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Photovoltaics: A Sun-Powered World

Curriculum Unit 12.04.07
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Introduction

The Sun radiates enough energy to the Earth in one hour to power all of our electricity needs for a year. But how do we harness it? Can we harness it all? Should we?

Global climate change has become part of casual conversation. Whenever the weather turns in a direction that is unsuitable, it's because of global climate change. Whenever the weather is preferable, global climate change isn't occurring. There seems to be quite a few people on the fence about whether or not this phenomenon is real and if it's actually anthropogenically influenced. Even if we take global climate change out of the equation, we still must face the fact that we will run out of most of our fossil fuels resources within 200 years. This figure takes into account our resources of oil, coal, and natural gas. So, even if we could sequester our CO_2 emissions and limit the toxins and particulates emitted from burning fossil fuels there still is the question of resources. Fossil fuels are a nonrenewable resource. They are not being produced fast enough to keep up with our consumption. For the reasons above, limiting our dependence on fossil fuels is necessary. To continue this way without a "plan b" is just foolhardy. We have other energy resource choices. There is, of course, nuclear. Nuclear power is an extremely efficient energy source and it creates no CO_2 emissions. The biggest problems with using nuclear are waste disposal and safety. We also have alternative energies such as hydroelectric, wind, biomass, and wave/tide energy. And then there's solar. Solar resources will be around to use without harm to ecosystems, fear of resource depletion, or harmful emissions, until the end of time. After all, the Earth can not function without the Sun. So, when the Sun, the "superstar" in the sky dies out, so will we. Fortunately we have about five billion years before that happens.

Solar energy is advocated by many as being the best alternative energy source, but do we truly understand how it works? There are three primary types of solar energy: 1. Passive solar energy is simply using the Sun's radiation in an unadulterated way, such as, facing a home in the direction of the morning sun to take advantage of its radiation. 2. Concentrated solar energy uses mirrors to concentrate the Sun's rays into a single point to heat water to steam to turn a turbine and a generator to produce electricity. 3. Photovoltaics uses the Sun's energy to generate a current that can be used to power our electricity needs. This unit will focus on the latter.

Goals and Methods

This unit is intended for science students in grades 9-12. Most specifically the unit addresses the content and inquiry standards included in the ninth grade curriculum of the New Haven Public School District which focuses on electricity and alternative energies. In these units students are exposed very briefly to solar energy with very little depth of knowledge. This unit is written to give students a working knowledge of how photovoltaic devices can transform solar radiation into electricity. It is also well suited for environmental science.

The purpose of the unit is to give students a firm understanding of photovoltaics (PV) how they work, what variables influence them, and how many are needed to power our current electricity needs. The unit focuses on the following objectives:

Objectives

By the end of this unit students will be able to:

1. Describe the process of converting solar radiation to electricity using a crystalline silicon solar cell.
2. Measure current and voltage of a PV cell.
3. Determine how lighting and shading, the angle of the Sun, wavelength, distance, and temperature affect PV cell performance.
4. Determine the number of PV cells necessary to power a home.

Methods

This unit is best delivered in alternating lecture and hands-on practice activities. Because electricity cannot be seen it is important to ground the student in reality at every opportunity. Some possible lessons have been included in the activities section.

Background

Photovoltaics

Photovoltaic devices convert light directly into electricity. Unlike so many other types of electricity generation, photovoltaics don't need to heat water to steam to turn a turbine to turn a generator.

Photovoltaics (PV) use the Sun's energy, electromagnetic radiation to produce electricity. Radiation is the product of the Sun's process of nuclear fusion. The Sun fuses together hydrogen atoms to form helium and the energy left over in the process is emitted by the Sun in packets of energy called quanta or more commonly called photons. Photons are particles that exhibit the properties of waves such as frequency, wavelength and amplitude. Photons travel through empty space at 186,000 miles per second, the speed of light, arriving at Earth eight minutes after their emission. When the photons reach Earth they immediately begin doing work by exciting the electrons in the various substances they encounter.

In 1886, Heinrich Hertz noticed that shining shorter wavelength light on metal caused the electrons of the metal to be emitted. A phenomenon called the photoelectric effect. [1] This was the first example of converting light energy to electric energy.

The flow of electrons (electric charge) or current is what we call electricity. Our modern world is heavily reliant on electricity to do work, such as power our light bulbs, keep our food cold, and operate our televisions and radios. Electricity is considered a secondary energy source. This means that another energy source must be transformed to produce electricity. For the last hundred years we have used the thermal energy from burning fossil fuels to create electricity.

Atoms want to be in equilibrium. They want to have an equal number of protons and electrons resulting in a neutral charge. When an atom is missing an electron an electron from a neighboring atom is attracted to this void and can move into the vacancy. This leaves a vacancy of its own which must be filled by another electron. This constant flow of electrons is called current. What makes the electrons flow is the potential (charge) difference between the two atoms. The atom with the higher energy potential or more electrons will want to give away those electrons to the atom with a lower energy potential or less electrons. This potential difference is called voltage.

Electrons flow differently through different types of materials. The intensity of electron exchange is based on atomic structure. In the center of an atom exists the protons and neutrons. Orbiting the nucleus, at different energy levels are the electrons. The electrons in the outermost level are the electrons available for transfer and are called the valence electrons. At this energy level atoms can have multiple missing electrons, too many electrons, or just the right amount. This factor is the primary cause of electron movement. Ultimately all the atoms want to have just the right amount.

The materials that have just the right amount hold onto their electrons very tightly and don't allow them to flow. These materials are called insulators. Rubber, plastic, and wood are examples of insulators. The handles of many kitchen utensils are made of these materials to prevent the conduction of thermal energy. Other materials that have too many or not enough electrons, allow electrons to flow easily. These materials are called conductors. Metals such as copper, aluminum, and gold are examples of conductors. The cord that you plug into the wall from an electric appliance has a copper interior to allow electrons to flow, covered by a plastic coating to prevent those same electrons from making a circuit with your hand. There are some atoms that have very few missing electrons. Materials made of these atoms do not readily exchange electrons because they can make covalent bonds with neighboring atoms, but can be encouraged to do so. Silicon for instance has four valence electrons. With this arrangement, silicon can bond with four other silicon atoms to form a very ordered crystalline structure. Having all of its valence electrons bonded silicon has no affinity for giving up electrons. This behavior can be changed by doping the silicon with another element such as phosphorus or boron. Phosphorus has five valence electrons leaving one electron available for transfer. Boron has three valence electrons leaving a vacancy to be filled. Adding energy to these materials allows the unbonded electron to rise to the conduction band, which is a higher energy level than the valence level. In the conduction band the electron is free to leave the atom's orbit and to move throughout the material. These materials are called semiconductors. Because the flow of electrons can be controlled in these materials they have been very useful in the development of electronics such as computers. Silicon and germanium are examples of semiconductors. Semiconductors are at the heart of how photovoltaics work. [2]

Photovoltaics fall into three main categories: Silicon, thin-amorphous, and dyesensitive. Each has its advantages and disadvantages based on materials used, efficiencies, optimal working conditions, and applications.

Silicon cells are the most widely used photovoltaics. They have been in use since the 1950s. This type of photovoltaic (PV) cell is commonly referred to as a crystalline silicon cell. It consists of thin slices of silicon. Silicon, the fourteenth element on the periodic table is considered a semiconductor because it is more conductive than nonmetals and less conductive the metals. Silicon has four valence electrons. Every silicon atom can bond with four other silicon atoms creating a tetrahedral lattice. This lattice is key to it's ability to conduct electricity. Silicon is one of the most abundant elements in nature, however it does not exist on it's own . Silicon can be found in the common mineral silicon dioxide, SiO_2, more commonly known as silica or quartz . [3] Before it can be used in solar cells it must first be purified. Monocrystalline solar cells are created by heating the mineral into a molten mixture and growing the silicon from a seed. This popular method is called the Czochralski method. [4] This method is time consuming and is energy intensive. Other methods are currently being researched. The multicrystalline or polycrystalline solar cell method also involves melting the silicon but it is cast instead of grown. Thin wafers are cut from the solid silicon.

A crystalline solar cell consists of two silicon layers the top layer is doped with another element such as phosphorus, which has five valence electrons, to make it act like it's electrically negative. Doping can occur in the melting process or a thin layer can be applied after it has cooled. This layer is called the n-type semiconductor. The bottom layer is doped with an element that has only three valence electrons such as boron. This makes the layer act like it's positively charged and it is called the p-type semiconductor. The n-type has extra electrons and the p-type has extra "holes" (empty spots for electrons), but in order for the electrons to jump from one to the other the proper energy is needed. On top of the n-type layer are metal contacts and an antireflective transparent layer for protection. At the bottom of the cell is another contact, usually made of aluminum or molybdenum. [5]

How a Photovoltaic Cell Works (see figure 1)

Step 1. Each silicon atom has four valence electrons. Everything fits neatly, there is no variation in charge to encourage movement of the electrons. At this point the silicon wafer is acting more like an insulator.

Step 2. In the n-type semiconductor layer phosphorous is added during the doping process. Phosphorous has five valence electrons. This leaves one free electron.

In the p-type semiconductor layer boron is added during the doping process. Boron has three valence electrons leaving a hole or a vacancy. Silicon can make another bond, but there is no electron to make a bond with.

The n-type layer is now has extra electrons and the p-type layer is now short electrons.

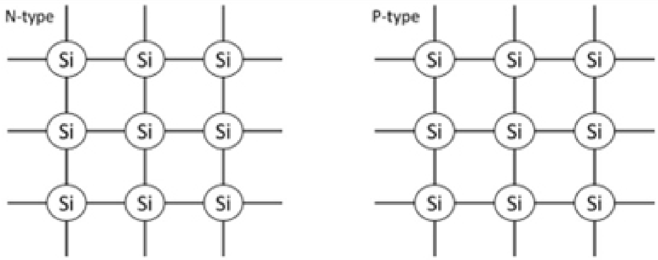
This discrepancy is the potential difference that encourages the electrons to flow from the n-type layer to the p-type layer.

Step 3. When the two layers are put together the extra electrons in the n-type layer move to the p-type layer. The n-type layer now has vacancies created around phosphorous and the p-type layer now has extra electrons that boron cannot accept. This creates a barrier, preventing anymore exchange of electrons. This barrier is called the pn junction. Without any other additions of energy the cell would remain in this state.

Step 4. When energy is added to the cell via photons from electromagnetic radiation the energy is absorbed by the electrons causing them to move to a higher energy state and break free. With no other additions the electron would eventually drop back down to a lower energy level and the energy would be emitted.

Step 5. Adding a circuit and a load to the cell allows the electrons to flow around the circuit back to the layer that has the vacancy. As this is successively repeated, electricity is produced.

How a Photovoltaic Cell Works

	In your own words describe what's happening.
Step 1	**In your own words describe what's happening.**
	
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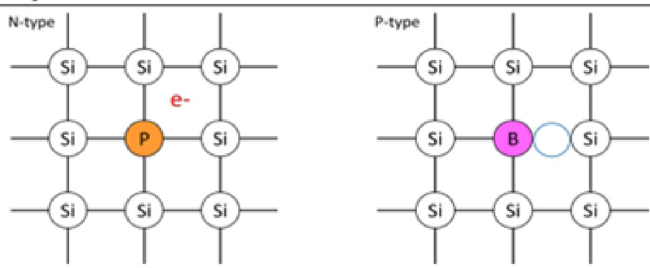	
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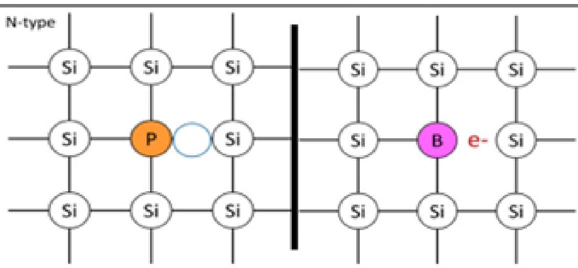	
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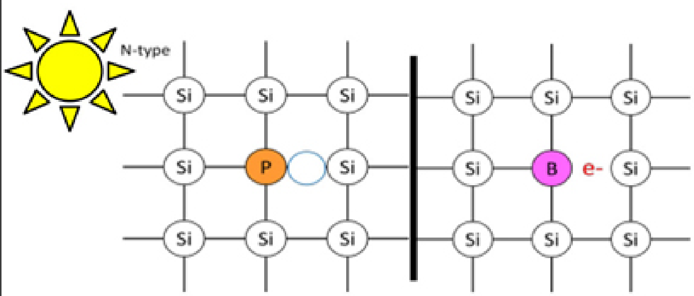	
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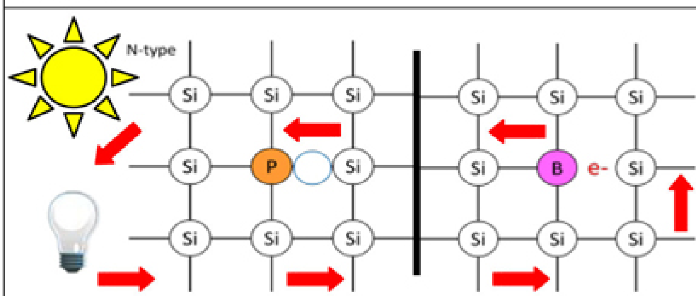
	

Figure 1

Solar cells take advantage of a limitless energy source, but they are only able to use a fraction of the incoming energy. Out of the 100 percent of sunlight that reaches a solar cell 55 percent of it is immediately unusable because it exists in a wavelength outside what the electrons need to move to another energy state. More energy can also be lost through heat. [6]

The energy conversion efficiency is calculated by dividing the useful energy output by the energy input. Efficiency ratings for solar cells range between 4 to 40 percent depending on the technology. [7] This poor performance makes solar energy look less desirable than some other fuels sources. However, when you consider that no natural resources are being depleted by using solar energy and no ecosystems are further being harmed by adding a solar panel to an existing structure, this efficiency rating could be considered quite high. Research and development of new photovoltaic technology is ongoing and efficiency is increasing. The are several other factors that can affect the performance of solar cells, many of which revolve around photon flux. Photon flux is the number of photons per second per unit area. Multiplying photon flux by the specific wavelength of a photon will yield the power density of an area.

Wavelength - The electromagnetic spectrum is made up of various wavelengths of radiation. Each wavelength carries with it a certain potential to do work. This potential is measured in electron-volts. The amount of energy that a wavelength carries is responsible for pushing the electrons across the p-n junction allowing it to flow and generate electricity. Energy is measured in electronvolts (eV). The eV necessary is different for all semiconductor materials and is the reason that they are not 100% energy efficient. Out of all the photons that are directed at a cell many of them are reflected and still others are absorbed as heat and light.

Temperature - PV cells work more efficiently at cooler temperatures. Heat increases resistance which decreases current. The exact temperatures are dependent on the type of material used. So, when planning to install solar cells the ambient temperature must be taken into consideration so that the correct type of PV cell can be chosen. If controlling for temperature is not an option than a system can be designed to cool the cells.

Intensity of Light - PV cells work differently under different lighting conditions. Some cells work best under bright lighting conditions and others work better under diffuse lighting conditions. In some cases efficiency can actually drop if light intensity is too high. So although it is typically thought that solar cells can only work in areas with full direct sun like the desert, there are types of solar cells that work better with a little bit of cloud cover.

Angle of Incidence - The output of a PV cell is largely dependent on the amount of light that hits the surface, so by changing the angle at which the Sun's rays hit the cell, the amount of light can be changed. As the angle of the Sun's rays is increased or decreased away from 90 degrees the concentration of energy that an area receives decreases and is instead spread out over a larger area. The closer the angle is to a 90 degree angle the more light it receives and the higher the output. [8]

Distance - Distance also plays a part in performance of the cell. The closer the cell is to the Sun the higher the performance. As the distance increases between the Sun and the cell the radiation spreads out and less photons hit a particular area. In New England this distance might be a factor worth considering as we are closer to the Sun in the winter time and further from it in the summer.

How Much Energy is Produced?

Energy equals power multiplied by time (E = P x t). Calculating energy starts with understanding electricity and its components. Electricity is the flow of electrons. The components of electricity are voltage (V), current (I), and resistance (R). According to Ohm's law, voltage equals current multiplied by resistance (V = I x R).

Voltage Voltage is the potential energy difference needed for electrons to flow. Increasing potential difference increases electron flow. Voltage is measured in the unit volts (V).

Current The number of electrons that pass a fixed point per second is called current. Current is measured in amperes (amps, A). (Current is represented as "I" in Ohms calculations.)

Resistance - Resistance is a property that slows down the flow of electrons. Resistance can be in the form of the wire used in the circuit or the load in the circuit. Resistance is measured in ohms (Ω). (Resistance is represented as "R" in Ohms calculations.)

The best example of this relationship is illustrated by flowing water from a garden hose. If the water is shut off at the spigot and the hose is set on the ground the remaining water will trickle out. If the back of the hose is picked up while leaving the opening on the ground the water will empty faster. This happens because the potential difference between the two were increased. In the case of the hose the height difference is increasing. This is gravitational energy, but the theory is the same. So, an increase in potential energy difference (voltage) increases the flow (current), for an equivalent resistance.

If two garden hoses are set up, one with a 1-inch diameter opening and one with a 1/2 inch diameter opening, water would flow slower through the smaller opening. The smaller opening is resisting the flow of the water, slowing is down. In the same way, changes in materials in an electric circuit can slow the flow of electrons; diameter or gauge of the wire, type of metal the wire is made of, and temperature of the wire.

The relationship between voltage, current, and resistance is as follows: voltage = current x resistance (V = I x R). In order for current to increase voltage must increase or resistance must decrease. Current can also be determined by rearranging the equation. Current = voltage / resistance (I = V / R). Written this way, it's easy to see the inverse relationship between resistance and current.

Once voltage and current are determined, power can be calculated. Power is defined as the rate at which work is being done. Power = voltage x current (P = V x I). Increasing voltage increases the rate at which work is being done. Using the hose example again, by increasing the height difference (voltage) more water can flow past a point in a given second. If the work to be done was to wash the sand of your feet after a day at the beach, increasing the height of the hose would increase the power allowing you to wash the sand away faster.

Electrical power specifically deals with the rate at which energy is transferred by applying voltage. Power is measured in watts (W). Watts = voltage x current (W = V x I).

Electrical energy is the amount of work being done in a given time. With time included in the discussion, it must also be added to the equation. Energy = power x time (E = P x t). It is customary to measure electrical energy in hours (h) and power equals watts (W), so the unit is power per time or watt-hours (Wh). The equation can be simplified to energy = watt-hours (E = Wh). Because the watthour is a small unit, the electric companies use the kilowatthour (kWh). A kilowatt is 1000 watts.

How much does it cost to play video games for two hours? The typical gaming console uses 125 watts of energy per hour (125 Wh x 2 h = 250 Wh). [9] The 250 Wh must be converted into kilowatt hours (250 Wh /1000 = 0.25 kWh). The average cost of electricity per kWh is $0.12. Multiply 0.25 kWh by 0.12 (0.25 kWh x 0.12 = 0.03). The cost to play video games for two hours is three cents.

Activities

Activity 1: Build a Model of a Solar Cell

Duration: One-45 minute period

Teacher Background:

Operation of a solar cell is very abstract. To help students better understand the process of converting sunlight into electricity students will construct a nonworking model of layered solar cell. The cell will be loosely held together by toothpicks so that they can take it apart throughout the lecture.

Purpose: Create a model of a solar cell.

Materials per cell:

Foam sheets, 4 x 5 inches

Clear plastic sheet, 4 x 5 inches

Toothpicks

Scissors

Pen/pencil

Glue

2 small nuts

2 alligator clips

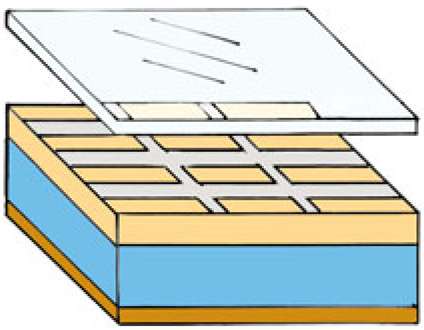
Mini-lamp assembly

Ruler

Procedure:

1. Create a 3D model based on the image below. Using the foam sheets create the layers in the same proportion as you see in the image
2. Use the clear plastic sheet to simulate the top protective layer.
3. Glue the nuts to the bottom of the cell, at about 1 inch apart. These will simulate the wire

connectors that hookup the solar cell to a circuit.
4. Insert a toothpick in the corner through all layers. This will allow you to separate the cell at will.
5. Connect one end of the alligator clips to the nuts, one on each. Connect the other ends of the clips to the mini-lamp.



Activity 2: Factors Affecting PV Cell Performance

Duration: Two-45 minute periods (and homework time)

Teacher Background:

The amount of sunlight of the total amount that shines down on a cell that is converted into electricity is called the cell's conversion efficiency. The efficiency rating is different for all the different types of solar cells and can be affected by various factors such as wavelength, temperature, intensity of light, angle of incidence, and distance. In this activity students will test cells to determine how various factors affect cell performance.

Purpose: To determine how various factors affect solar cell performance.

Part 1: Wavelength

Visible light is made up of a rainbow of colors from red to violet with various wavelengths of radiation from 400nm to 780nm. Each wavelength carries with it a certain amount of energy. Solar cells are designed to take advantage of certain wavelengths. In this section, you will determine how wavelength affects solar cell performance.

Materials Per Group:

Ring stand

Meter stick

1 sheet of red film 20 x 26 cm

1 sheet of yellow film 20 x 26 cm

1 sheet of green film 20 x 26 cm

1 sheet of blue film 20 x 26 cm

Lamp with 100 watt light bulb

Multimeter

Crystalline silicon solar cell

Procedure:

Record all data in the data table

1. Set up the lamp on a ring stand at 30 cm away from the solar cell.
2. Set up the solar cell with the multimeter set to measure volts.
3. Turn on light and measure voltage.
4. Turn lamp off and set multimeter to amps.
5. Turn lamp on and measure current.
6. Turn lamp off and set multimeter to measure volts.
7. Position the red colored film 15 cm from light.
8. Turn on the lamp and measure the voltage.
9. Turn off the lamp and switch multimeter to amps.
10. Turn on lamp and measure the current.
11. Repeat this for the other colors.

PV Cell	Voltage	Current	Power
Control			
Red film			
Yellow film			
Green film			
Blue film			

Questions:

1. What is the independent variable?
2. What is the dependent variable?
3. Write a hypothesis for this experiment.
4. Graph the data.
5. Analyze the data by writing a conclusion. Make sure that you include references to the data in your conclusion.

Part 2: Temperature

PV cells work more efficiently at cooler temperatures. The exact temperatures are dependent on the type of material used. So, when planning to install solar cells the ambient temperature must be taken into consideration so that the correct type of PV cell can be chosen. If controlling for temperature is not an option than a system can be designed to cool the cells.

Materials Per Group:

Ring stand

Meter stick

Fan

Thermometer

Lamp with 100 watt light bulb

Multimeter

Crystalline silicon solar cell

Procedure:

Record all data in the data table

1. Set up the lamp on a ring stand at 30 cm away from the solar cell.
2. Set up the solar cell with the multimeter set to measure volts.
3. Place a small thermometer near the cell. Wait two minutes and record temperature.
4. Turn lamp on and measure voltage.
5. Turn lamp off and set multimeter to amps.
6. Turn lamp on and measure current.
7. Turn lamp off.
8. Set up a fan 15 cm perpendicular to the solar cell.
9. Repeat steps 1-7.
10. Repeat steps 1-9 two more times.

	Voltage	Current	Temperature	Power
Cell without fan Trial 1				
Trial 2				
Trial 3				
Average				
Cell with fan Trial 1				
Trial 2				
Trial 3				
Average				

Questions:

1. What is the independent variable?
2. What is the dependent variable?
3. Write a hypothesis for this experiment.
4. Graph the data.
5. Analyze the data by writing a conclusion. Make sure that you include references to the data in your conclusion.

Part 3: Intensity of Light

PV cells work differently under different lighting conditions. Some cells work best under bright lighting conditions and others under diffuse lighting conditions. In this section you will determine which lighting condition is ideal for the PV cell. First you will test the cell under direct lighting and then under diffuse lighting.

Materials Per Group:

Ring stand

Meter stick

1 sheet of mesh, 20 x 26 cm

Lamp with 100 watt light bulb

Multimeter

Crystalline silicon solar cell

Procedure:

Record all data in the data table

1. Set up the lamp on a ring stand at 30 cm away from the solar cell.
2. Set up the solar cell with the multimeter set to measure volts.
3. Turn lamp on and measure voltage.
4. Turn lamp off and set multimeter to amps.
5. Turn lamp on and measure current.
6. Turn lamp off.
7. Place a piece of mesh 15 cm below lamp.
8. Repeat steps 1-6.
9. Repeat steps 1-8 two more times.

	Voltage	Current	Power
Direct Light Trial 1			
Direct Light Trial 2			
Direct Light Trial 3			
Average			
Diffuse Light Trial 1			
Diffuse Light Trial 2			
Diffuse Light Trial 3			
Average			

Questions:

1. What is the independent variable?
2. What is the dependent variable?
3. Write a hypothesis for this experiment.
4. Graph the data.
5. Analyze the data by writing a conclusion. Make sure that you include references to the data in your conclusion.

Part 4: Angle of Incidence

The output of a PV cell is largely dependent on the amount of light that hits the surface, so by changing the angle at which the sun's rays hit the cell, the amount of light can be changed. The closer it is to a 90 degree angle the more light it receives and the higher the output.

Materials Per Group:

Ring stand

Meter stick

Protractor

Lamp with 100 watt light bulb

Multimeter

Crystalline silicon solar cell

Procedure:

Record all data in the data table

1. Set up the lamp at a 90 degree angle to the solar cell on a ring stand. Maintain a 30 cm distance.
2. Set up the solar cell with the multimeter set to measure volts.
3. Turn lamp on and measure voltage.
4. Turn lamp off and set multimeter to amps.
5. Turn lamp on and measure current.
6. Turn lamp off.
7. Set up the lamp at a 60 degree angle to the solar cell on a ring stand. Maintain a 30 cm distance.
8. Repeat steps 2-6.
9. Set up the lamp at a 45 degree angle to the solar cell on a ring stand. Maintain a 30 cm distance.
10. Repeat step 2-6.
11. Set up the lamp at a 25 degree angle to the solar cell on a ring stand. Maintain a 30 cm distance.
12. Repeat step 2-6.

	Voltage	Current	Power
90 degree angle			
60 degree angle			
45 degree angle			
25 degree angle			

Questions:

1. What is the independent variable?
2. What is the dependent variable?
3. Write a hypothesis for this experiment.
4. Graph the data.
5. Analyze the data by writing a conclusion. Make sure that you include references to the data in your conclusion.

Part 5: Distance

Distance also plays a part in performance of the cell. The closer the cell is to the Sun the higher the performance. This is because the Sun's rays spread out. Think of a flashlight. The closer you hold it to a wall the more intense the light, but if you move further away the light isn't as bright. In New England this distance might be a factor worth considering as we are closer to the Sun in the winter time and further from it in the summer. In this section you will determine whether the distance between the cell and the light source affect performance.

Materials Per Group:

Ring stand

Meter stick

Lamp with 100 watt light bulb

Multimeter

Crystalline silicon solar cell

Procedure:

Record all data in the data table

1. Set up the lamp on a ring stand at 60 cm away from the solar cell.
2. Set up the solar cell with the multimeter set to measure volts.
3. Turn lamp on and measure voltage.
4. Turn lamp off and set multimeter to amps.
5. Turn lamp on and measure current.
6. Turn lamp off.
7. Set up the lamp on a ring stand at 45 cm away from the solar cell.
8. Repeat steps 2-6.
9. Set up the lamp on a ring stand at 30 cm away from the solar cell.
10. Repeat steps 2-6.
11. Set up the lamp on a ring stand at 15 cm away from the solar cell.
12. Repeat steps 2-6.

Distance from Lamp	Voltage	Current	Power
60 cm			
45 cm			
30 cm			
15 cm			

Questions:

1. What is the independent variable?
2. What is the dependent variable?
3. Write a hypothesis for this experiment.
4. Graph the data.
5. Analyze the data by writing a conclusion. Make sure that you include references to the data in your conclusion.

Activity 3: Are Photovoltaics the Most Cost Efficient Choice for Your Home?

Duration: Two - 45 minute period

Teacher Background:

In order to determine how many solar cells are needed to power all the electricity needs a home has you need to know the home's average energy consumption, the amount of solar radiation the home's geographic area receives, and the size of the solar module.

To tailor this lesson to your geographic area, use the following sources: Average energy consumption and cost per household by state: http://www.eia.gov/tools/faqs/faq.cfm?id=97&t=3. Average solar radiation: http://rredc.nrel.gov/solar/old_data/nsrdb/1961-1990/redbook/atlas/serve.cgi

Purpose: In this activity you will determine where in the United States photovoltaic systems are the most cost efficient source of energy.

Materials:

Pen/pencil

Calculator

Data table

Procedure:

Using the data table below calculate how many years it would take for a photovoltaic module system to pay for itself. Use the following table to record your calculations.

1. Calculate the, kWh/day, usage by dividing, kWh/month, by 30 days.
2. Convert, kWh/day, to watt-hours /day, by multiplying by 1000.
3. Calculate, watts from module/day, by multiplying number of, peak hours of sunlight, by, solar module wattage.
4. Calculate, modules needed, by dividing, watt-hours /day, by, watts from module/day.

5. Determine the, cost for all modules, needed by multiplying the number of, modules needed, by $400 (average cost).
6. Calculate each household's, current electricity cost/year, by multiplying, kWh/month, by, cost of electricity/kWh, and then by 12 months.
7. Determine, years to pay off solar modules, by dividing the, cost of all modules, by the current electricity cost/year. Round to the higher whole number.

Questions:

1. In which state would the photovoltaic system pay itself off the quickest?
2. If the electricity consumption and cost per kWh were equal which state would find photovoltaics the best option?
3. Why do you suppose that Hawaii's electricity cost is so high?
4. Did any of these results surprise you? Why?
5. For the states where photovoltaic systems are not as cost effective, what other renewable energy sources might they use? Explain your answer.

Location	kWh/ month	kWh/day	Watt-hours/ day	Peak hours of sunlight	Solar module wattage	Watts from module/ day	Modules needed	Cost of all modules	Current electricity cost / kWh	Current electricity cost/year	Years to pay off solar modules
Tennessee	1393			5	250				0.09		
Florida	1194			6	250				0.11		
Connecticut	750			5	250				0.19		
Maine	521			5	250				0.16		
Montana	845			6	250				0.09		
California	562			7	250				0.15		
Hawaii	601			6	250				0.28		
Alaska	641			3	250				0.16		
Arizona	1059			8	250				0.11		
Missouri	1153			6	250				0.09		

Resources

References Cited

[1] Sherrill, David. *The Photoelectric Effect* . Georgia Tech, 2006. http://vergil.chemistry.gatech.edu/notes/quantrev/node4.html. Accessed 6/29/12. Brief explanation of the photoelectric effect.

[2] ScienCentral Inc and The American Institute of Physics. Conduction, PBS, 1999. http://www.pbs.org/transistor/science/info/conductors.html. Accessed 6/24/12. Explanation and examples of conductors, insulators, and semiconductors.

[3] Royal Society of Chemistry. *Visual Elements Periodic Table* . 2011. http://www.rsc.org/periodic-table/element/14/Silicon. Accessed 6/15/12. Facts about the element silicon.

[4] Khan, Aurangzeb. *Lecture 4: Crystal Growth* . University of South Alabama. http://www.southalabama.edu/engineering/ece/faculty/akhan/Courses/EE539-Fall04/Lecture-slides/lecture-4-crystal%20growth.pdf. Accessed 6/29/12. Detailed lecture notes about the Czochralski method.

[5] Lynn, Paul A. *Electricity from Sunlight* . West Sussex: John Wiley & Sons, 2010. Book explaining photovoltaics from solar energy to future applications.

[6] Energy Efficiency and Renewable Energy. *Energy Basics* : *Photovoltaic Cell Conversion Efficiency.* U.S. Department of Energy, 2011. http://www.eere.energy.gov/basics/renewable_energy/pv_cell_conversion_efficiency.html. Accessed 5/25/12. Explains factors that affect cell performance.

[7] National Center for Photovoltaics. Best Research - Cell Efficiencies. National Renewable Energy Laboratory. http://www.nrel.gov/ncpv/images/efficiency_chart.jpg. Accessed 6/22/12. Graph detailing energy conversion efficiencies by technology and the research institutions who are working on that technology.

[8] Wright, Chuck. The Solar Sprint PV Panel. Chuck-Wright.com. http://www.chuck-wright.com/SolarSprintPV/SolarSprintPV.html. Accessed 4/29/12. Explains how the angle of incidence affects cell performance.

[9] Hittinger, E. *Power Consumption of Video Game Consoles Under Realistic Usage Patterns* http://wpweb2.tepper.cmu.edu/ceic/pdfs/CEIC_11_01.pdf. Carnegie Mellon University, 2011. Accessed 6/29/12. Paper comparing energy usage of various gaming consoles.

Additional Resources for Teacher and Students

American Solar Energy Society, www.ases.org . National organization for professionals in the solar industry.

Energy Efficiency and Renewable Energy. *History of Solar* . U.S. Department of Energy. http://www1.eere.energy.gov/solar/pdfs/solar_timeline.pdf. Timeline detailing the history of solar energy, beginning in the 7th century B.C.

Energy Efficiency and Renewable Energy. *Photovoltaics.* U.S. Department of Energy. http://www.eere.energy.gov/basics/renewable_energy/photovoltaics.html

Introduction to photovoltaics.

Energy For Educators. *Need a Lesson Plan? Why Not Renewable Energy* . Idaho National Laboratories. www.energyforeducators.org. Many stem lesson plans dealing with energy.

European Photovoltaics Industry Association. PV Technologies: Cells and Modules. http://www.epia.org/solar-pv/pv-technologies-cells-and-modules.html. European organizational for professional in the solar industry.

Florida Solar Energy Center, www.fsec.ucf.edu/en/consumer/solar_electricity/basics/index.htm. Solar electricity basics.

History Channel, http://www.history.com/videos/historyrewindsolarpowerenergy1954#historyrewindsolarpowerenergy1954. Video about the history of solar power.

How Stuff Works. How Solar Cells Work. www.howstuffworks.com/solarcell.htm. Explanation of how solar cells work.

Life's Good. *Life's Good with LG Solar* . http://www.lg.com/us/solar/products/monox/index.jsp. Company website for silicon solar cells.

Massachusetts Institute of Technology. *Photovoltaic (PV) Tutorial.* http://web.mit.edu/taalebi/www/scitech/pvtutorial.pdf. Slide presentation on solar power geared toward commercial applications.

National Energy Education Development Project. *Home* . www.NEED.org. Entire website dedicated to energy literacy.

National Renewable Energy Laboratory. *Solar Energy Basics* . www.nrel.gov/learning/re_solar.html. Introduction to solar energy.

Popular Science. *Making Silicon from Sand.* http://www.popsci.com/diy/article/2005-10/making-silicon-sand?single-page-view=true. Procedure for purifying silicon.

Power Film, http://www.powerfilmsolar.com/ . Company website for thin-film solar panels. They offer products in many shapes and sizes.

Rader, Andrew. *Electricity.* Rader's Physics 4 Kids. http://www.physics4kids.com/files/elec_intro.html. An introduction to electricity.

Sandia National Laboratories. Photovoltaics. http://photovoltaics.sandia.gov. Photovoltaics research.

Solar Electric Power Association. *Welcome* . www.solarelectricpower.org. Company website focusing on solar for utility companies.

Solar Energy Industries Association. *Home* . www.seia.org. National trade organizaion for the solar power industry.

Uni-Solar, http://www.uni-solar.com/real-stories-2/notable-projects/. Company website for thin-film solar panels.

U.S. Energy Information Administration. Energy Kids. www.eia.doe.gov/kids. *Energy basics at an introductory level.*

Wholesale Solar Inc. *The Basics of Solar Electricity are Simple* .
http://www.wholesalesolar.com/pdf.folder/Download%20folder/System_Worksheet.pdf.

Instructions for calculating solar panel needs.

Sources for Purchasing Materials

Pitsco Education. http://shop.pitsco.com/. Source for solar cells, motors, etc.

School Specialty. https://store.schoolspecialty.com/OA_HTML/ibeCCtpItmDspRte.jsp?minisite=10206&item=515773. Source for foam sheets.

Appendix I - District Standards

This unit is aligned with the following New Haven Public School District science content standards:

D3 - Describe energy transformations among heat, light, electricity and motion.

D4 - Explain the relationship among voltage, current and resistance in a simple series circuit.

D9 - Describe the availability, current uses and environmental issues related to the use of hydrogen fuel cells, wind and solar energy to produce electricity.

This unit is aligned with the following New Haven Public School District science inquiry standards:

DINQ1 - Identify questions that can be answered through scientific investigation.

DINQ3 - Formulate a testable hypothesis and demonstrate logical connections between the scientific concepts guiding the hypothesis and the design of the experiment.

DINQ4 - Design and conduct appropriate types of scientific investigations to answer different questions.

DINQ5 - Identify independent and dependent variables, including those that are kept constant and those used as controls.

DINQ6 - Use appropriate tools and techniques to make observations and gather data.

DINQ7 - Assess the reliability of the data that was generated in the investigation.

DINQ8 - Use mathematical operations to analyze and interpret data, and present relationships between variables in appropriate forms.

DINQ9 - Articulate conclusions and explanations based on research data, and assess results based on the design of the investigation.