amount of voltage.

Current

Electrons can be likened to molecules of water. In stationary water, the molecules are relatively stationary and will perform no work. In moving water (small river or a vertical pipe), the molecules are moving, analogous to electrons moving in a closed circuit. In water, the current of the water would vary directly with the number of molecules flowing by a fixed point, just as electrical current would vary directly with the number of electrons flowing by a fixed point. **Current (I)** is the measure of electron flow in a conductor between two points having a difference in potential (voltage). **Current** is measured in units of **Amperes or Amps (A).**

Using our tank full of water suspended 2 feet above the ground, imagine how much water would flow if the same 1 inch pipe were attached to the bottom.
Then ask, what would happen if the 1 inch pipe were replaced with a 4 inch pipe? Or a ¼ inch pipe?





With the larger cross-sectional flow area, the water flow would be increased and, hence, the flow of current would be increased. Conversely, the smaller the cross-sectional flow area of the pipe (the ¼ in. pipe), the less water would flow.

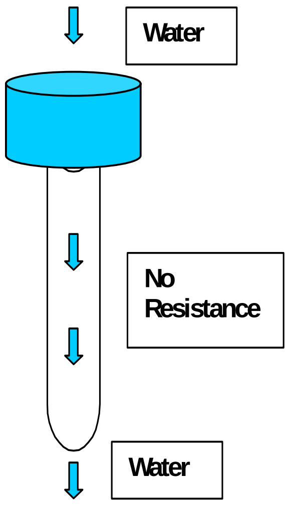
With electricity, conducting wires take the place of the pipe. The bigger the cross sectional area of the wire, the more current it can allow to flow through it. The smaller the cross sectional area, the less current it can allow to flow through it. As current flows through a wire, the rapidly moving and vibrating electrons cause the wire to heat up. Small wires with lots of current flowing through it will heat up, melt the protective coating and potentially cause a fire. The same current flowing through a much larger wire, though it would heat up, would do so to a much lesser degree and not pose a fire threat. It is important to size wires according to the amount of current expected to flow through them to avoid over-current problems. Similar to the over-current problem in wires, trying to force too much water through too small a pipe may cause the pipe to burst.

For electrical current to flow, the conductor (wire) must form a complete or **closed circuit**. If there is a break in the conductor, no electricity can flow and it is called an **open circuit**.

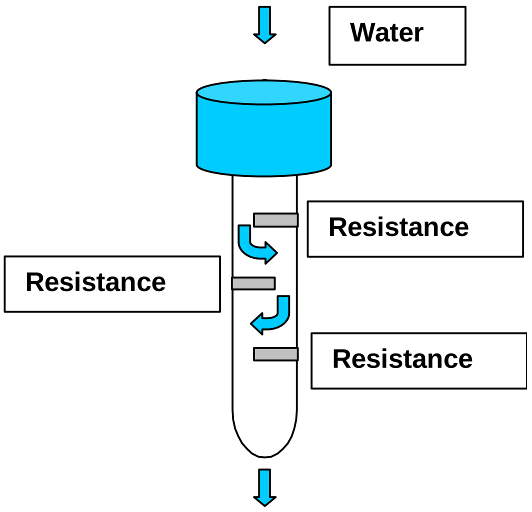
The direction of current flow in a circuit is determined by the **polarity** of the voltage source. The conventional current direction describes current flowing from the positive terminal of the voltage source through a resistance or load to the negative terminal of the voltage source. (Point of interest: The actual direction of electron flow is the opposite of this—the electrons flow from the negative terminal through the resistance to the positive terminal. We will only use the conventional current direction description.)

Resistance

With water in a pipe, resistance can be thought of as impediments to water flow such as a smaller pipe or fins extending across the flow area on the inside of the pipe, thereby restricting and slowing water movement. For conducting wires, the resistance of the wire is actually a constant that is dependent on the conductor material (the wire may be made out of copper, aluminum, silver—all have different resistance properties) and the size of the wire (diameter). **Resistance (R)** is measured in units of **Ohms (Ω)**. There are electrical devices, called resistors, that are designed with a specific, built-in resistance to be placed in a closed circuit to reduce or control the current flow. The load or appliance that we are operating with electricity has a built-in resistance as well.



No Additional Resistance Analogy



Additional Resistance using Water

The example on the left can be thought of as a circuit with no load or appliance connected to it (you will see this when you use the Genecon generator that is not connected to anything). On the right, electrically, the resistances could be several of the lights that you have in one room at home that are all connected to the same circuit.

Ohm’s Law

Ohm’s Law is an experimental, rather than physical, relationship between voltage (V), current (I), and resistance (R). This means that this relationship was observed to happen consistently and the Law was derived from the observations, rather than the Law being derived from theoretical physics and then “proved” through experimentation.

Ohm’s Law states:

V = I * R [Units: Volts = Amps * Ohms or V = I * Ω]

or Voltage = Current x Resistance

From basic Algebra, if we can solve for V by multiplying I and R, we should be able to work backwards to find R if we know V and I simply by dividing V by I.

R = V / I

or Resistance = Voltage / Current

Ohm’s Law Calculations

Let’s try a few examples:

* At home, if we used 2 A (amps) of current to operate a lamp that had a resistance of 60 Ω (Ohms), what would the voltage of the circuit be?

V = I * R

or Voltage = Current x Resistance

so V = 2 A * 60 Ω̣□̣ı□̣̃V

* In your car, we use a 12 Volt battery. If the radio requires 0.5 Amps of current, what is the Resistance of the radio in Ohms?

R = V / I

or Resistance = Voltage / Current

so R = 12 V / 0.5 A = 24 Ω

* In a small flashlight, AA batteries are typically used. These are 1.5 V batteries. If the resistance of one bulb is 3 Ω, how much current is needed to operate the flashlight?

I = V / R

or Current = Voltage / Resistance

so I = 1.5 V / 3 Ω = 0.5 A

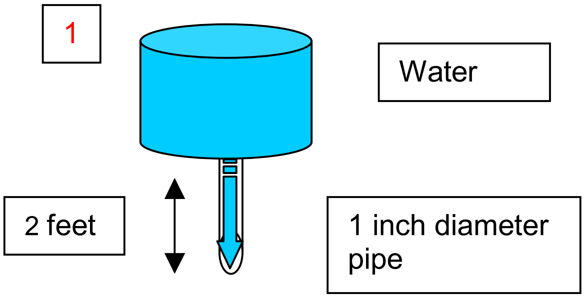
Now fill in the following table using the relationships above:

Voltage	=	Current	*	Resistance
1.5 V	=	_____ A	*	2 Ω
___V	=	3 A	*	4 Ω
120 V	=	1.5 A	*	_____ Ω

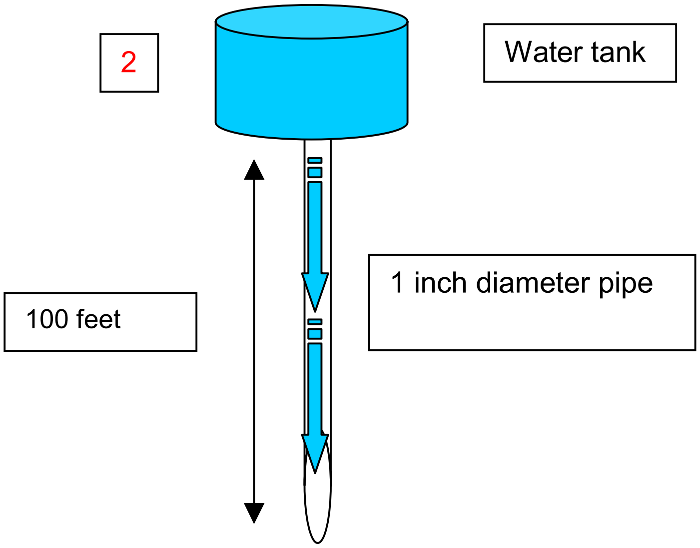
Electrical Power

Continuing with the water analogy, electric power is the combination of the water pressure (voltage) and the rate of flow (current) that results in the ability to do work. The power of water falling through a 2-inch pipe that is 2 feet high is considerably less than that of a 4-inch pipe that is 100 feet high.

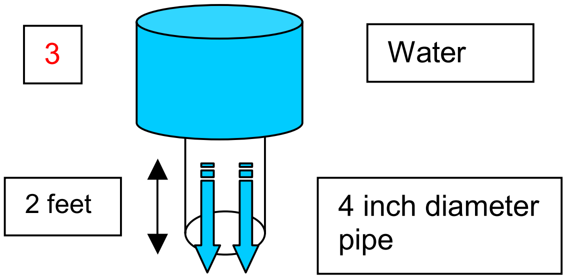
1



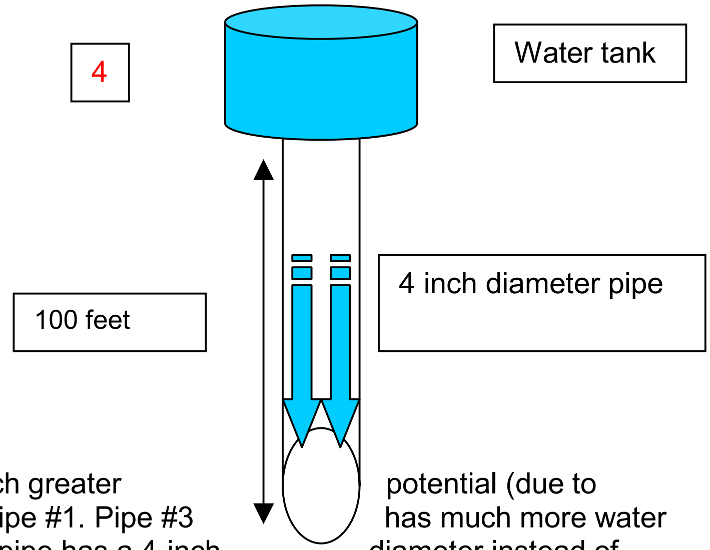
2



3



4



As we compare the pipes, pipe #2 has a much greater potential (due to water falling 100 feet instead of 2 feet) that pipe #1. Pipe #3 has much more water flowing through it than #1 or #2 because the pipe has a 4-inch diameter instead of only 1 inch. However, considerably more work could be accomplished by moving water by using the pipe at the bottom right (# 4)—it has both **more water (current)** flowing and it is being pushed with a **greater pressure (voltage potential)**—it produces more **water power** than that of the other 3 pipes.

Of course, controlling the power or transforming it into more useful forms of power become very important issues in both generating and using power.

What Is Electrical Power?

Electrically, **power** is the **rate** at which energy is converted or the **rate** of doing work. **Power (P)** is measured in units of **Watts (W).** When talking in terms of **Watts**, we are talking about the **rate** that electricity is being produced or consumed.

One of the ideas that causes confusion with **power** is that it does **NOT sound** like a rate and Watts does **NOT sound** like a rate—there is no “something **per** something” which is what we usually think of when we say “rate”.

Let’s look at a more familiar example. We often talk of traveling at 60 **miles per hour**—that is a **rate of traveling**. Or our car gets 30 **miles per gallon**—that is a **rate of gasoline consumption.**

Power is calculated from the amount of current flowing due to an applied voltage. The basic relationship is:

$P = V \times I$ [Units: Watts = Volts × Amps or W = V × A]

or $Power = Voltage \times Current$

Power is the amount of electricity it takes to turn a light bulb ON or the amount of electricity needed to operate a drill. It is the electricity required to start or to instantaneously operate a device. It might be best thought of the amount of electricity to run a device for 1 second.

The general confusion about units of electricity often begins with power and energy. The reason is that electricity is a somewhat generic, all-encompassing term that usually includes power, energy, voltage and current, among others. There is both electrical power and electrical energy, and many people often use them interchangeably. Unfortunately, they represent entirely different concepts using entirely different units of measure and they **are not** interchangeable. Since we all have experience with what electricity **does**, we tend to not pay attention to exactly what it **is**. The following 7-8 paragraphs will attempt to clarify the difference between power and energy.

In talking about power, the term Watt is often a confusing one—a Watt is **not** a quantity of work performed (though it seems to **‘sound like one’**). A Watt is the **rate** at which work is performed or electricity is produced or consumed. Technically, 1 Watt is the rate of doing work when 1 Joule of energy is expended in 1 second (1 Watt = 1 joule/second). In this form, 1 joule per second, 1 Watt does appear to be a rate because it is energy expended per time interval (1 second). But, when it stands alone, 1 Watt does not ‘seem’ like a rate, **though it is one.**

A 50 Watt light bulb uses electricity or electrical power at a **rate** of 50 Watts. We could say it is consumed at a **rate of 50 joules per second** and **it would look like a rate** and we would be happy. However, the conventional language uses only Watts and we must accept that Watts is a rate.

Before going any further, let’s do some calculations with Voltage (Volts), Current (Amps), and Power (Watts).

Power Calculations

The following calculations will help to clarify the relationship between voltage, current, and power. Again, using basic Algebra, we can work forward or backward through the power equation as long as we know two of the three variables.

- Using a 6 V car battery that pushes 2 A of current through a light bulb, how much power does the light bulb require?

$$P = V \times I$$

$$\text{or } Power = Voltage \times Current$$

Power = 6 V x 2 A = 12 W

- At home we typically have 120 V coming out of our outlets. If a blender requires 3 A of current to operate, how much power does it need?

$$P = V \times I$$

Power = 120 V x 3 A = 360 W

To test if we really understand this algebraic relationship, we will work backwards through similar calculations to find that the basic power equation could be used to find current or voltage, as well as power, with simple algebraic manipulation.

- If a refrigerator was using power at a rate of 600 W while connected to a 120 V outlet, how much current is required to operate the refrigerator?

$$P = V \times I$$

600 W = 120 V $\boxed{?}$ A = or

re-arrange so I = P / V

Current = 600 W ÷ 120 V = 5 A

Fill in the following table using the relationships above:

Power	=	Voltage	*	Current
20 W	=	1.5 V	*	_____ A
_____ W	=	120 V	*	1.5 A
45 W	=	_____ V	*	3 A
_____ W	=	240 V	*	12 A