

# Estimating PV System Size and Cost



**RENEWABLE ENERGY**  
THE INFINITE POWER  
OF TEXAS

## For High School

### OVERVIEW

In this unit, students will learn about photovoltaic (PV) systems that can be used for stand-alone purposes or connected to the grid. A prerequisite of this unit is Unit 18, “Introduction to Photovoltaic Systems.” Students will determine a household load (watt hours/day) and their regional insolation value to estimate the cost of a photovoltaic system tied to the grid. Students will also determine the costs of a battery bank, inverter, and other expenses for a stand-alone photovoltaic system. Students will construct electrical series and parallel circuits using photovoltaic cells in an activity, since PV modules are wired together both in parallel (for increased amps) and in series (for increased voltage). Finally, in the Follow Up Lab, students will construct a simple photovoltaic device to help them understand the principles.

### OBJECTIVES

See High School Teacher Resource Guide for TEKS objectives and additional information regarding this and other high school units.

### SUGGESTED TIMEFRAME

Teacher will need to determine how many class periods to devote to each activity, based on the suggested timeframe and length of classes.

Time	Activity Description	Content Area
60 minutes	1 – Introduction and Reading Passage	Science Vocabulary Reading
45 minutes	2 – Worksheet – Estimating the Size and Cost of a Photovoltaic System	Science Mathematics Reading

Time	Activity Description	Content Area
120 minutes over consecutive periods	3 – Lab Activity – Wiring in Series and Parallel	Science Vocabulary Reading
30 minutes	4 – Assessment	Science Reading
120 minutes over consecutive periods	5 – Follow Up Lab Activity – Making a PV Cell	Science Mathematics Vocabulary

### REQUIRED MATERIALS

- copy of the Reading Passage and Student Data Sheets for each student
- an equipment kit for the Lab Activity for each student pair containing the following:
  - goggles for each student
  - 2 small solar cells (at least 0.5V output each)
  - 60 cm of thin electrical wire (use with alligator clips unless meter leads have alligator clips on their ends)
  - 1 DC ammeter (reads amps)/volt meter (reads volts), or separate volt meter and ammeter
  - 1 light source (desk lamp, flashlight or sunlight)
- an equipment kit for the Follow Up Lab for each student pair containing the following:
  - copper sheet cut into strips, 8 cm by 15 cm, two strips per lab pair (copper flashing is available at hardware stores)
  - alligator clip leads
  - micro-ammeter (0 to 50 microamperes scale) or galvanometer
  - electric hot plate whose burner gets red hot
  - bottom cut from clear plastic 2-L bottle
  - table salt or sodium chloride
  - fine sandpaper

- sheet metal shears or big scissors
- goggles for each student
- gloves for each student

## BACKGROUND INFORMATION

Electrical circuits and devices, such as batteries, solar cells and solar modules, have a positive and a negative node or terminal. If a greater output—power, voltage or current—is desired than a single circuit or device can produce, multiple circuits or devices can be combined to form one circuit. When combining (or connecting) multiple circuits/devices, both the positive and negative terminals must be connected in order for the electric current to flow. The manner in which the circuits are connected depends on the desired increase in output. If greater voltage is desired, the circuits will be connected in series. If greater current is desired, the circuits will be connected in parallel.

In a series connection, the positive terminal of one circuit/device is connected to the negative terminal of another circuit/device. The series components or cells are connected one after another with only one path for electrons to take, like a closed racetrack. The disadvantage of a series circuit is that if there is a break in any part of the circuit, the entire circuit is opened and no current can flow. In the activity, students will discover that they can increase the total voltage by adding more cells to the series circuit.

In a parallel connection, the positive terminal of one circuit/device is connected to the positive terminal of another circuit/device, and similarly the negative terminals are connected together. The parts or cells are connected on separate branches, like a ladder with interconnecting rungs. There are several paths for the electrons to flow in a parallel circuit. If there is a break in one branch of a parallel circuit, electrons can still move through the other branches. The current will still flow. Students will find that they can increase the amount of total current generated by connecting more cells in parallel.

## SUMMARY OF ACTIVITIES

### Activity 1 – Introduction and Reading Passage

Read through the entire sequence of student activities first. Explain to the class the topic that will be covered in this unit of study. Teachers can include material from the teacher background information section. Each student will need a copy of the Reading Passage and the Student Data Sheets (including reading comprehension questions, vocabulary words and Lab Activity). Instruct students to study the Reading Passage and to complete the Student Data Sheet. Inform students that during the Lab Activity, they will measure current (in amperes or amps) for one photovoltaic cell and current for two cells both in series and in parallel. Students will also measure voltage for one photovoltaic cell and voltage for two cells in series and two cells in parallel. Emphasize to the class safety precautions when taking current and voltage readings using voltmeters and ammeters. Use either meter leads that have insulated alligator clips on the ends, or attach insulated alligator clips to the wire ends that come into contact with the meter leads. Students should never touch any bare or exposed metal in a circuit that is generating electricity (i.e. meter leads, bare wire, etc.). Give students clear instructions on how to safely measure voltage and current using meters. Photovoltaic systems have cells (or modules) connected in series to raise the voltage to a useful level, but also have cells (or modules) connected in parallel to increase the current output.

Students will compare the outputs for one cell, two cells in series and two cells in parallel to observe the effect of these configurations. Students can see the consequences of adding even more than two cells (series or parallel) to the string. Before starting the activity the teacher should review the concepts of power, wattage, and current: watts (power) = volts (electric potential difference) × amps (current). Students should also review the concept of series and parallel circuits.

### Activity 2 – Worksheet – Estimating the Size and Cost of a PV System

Explain to the class that during this activity they will perform a series of calculations to determine the size and resulting cost of a PV system. Before beginning the lab, students should review the instructions so they will

understand the purpose and the goals. To enhance the class' scientific inquiry in this lab, instruct each student to develop statements for the following: hypothesis, predictions, conclusions and finally significance/ implications. Note that the hypothesis and predictions should be made before beginning the Lab Activity. Refer to the Teacher Resource Guide for more information.

The worksheet requires students to estimate their energy load in watt-hours (Wh). Students can use the example provided in Table 1 of the Reading Passage, or you can instruct them to create a similar table using actual loads in their houses. Students would be required to list all the major appliances and electrical devices in their homes that use electricity from power outlets (not battery operated devices), identify each item's watt rating (can be derived by the operating current and voltage listed on the appliance) and estimate the number of hours each item is used daily. This could be assigned as homework. Students should read the instructions and complete the calculations listed on the worksheet. Students can work independently. Review the calculations with the class once they have completed the activity.

### **Activity 3 – Lab Activity – Wiring in Series and Parallel**

Explain to the class that they will learn about connecting circuits in series and in parallel and study the effect each type of connection has on the resulting current and voltage. Students will work in pairs to wire 2 small PV cells both in series and in parallel, apply a light source to the PV cells and measure the resulting current and voltage with a volt meter and ammeter. The activity consists of 3 parts: building the circuits, taking the measurements and recording and analyzing the data. Review the Lab Activity section of the Student Data Sheets with the class. Students should record the current and voltage measurements for both types of connections on the Data Table provided in the Lab Activity. After students have completed their Data Tables, they should answer the data summary questions listed in the Lab Activity.

### **Expected Observations**

Students should observe that the voltage increases when PV cells are connected in series. The current may also increase by a small amount. When connected in parallel, the current will increase but the voltage will stay about the same.

### **Activity 4 – Assessment**

Distribute a copy of the Assessment Questions to each student. Instruct each student to work alone and answer the short answer and multiple choice questions. Collect the handouts, grade and return them to the students.

### **Activity 5 – Follow Up Lab**

Students will work in pairs to make a simple PV cell using copper strips. Primitive photovoltaic cells can be made easily and inexpensively. While none of these cells will provide sufficient power to operate an appliance, the activity will illustrate the principles of operation.

The copper (I) oxide strips are difficult, time consuming to make and require waiting periods of up to 30 minutes. They also involve high heat. During the waiting periods, you should have activities or discussion topics prepared to keep the class engaged, such as a debate about whether the upfront equipment costs for a PV system can be justified for economic and environmental reasons. Or you may wish to prepare the strips ahead of time and skip that part of the Lab Activity to save class time and reduce risk.

## **ADDITIONAL ACTIVITIES**

### **1. PV System Sizing Visual Aid**

Instruct students to outline or create a graphic organizer, such as a bubble graph, concept map or web, regarding the main points in photovoltaic system sizing. Main points that should be included are: load determination, daily insolation value, PV array cost, balance of system (miscellaneous costs), battery bank, inverter, percent increase for loss and inefficiency.

### **2. PV Billboard Advertisement**

Based on the new knowledge students have gained as a result of this unit, instruct students to design a billboard to advertise a photovoltaic system for a home. Billboards typically are very eye-catching and use few words to deliver a message. Students should consider the use of graphics (such as a home PV system), listing at least one benefit of PV, and the effectiveness of providing technical information about PV such as a summary of typical system components, how the technology works, etc.

# Feasibility of Photovoltaic Systems



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## HIGHLIGHTS

- **Off-grid photovoltaic (PV) systems can use batteries for night time energy needs**
- **Grid-connected PV systems use the utility as backup**
- **PV can be affordable compared to other power options**

## INTRODUCTION

Photovoltaic (PV) energy generating systems (or PV systems) convert the sun's energy directly into electricity using state-of-the-art semiconductor materials. PV systems vary in complexity. Some are called "stand-alone" or "off-grid" systems, which means they are the sole source of power to a home, water pump or other load. Stand-alone systems can be designed to run with or without battery backup. Remote water pumps are often designed to run without battery backup, since water pumped out of the ground during daylight hours can be stored in a holding tank for use any time. In contrast, stand-alone

home power systems store energy generated during the day in a battery bank for use at night. Stand-alone systems are often cost-effective when compared to alternatives, such as lengthy utility line extensions.

Other PV systems are called "grid-connected" systems. These work to supplement existing electric service from a utility company. When the amount of energy generated by a grid-connected PV system exceeds the customer's loads, excess energy is exported to the utility, turning the customer's electric meter backward. Conversely, the customer can draw needed power from the utility when energy from the PV system is insufficient to power the building's loads. Under this arrangement, the



**GRID-CONNECTED RESIDENTIAL PV** *More Austin homes are using solar electric systems tied to the utility for their power.*

SOURCE: ANDREW MCCALLA

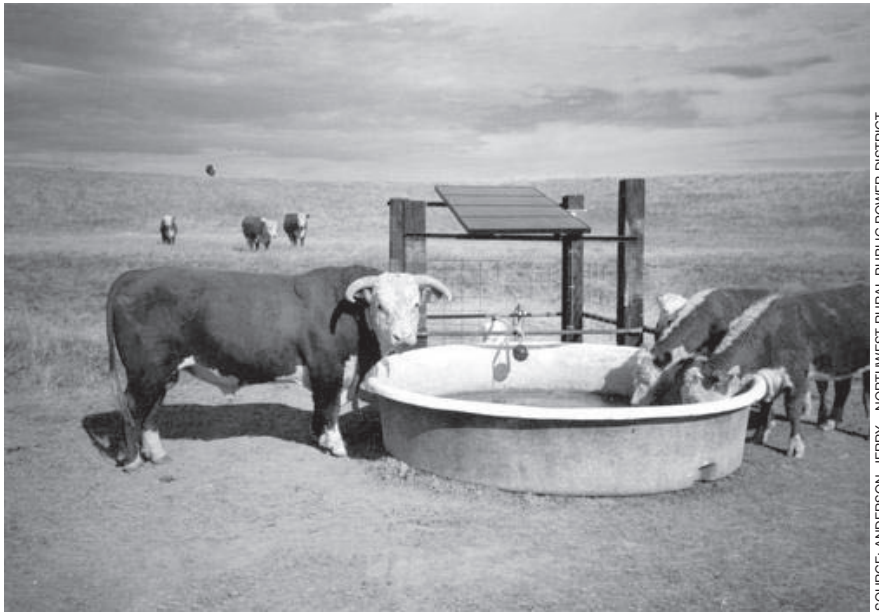
customer's monthly electric utility bill reflects only the net amount of energy received from the electric utility. However, a grid-connected PV system without battery backup will not generate power for the house when the utility grid is down.

Each type of system requires specific components besides the PV modules. Generating AC power requires a device called an inverter. Battery storage requires special batteries and a battery charge controller. The final cost of any PV system ultimately depends on the PV array size, the battery bank size, and on the other components required for the specific application.

The average Texas household uses approximately 1,100 kilowatt-hours (kWh) of electricity per month, or about 36,000 watt-hours (Wh) of electricity per day. In contrast, a home designed to be energy efficient can use as little as 6,000-10,000 Wh per day. As you might guess, a PV system designed to power an energy efficient home will cost much less.

## COMPARE TO ALTERNATIVES

Once you have estimated the total cost of a PV system that meets your needs, a final step in an economic feasibility study is to compare estimated costs of the PV system to other alternatives. The most common alternative to off-grid PV is a line extension from an electric utility company. Utilities in Texas typically charge anywhere from \$5,000 to \$30,000 per mile for line extensions; so for many small- or medium-sized loads in remote locations, PV systems are the economically feasible choice. For this reason, several rural electric cooperatives in the State now offer their customers PV systems in lieu of more costly line extensions. Line extensions also may be prohibitively expensive even when the distance traveled is short, such as in urban areas where pavement cuts are required.



**RURAL PV** Remote water pumps for livestock are often economically powered by PV.

SOURCE: ANDERSON, JERRY – NORTHWEST RURAL PUBLIC POWER DISTRICT

Other alternatives include on-site diesel generators, hybrid wind-solar systems, or simply making energy improvements such as installing energy-efficient appliances, improving insulation and sealing ducts. Each alternative comes with its own benefits and drawbacks, many of which are difficult to quantify. For example, the cost of purchasing and delivering diesel fuel to a remote generator should be considered in an economic analysis of alternatives, as well as the noise and exhaust generated as byproducts of the energy production.

## STICKER SHOCK? THE IMPORTANCE OF EFFICIENCY

Once you have estimated the cost of a PV system for your home, chances are the price will seem a bit high. This is why most people who use PV to power their homes design them to be energy efficient. This means they build their homes with excellent insulation, take advantage of energy efficient designs, and pay attention to important factors such as site selection, shading, and orientation. With some careful planning, it is possible to reduce a home's electrical loads by 50 to 80 percent without sacrificing comfort and convenience.

### Understanding the Reading Passage

1. What is the most important consideration in determining if solar photovoltaic systems are a practical alternative where you live?  
 \_\_\_\_\_  
 \_\_\_\_\_
2. Explain the difference between grid-connected and off-grid systems. Why would anyone want to build a grid-connected system?  
 \_\_\_\_\_  
 \_\_\_\_\_
3. An average home uses 36,000 Wh of electricity per day. An energy efficient home uses 10,000 Wh of electricity per day. What percentage decrease is this? \_\_\_\_\_% If electricity costs 3.30 cents per kWh, how much money is saved every day? \$\_\_\_\_\_

### Vocabulary

Based on the Reading Passage, write down your understanding of these words or word pairs and verify your definitions in a dictionary, on the Internet if available or with your teacher:

alternating current (AC) \_\_\_\_\_

array \_\_\_\_\_

direct current (DC) \_\_\_\_\_

feasibility \_\_\_\_\_

inverter \_\_\_\_\_

kilowatt-hours (kWh) \_\_\_\_\_

module \_\_\_\_\_

parallel circuit \_\_\_\_\_

photovoltaic (PV) \_\_\_\_\_

photovoltaic cell \_\_\_\_\_

series circuit \_\_\_\_\_

solar insolation \_\_\_\_\_

utility grid \_\_\_\_\_

## Worksheet: Estimating the Size and Cost of a Photovoltaic System

This worksheet will explain how to estimate the size of a PV array and battery bank and total cost of a stand-alone PV system. It can be used for grid-connected systems, too, but with several caveats that are identified in the step-by-step instructions. The worksheet is adapted from a method developed by Sandia National Laboratories, and the analysis is conducted in two sections.

### INSTRUCTIONS

In the first section, you will identify the system specifications by determining the load, available sunlight, and the size of the PV array and battery bank needed. In the second section, you will estimate the cost of the PV system based on your system specifications. Let's walk through the analysis, step by step.

### STEP 1. DETERMINE LOAD, AVAILABLE SUNLIGHT, PV ARRAY SIZE, AND BATTERY BANK SIZE

**1.a. Determine Load.** The preferred method for determining PV system loads is a “bottom-up” approach in which every daily load is anticipated and summed to yield an average daily total. For PV systems designed to power simple loads, such as a single water pump, electric light or other appliance, this method is easy. Simply look at the nameplate power rating on the appliance to calculate its power consumption in watts. Some labels show amperage and voltage only; to obtain watts, just multiply amps by the voltage. Then multiply by the number of hours it is expected to operate on an average day to obtain watt-hours (Wh).

For more complex loads, such as powering a whole house, you will need to estimate all the different loads in the house on a typical day and sum them. Table 1 provides an example calculation for a household using this method.

For complex loads like households, it is sometimes difficult to anticipate every electric load. Electric clocks, TVs, stereos and other appliances sometimes draw small amounts of power even when they are turned off. For this reason, we recommend multiplying your estimated daily load by a “fudge factor” of 1.5. Some other elements accounted for by this factor are all the system efficiencies, including wiring and interconnection losses, as well as the efficiency of the battery charging and discharging cycles. Of course, for grid-connected systems, you can simply review your monthly utility bills to get an accurate idea of monthly energy consumption.

**1.b. Determine Available Sunlight.** The amount of useful sunshine available for the panels on an average day during the worst month of the year is called the “insolation value.” We use the worst month for analysis to ensure the system will operate year-round. In most of Texas, average solar insolation values range from about 3.3 to 5.0 hours per day in December, with the lowest values in east Texas and the highest values in the Panhandle and far west Texas (see Figure 1). The insolation value also can be

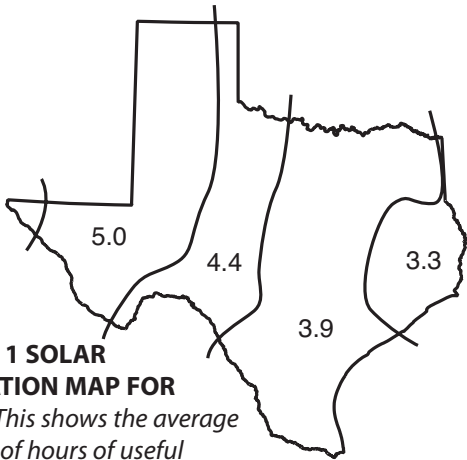
interpreted as the kilowatt-hours per day of sunlight energy that fall on each square meter of solar panels at latitude tilt.

**1.c. Determine PV Array Size.** For a PV system powering loads that will be used every day, the size of the array is determined by the daily energy requirement (1.a.) divided by the sun-hours per day (1.b.). For systems designed for non-continuous use (such as weekend cabins), multiply the result by the days per week the loads will be active divided by the total number of days in the week. For example, for a weekend cabin, multiply by 2/7. Generally, grid-connected systems are designed to provide from 10 to 60% of the energy needs with the difference being supplied by utility power.

**1.d. Determine Battery Bank Size.** Most batteries will last longer if they are shallow cycled—discharged only by about 20% of their capacity—rather than being deep-cycled daily. A conservative design will save the deep cycling for occasional duty, and the daily discharge should be about 20% of capacity. This implies that the capacity of the battery bank should be about five times the daily load. It also suggests that your system will be able to provide power continuously for five days without recharging, such as during a winter storm. Multiply the daily load (1.a.) by 5, and then divide the result by the voltage of the battery bank you will use (typically 12 volts). The result is the recommended amp-hour rating of the battery bank. If you wish to be more secure and design for more days of cloudy weather, multiply by a number greater than 5. However, it is generally not recommended to design for more than 12 days of cloudy weather unless it is a highly critical load. Of course, you can skip this step entirely if your system does not incorporate a battery bank, such as a water pump, or is grid-connected since the availability of grid power eliminates the need for storage.

Appliance	AC or DC Watts		Hours Used/Day	=	Watt Hours/Day
Ceiling Fan	100	x	8.0	=	800
Coffee Maker	600	x	0.3	=	180
Clothes Dryer	4,856	x	0.8	=	3,885
Computer	75	x	2.0	=	150
Computer Monitor	150	x	2.0	=	300
Dishwasher	1,200	x	0.5	=	600
Lights, 4 Compact Fluorescents	4 x15	x	5.0	=	300
Microwave Oven	1,300	x	0.5	=	650
Radio	80	x	4.0	=	320
Refrigerator	600	x	9.0	=	5,400
Television	300	x	8.0	=	2,400
Vacuum Cleaner	600	x	0.2	=	120
VCR	25	x	8.0	=	200
Washing Machine	375	x	0.5	=	188
<b>TOTAL</b>					<b>15,493</b>

**TABLE 1** Typical household electrical appliances and run times



**FIGURE 1 SOLAR INSOLATION MAP FOR TEXAS** This shows the average number of hours of useful sunlight available in December for a PV module at latitude tilt.

## STEP 2. CALCULATE PV SYSTEM COSTS

**2.a. Estimate PV Array Cost.** Many PV modules can be purchased at retail for about \$5 per watt for most small systems in the 150 – 8,000 watt range. Of course, there are opportunities to purchase modules for a lower price, especially when your system is larger and you can buy in bulk. When purchasing modules, look for a UL listing, which certifies that the modules meet electrical safety standards, and long-term warranties. Manufacturers typically offer modules with 25-year warranties.

**2.b. Estimate Battery Bank Cost (if needed).** Many flooded lead acid batteries designed for use with PV systems can be purchased at retail for under \$1 per amp-hour.

**2.c. Estimate Inverter Cost .** An inverter will be needed for systems that output AC power, the current used by the most common appliances and electric devices. For stand-alone systems the inverter should be sized to provide 125% of the maximum loads you wish to run simultaneously at any one moment. For example, if the total loads you wish to run will be 1,600 watts (a dishwasher, television and ceiling fan from Table 1) choose an inverter with a rated continuous power output of 2,000 watts. For grid-connected systems the maximum continuous input rating of the inverter should be about 10% higher than the PV array size to allow for safe and efficient operation. The input rating of the inverter should never be lower than the PV array rating. For more information contact an inverter supplier. Inverters designed for residences and other small systems can be purchased at retail for about \$1 per rated watt.

**2.d. Estimate Balance of System Cost.** Besides PV modules and batteries, complete PV systems also use wire, switches, fuses, connectors and other miscellaneous parts. We use a factor of 20% to cover balance of system costs.

## CALCULATIONS

Based on the information provided in the Reading Passage and in the instructions, following the steps below to calculate the size and cost of a PV system.

### Step 1. Determine the load, available sunlight, array size, battery bank size:

- a. Determine the energy load required in watt-hours (Wh) per day. Multiply the number of watts the load will consume by the hours per day the load will operate (see Table 1 in the Reading Passage). (Based on your teacher's directions, you can use the Wh energy load in Table 1 or create a new chart with your own values.) Multiply your result by 1.5.

$$\text{Total Wh per day required } \underline{\quad} \times 1.5 = \underline{\quad} \text{ Wh}$$

- b. Determine the hours per day of available sunlight at the site (see Figure 1).

$$\text{Total available sunlight: } \underline{\quad} \text{ hrs/day}$$

- c. Determine the PV array size needed. Divide the energy needed (1.a.) by the number of available sun hours per day (1.b.).

$$\text{Total array size required: } \underline{\quad} \text{ Watts}$$

- d. Determine the size of the battery bank (if one is desired). Multiply the load (1.a.) by 5 (result is watt-hours, Wh). Then divide by the battery voltage (for example, 12 volts) to get the amp-hour (Ah) rating of the battery bank.

$$\text{Total Battery Bank Required: } \underline{\quad} \text{ Ah}$$

### Step 2. Calculate the cost of the PV system needed for this application:

- a. Multiply the size of the array (1.c.) by \$5 per watt.

$$\text{Cost estimate for PV array: } \$ \underline{\quad}$$

- b. If a battery bank is used, multiply the size of the battery bank (1.d.) by \$1 per amp hour.

$$\text{Cost estimate for battery bank: } \$ \underline{\quad}$$

- c. If an inverter is used, multiply the size of the array (1.c.) by \$1 per rated watt.

$$\begin{aligned} \text{Cost estimate for Inverter: } & \$ \underline{\quad} \\ \text{Subtotal: } & \$ \underline{\quad} \end{aligned}$$

- d. Multiply the subtotal above by 0.2 (20%) to cover balance of system costs (wire, fuses, switches, etc.).

$$\begin{aligned} \text{Cost Estimate for Balance of System: } & \$ \underline{\quad} \\ \text{Total Estimated PV System Cost: } & \$ \underline{\quad} \end{aligned}$$



## Lab Activity – Wiring in Series and Parallel

### INTRODUCTION

The purpose of this activity is to learn how to increase the voltage output, current output (amps), or power output of a PV array. The individual PV cells can be connected in series or in parallel.

### BEFORE YOU START

Review the vocabulary words from the Reading Passage. Ask your teacher if you are unsure of any of the meanings.

### MATERIALS

- goggles
- 2 small solar cells (at least 0.5V output each)
- 60 cm of thin electrical wire (use with alligator clips unless meter leads have alligator clips on their ends)
- 1 DC ammeter (reads amps)/volt meter (reads volts), or separate volt meter and ammeter
- 1 light source (desk lamp, flashlight or sunlight)

### A. Constructing the Experiment (wear goggles)

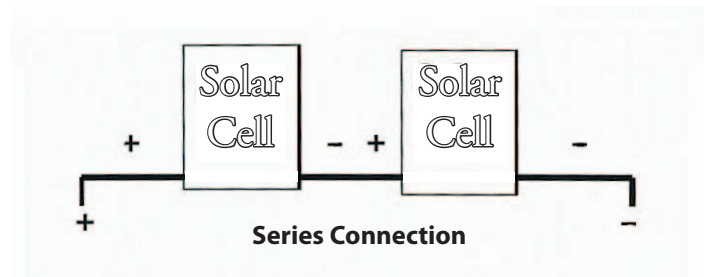
1. If your solar cell does not already have wires attached to it, attach 15 cm of wire to each node of the photovoltaic (PV) cell. The cell should either have clips or hooks around which you can manually twist the wire.
2. Follow your teacher's safety instructions and attach the red wire from the PV cell to the red lead of the voltmeter (either clip or wrap the wires together).
3. Attach the black wire from the PV cell to the black lead of the voltmeter.
4. Shine a light source (sunlight or lamp) on the PV cell to check if you are getting a reading in volts. If the meter shows no reading check the connections.

### B. Performing the Activity

Series Circuit:

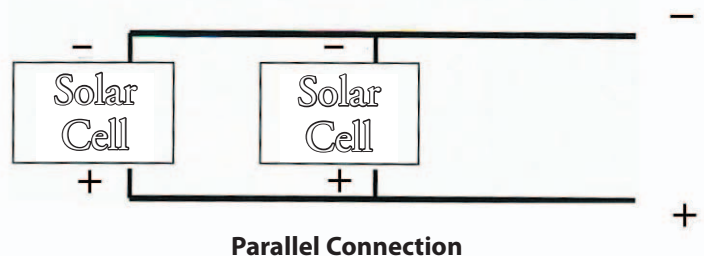
1. Record the voltage of a single PV cell under a light source (sun or lamp) on the Data Table.

2. Join a second PV cell to the first cell, using a series hookup (see diagram), and record the new voltage produced by the two cells in series under the same light source.
3. Hook the two solar cells in series to the ammeter; read and record the current in amperes. Be sure to hook the black lead to the black wire on the ammeter and the red lead to the red wire.
4. Unhook the cells.
5. Remove one solar cell and read the current in amperes with just one cell and record.



Parallel Circuit:

1. Measure the amperage (current) output of a single PV cell under a light source (sun or lamp) by attaching the red lead of the PV cell to the red lead of the ammeter and the black lead of the PV cell to the black lead of the ammeter. Record the amps generated.
2. Join a second PV cell to the first, using a parallel hookup (see diagram). Record the current (ampere) reading produced by the two cells in parallel under the same light source.
3. Hook the 2 PV cells in parallel to the voltmeter (black lead of PV cell to black lead of voltmeter; red lead of PV cell to red lead of voltmeter) and read the number of volts generated and record.



**Data Table. Voltage and Current Measurement of PV Cells**

Number of Cells	Voltage (V)	Amperage (I)
1		
2 in series		
2 in parallel		

**DATA SUMMARY**

1. How does the voltage change if the number of cells in series is increased?

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2. How does the current change if the number of cells in series is increased?

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3. How does the voltage change if the number of cells in parallel is increased?

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4. How does the current change if the number of cells in parallel is increased?

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**Assessment Questions**

1. Assuming future price increases for electricity, would you consider using a photovoltaic system for your future home? Why or why not?

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2. What advantage in cost do photovoltaic systems have for remote areas?

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3. If individual homes with PV systems were providing significant excess electricity to the grid, what environmental impact would this have?

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4. What impact is technology having on electricity consumption today?

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5. What are the advantages of increasing size for

a) a series circuit? \_\_\_\_\_

b) a parallel circuit? \_\_\_\_\_

**Multiple Choice Questions**

1. An inverter is required on a PV system if:
  - a) batteries are used
  - b) DC power is needed
  - c) AC power is needed
  - d) if the load is very large
2. If a PV system is tied into the electric utility grid:
  - a) it does not have to use batteries
  - b) it needs batteries
  - c) it requires power storage
  - d) it cannot provide AC
3. A stand-alone PV system can provide electricity when no sunlight is present with:
  - a) batteries
  - b) no batteries
  - c) a battery charge controller
  - d) a and c
4. What appliances as a group use the largest number of watts per hour?
  - a) VCR, clothes dryer, computer
  - b) clothes dryer, microwave oven, dishwasher
  - c) vacuum cleaner, clothes dryer, ceiling fan
  - d) VCR, fluorescent lights, coffee maker
5. In most of Texas, solar insolation values range from:
  - a) 10-12 hours
  - b) 12-15 hours
  - c) 2-4 hours
  - d) 3-5 hours
6. A series circuit:
  - a) follows one path
  - b) follows many paths
  - c) increases voltage when cells are added
  - d) a and c
7. A parallel circuit:
  - a) follows one path
  - b) follows many paths
  - c) increases amperage when cells are added
  - d) b and c
8. The red wire from the solar cell is attached to:
  - a) black wire of voltmeter
  - b) red wire of voltmeter
  - c) black wire of ammeter
  - d) none of the answers
9. Current (amperes) can be increased by:
  - a) adding to a series circuit
  - b) increasing voltage
  - c) removing solar cells
  - d) adding to a parallel circuit
10. When planning your home in the future, you would:
  - a) research using a PV system
  - b) consider a PV system hooked to the grid
  - c) consider a stand-alone PV system
  - d) all answers a, b, and c

## Follow Up Activity – Making a PV Cell

### INTRODUCTION

High-efficiency solar cells are made from purified silicon. Constructing these devices requires specialized equipment and extensive resources. However, the photovoltaic process can be demonstrated using copper that has been coated with a layer of copper (I) oxide.

Copper forms two different compounds with oxygen. They are copper (I) oxide,  $\text{Cu}_2\text{O}$ , and copper (II) oxide,  $\text{CuO}$ . Copper (I) oxide is the semiconductor. In order to get complete oxidation of the copper surface, the copper is over heated, creating a layer of black copper (II) oxide. When the black layer flakes off, the red copper (I) oxide layer underneath is exposed. For more information, refer to any high school chemistry textbook.

Copper (I) oxide is a semiconductor. In a semiconductor, there is a gap between the electrons that are bound tightly to the atom and the electrons that are farther from the atom, which can move freely and conduct electricity. Normally, electrons do not have enough energy to jump past this gap, so the material acts like an insulator. However, when sunlight hits the electrons in a semiconductor such as copper (I) oxide, some of the electrons gain enough energy from the sunlight to jump past the band gap and become free to conduct electricity. In this activity, the free electrons will move into the saltwater, then into the clean copper plate, into the wire, through the meter, and back to the cuprous oxide plate.

### MATERIALS

- two copper strips 8 cm by 15 cm
- two alligator clip leads
- micro-ammeter (0 to 50 microamperes scale) or galvanometer
- electric hot plate
- bottom cut from clear plastic 2-liter bottle
- table salt or sodium chloride
- fine sandpaper
- goggles
- gloves

**I. Preparing the copper strips** (This lab involves high heat and sharp objects. Wear goggles and gloves at all times and observe all safety precautions.)

1. Obtain a materials kit from your teacher.
2. Wash your hands thoroughly.
3. Wash both copper strips with soap or cleanser to remove all traces of oil or grease. Dirt and oil on the sheet will prevent proper coatings from forming.
4. Continue cleaning the copper strips by using fine sandpaper. Make sure they are very clean. They should be a light pink color.
5. After the copper strips have been cleaned and dried, place one copper strip on the burner and turn the burner to its highest setting. Set the other strip aside to be used later.
6. As the copper starts to heat up, oxidation patterns will begin to form. You will see the oxidation patterns as shades of orange, purple, and red covering the copper.
7. Continue to allow the copper strip to heat for about thirty minutes, until the copper is covered with a thick, black coating. This black coating is copper (II) oxide.
8. Turn off the burner but leave the copper strip on the burner and allow it to cool slowly. As it cools, differential shrinkage will cause the copper (II) oxide to flake off, exposing a coating of copper (I) oxide underneath. Clean up the black flakes that collect and discard. Do not try to scrape off any remaining black bits because this might damage the copper (I) oxide coating.

### II. Assembling the cell

1. Retrieve the other clean copper strip. Carefully and gently bend both strips so that they will fit inside the clear plastic bottle bottom. They must not

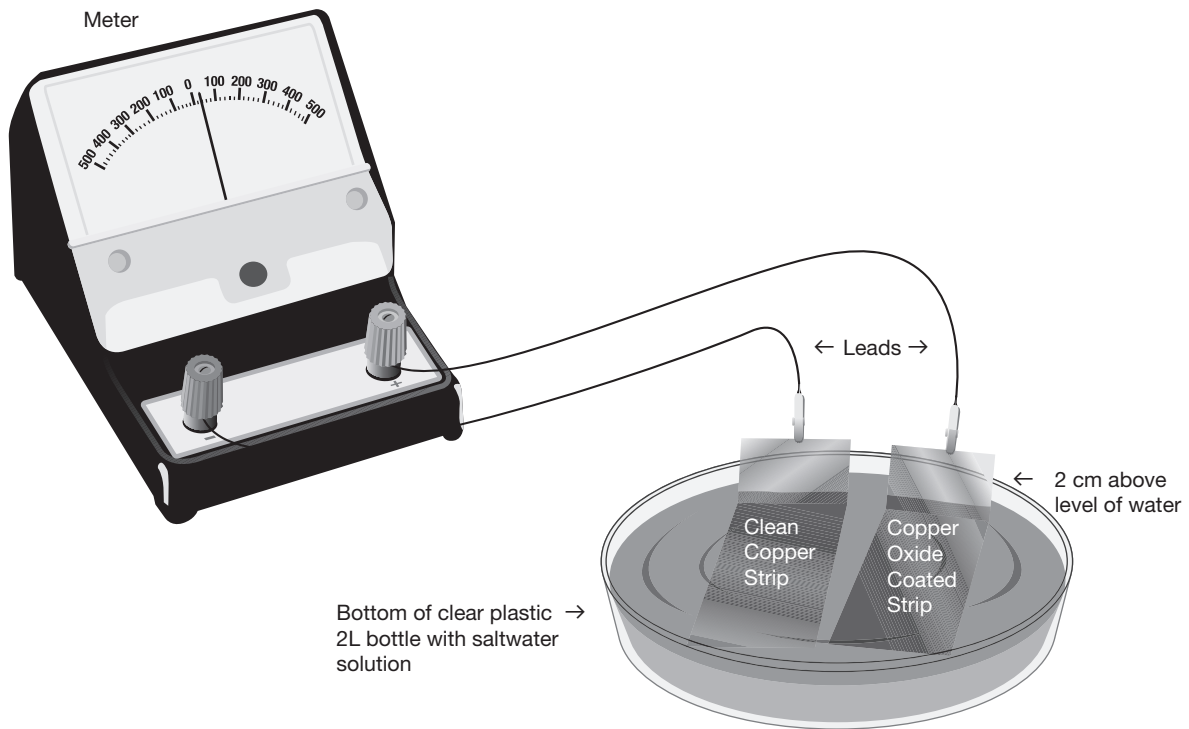
touch each other. The oxide coating that was facing up on the burner should face outside.

2. Dissolve two tablespoons of salt into 500 mL of hot water from the tap. Pour the saltwater into the clear plastic bottle bottom leaving two cm of copper strip above the level of the water.
3. Attach the two alligator clip leads, one to the clean copper strip, and one to the oxide coated strip. Connect the lead from the clean copper strip to

the positive terminal of the meter. Connect the lead from the copper (I) oxide coated strip to the negative terminal of the meter.

**III. Testing the Cell**

1. Take the assembled photovoltaic cell outside and face the oxide coated strip toward the sun. Read the meter.
2. Shade the cell from the sun and read the meter again.



**DATA SUMMARY**

1. What is the reading of the meter in the sun? \_\_\_\_\_
2. What is the reading of the meter in the shade? \_\_\_\_\_
3. If the reading of the meter in the shade is not zero, explain why not?

\_\_\_\_\_

\_\_\_\_\_

## Understanding the Reading Passage

- Answers may vary, but should be supported by a logical argument. The availability of solar energy (insolation) is probably the best choice with total household load the second consideration.
- Grid-connected systems, as the name implies, are connected to the local electric grid. The advantage of a grid-connected system is that the excess power can be traded back to the electric utility. Off-grid systems are not connected to the local electric utility grid. Off-grid systems are the best choice if grid supplied electric power is unavailable because PV systems are usually less expensive than extending existing power lines to the load (house, water pump, etc.) which can be miles away.
- $(36,000 - 10,000)/36,000 \times 100 = \underline{72\%}$ ; 26,000 Wh saved per day = 26 kWh @ 3.30 cents/kWh = 86 cents

## Lab Activity Data Summary

- The voltage increases.
- The current may increase slightly.
- The voltage stays the same.
- The current increases.

## Assessment Questions

- Reasons to use photovoltaics include: imported fuels have variable prices and can easily rise; the U.S. will not be dependent on other countries for energy; to reduce pollution (1/4 of all air pollution is a byproduct of electric power production caused by burning fossil fuels); to avoid blackouts; to reduce a household's costs over time.
- Photovoltaic systems can be independent from utility connection thereby avoiding potentially high fees charged for running new electric lines to a property.
- Cleaner air would result, impacting the health of people with respiratory diseases positively, and allowing for more solar insolation in affected areas because of less particulate matter in the air.
- The creation of new entertainment technology (TV, video and DVD, CD players), computers and new kitchen appliances leads to greater consumption. Growing population is a compounding factor.
- When a series circuit grows larger, the voltage increases; when a parallel circuit grows larger, the current (amps) increases.

## Multiple Choice Questions

1 c; 2 a; 3 d; 4 b; 5 d; 6 d; 7 d; 8 b; 9 d; 10 d (best answer)

## Follow Up Lab Data Summary

- 33 microamperes is typical
- 10 to 20 microamperes is typical
- The PV cell may be acting like a voltaic cell, wet cell, or battery.

## Vocabulary Definitions

**alternating current (AC)** – an electric current that reverses its polarity or changes direction at regular intervals; common household current in US

**array** – modules wired into series and parallel circuit arrangements

**direct current (DC)** – electric current that flows in one direction only

**feasibility** – the state of being capable of being used or dealt with successfully

**inverter** – equipment used in a photovoltaic (PV) system to convert the DC power generated by the solar modules into AC power

**kilowatt hour (kWh)** – a unit of energy equal to that produced in one hour by a power of a thousand watts (amps  $\times$  volts = watts)

**module** – dozens of photovoltaic cells interconnected and sealed to be weather proof

**parallel circuit** – a connection in which the positive terminal of one circuit/device is connected to the positive terminal of another circuit/device, and similarly the negative terminals are connected together; there are several paths for the electrons to take

**photovoltaic (PV)** – comes from “photo” meaning light and “voltaic” referring to producing electricity; solar cells that use sunlight to produce electricity by the flow of electrons through the solar cell's semiconductor material

**photovoltaic cell** – cell that converts sunlight into electricity; made from at least 2 layers of semiconductor material (silicon)

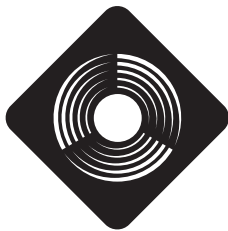
**series circuit** – a connection in which the positive terminal of one circuit/device is connected to the negative terminal of another circuit/device cells connected; circuits that have only one path for electrons to take

**solar insolation** – exposure to the sun's rays (usually in hours per day)

**utility grid** – a network of high voltage transmission lines by which electrical power from generating stations is distributed throughout a region

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