

## Series and Parallel Circuits

### Student Objective

The student:

- will calculate the current, voltage and power output for modules in which the cells are connected in series and parallel
- will calculate the current, voltage and power output for arrays in which the modules are connected in circuits wired in series and parallel
- will determine in what combination of series and parallel circuits the individual cells or modules should be wired to obtain a desired current and voltage output.

### Key Words:

array  
parallel circuit  
photovoltaic cell  
photovoltaic panel  
series circuit

### Time:

1- 2 class periods

### Materials:

- laboratory manual
- keyword list
- (4) photovoltaic cells
- (8) wires with alligator clips
- variable resistor (rheostat)
- insolation meter (solar meter)
- multipurpose meter
- protractor
- graph paper
- piece of cardboard large enough to hold four cells in a horizontal line
- thermometer
- tape

### Procedure

1. **Engage:** Share a few student generated news reports or group analysis answers from the *Irradiance and Temperature* activity. Answer any questions that the students have from the problem set. General questions can be given to students for outside research. Points that may be brought up in discussion that will be covered more thoroughly during this investigation are:

- the way that cells are wired together to make modules, modules into panels and panels into arrays
  - how to increase either voltage or current for a specific application.
2. **Explore:** Students should work in teams of 3 - 5 per team as they explore this new investigation. Pass out materials.
  3. Students should complete the activities and assessment problems in the Laboratory Manual to explain, compare, and apply the new knowledge gained from this investigation.

### **Related Reading**

- ***Photovoltaics: Design and Installation Manual*** by Solar Energy International (New Society Publishers, 2004)  
Solar Energy International (SEI) is a non-profit that trains adults and youth in renewable energy and environmental building technologies. This manual is well-suited for those who have some electrical experience, and students in high school tech prep-level courses. The book contains an overview of photovoltaic electricity and a detailed description of PV system components, including PV modules, batteries, controllers and inverters. It also includes chapters on sizing photovoltaic systems, analyzing sites and installing PV systems.

### **Internet Sites**

**[http://www.fsec.ucf.edu/en/consumer/solar\\_electricity/basics/index.htm](http://www.fsec.ucf.edu/en/consumer/solar_electricity/basics/index.htm)**

Florida Solar Energy Center's photovoltaic fundamentals page explains the basics of photovoltaic cells including their manufacture, the components of systems, as well as the pros and cons of photovoltaic power.

**<http://www.mathconnect.com/ENGINEERING-Formula.htm>**

Common electrical formulas and conversions

**<http://www.article19.com/shockwave/oz.htm>**

Article 19 Group's interactive circuit building webpage, allows placement of resistors, light bulbs, wires, ammeters and voltmeters, plus demonstrations of several circuits and Ohms law.

**[http://solar.anu.edu.au/level\\_1/Sun/PVPanel/PVPanel.html](http://solar.anu.edu.au/level_1/Sun/PVPanel/PVPanel.html)**

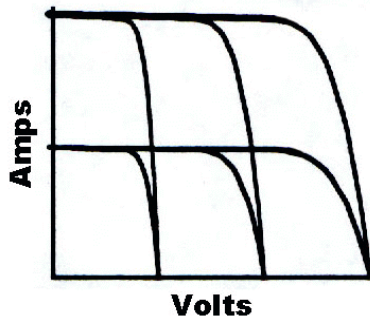
Centre for Sustainable Energy Systems (CSES) interactive page calculates the power output of an array based on a variety of parameters including number of modules in series and in parallel.

## Series and Parallel Circuits

### Answers - Laboratory Manual

1. Data will vary, but should show consistency between groups collecting data at the same time.
2. I-V curves should show similarity between groups, and be labeled and titled correctly. The x- axis is voltage, y-axis is current, and graph intervals should be even. The maximum power point should be indicated. The title of the graph should include the average temperature and irradiance reading.
3. Answers should come from the appropriate point on the graph.
4. Answers will vary. Most students unless they have had previous electrical experience will probably hypothesize that both the current and the voltage will increase.
5. Data will vary, but should show consistency between groups that are collecting data at the same time.
6. I-V curves should show similarity between groups, and be labeled and titled correctly. The x- axis is voltage, y-axis is current, and graph intervals should be even. The two separate curves should be labeled clearly, and the maximum power points should be indicated. The title of the graph should include the average temperature and irradiance reading.
7. Answers should come from the appropriate points on the graph.
8. In series circuits, the voltage is increased. The voltages of the individual cells are added together.
9. In series circuits, the amperage remains the same as the lowest single cell amperage.
10. For series circuits:  $I_{\text{total}} \approx I_A$  and  $V_{\text{total}} \approx X (V_A)$
11. Answers will vary, most students probably did not hypothesize that the current would remain the same.
12. Answers will vary. Most students unless they have had previous electrical experience will probably hypothesize that both current and voltage will increase. Some students may realize from the previous experiment that different results may occur.
13. Data will vary, but should show consistency between groups that are collecting data at the same time.
14. I-V curves should show similarity between groups, and be labeled and titled correctly. The x- axis is voltage, y-axis is current, and graph intervals should be even. The two separate curves should be labeled clearly, and the maximum power points should be indicated. The title of the graph should include the average temperature and irradiance reading.
15. Answers should come from the appropriate points on the graph.
16. In parallel circuits, the voltage remains the same as the single cell voltage.
17. In parallel circuits, the amperage is increased. The amperage of the individual cells are added together.

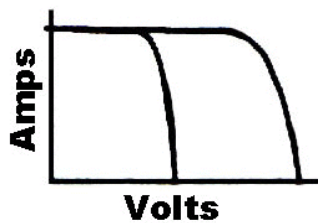
18. For parallel circuits:  $I_{\text{total}} \approx X (I_A)$  and  $V_{\text{total}} \approx V_A$
19. Answers will vary, most students probably did not hypothesize that the voltage would remain the same.
20. In applications (loads) where a higher voltage is required.
21. In applications (loads) where a higher current is required.
22. Drawings may vary, but should be similar to the one below. Volts are on the x-axis, amperage on the y-axis.



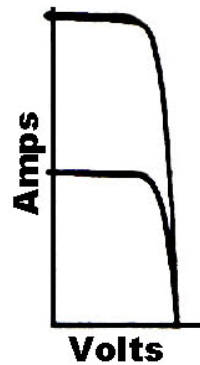
23. This will vary depending on what module the class has been using for its experiments. The small 3V modules from Pitsco or Solar World (Siemens) are wired in series.

#### Answers - Problem Set

1. b. increase the voltage, current stays the same
2. a. increase the current, voltage stays the same
3. d. 60 volts, 5 amps
4. Drawings should be similar to the ones below. Voltage is on the x-axis, current is on the y-axis. Series circuits will add the voltage values together, Parallel circuits add the current values together.



Series Circuit



Parallel Circuit

5. a. 3                      b. 1  
 c. 2                      d. 1

## Series and Parallel Circuits

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	
<b>Nature of Science</b>																						
<b>Standard 1</b>	SC.912.N.1.	X																				
<b>Earth and Space</b>																						
<b>Standard 5</b>	SC.912.E.5.				X																	
<b>Physical Science</b>																						
<b>Standard 10</b>	SC.912.P.10.	X												X	X							
<b>Mathematics Standards</b>		MA.912.A.1.4, MA.912.A.2.1, MA.912.A.2.2, MA.912.A.2.7, MA.912.A.2.8, MA.912.A.2.12, MA.912.A.2.13, MA.912.A.10.1																				

### Science Standards

#### Standard 1: The Practice of Science

- SC.912.N.1.1- Define a problem based on a specific body of knowledge, for example: biology, chemistry, physics, and earth/space science, and do the following:
  1. pose questions about the natural world
  2. conduct systematic observations
  6. use tools to gather, analyze, and interpret data (this includes the use of measurement in metric and other systems, and also the generation and interpretation of graphical representations of data, including data tables and graphs)
  7. pose answers, explanations, or descriptions of events
  8. generate explanations that explicate or describe natural phenomena (inferences)
  9. use appropriate evidence and reasoning to justify these explanations to others
  10. communicate results of scientific investigations, and
  11. evaluate the merits of the explanations produced by others.

#### Standard 5: Earth in Space and Time

- SC.912.E.5.4 - Explain the physical properties of the Sun and its dynamic nature and connect them to conditions and events on Earth.

#### Standard 10: Energy

- SC.912.P.10.1 - Differentiate among the various forms of energy and recognize that they can be transformed from one form to others.
- SC912.P.10.14 - Differentiate among conductors, semiconductors, and insulators.

- SC912.P.10.15 - Investigate and explain the relationships among current, voltage, resistance and power.

### **Mathematics Standards**

#### **Algebra - Standard 1: Real and Complex Numbers**

- MA.912.A.1.4 - Perform operations on real numbers (including integer exponents, radicals, percent, scientific notation, absolute value, rational numbers, irrational numbers) using multi-step and real-world problems.

#### **Algebra - Standard 2: Relations and Functions**

- MA.912.A.2.1 - Create a graph to represent a real-world problem.
- MA.912.A.2.2 - Interpret a graph representing a real-world situation.
- MA.912.A.2.7 - Perform operations (addition, subtraction, division, and multiplication) of functions algebraically, numerically, and graphically.
- MA.912.A.2.8 - Determine the composition of functions.
- MA.912.A.2.12 - Solve problems using direct, inverse, and joint variations.
- MA.912.A.1.13 - Solve real-world problems involving relations and functions.

#### **Algebra - Standard 10: Mathematical Reasoning and Problem Solving**

- MA.912.A.10.1 - Use a variety of problem-solving strategies, such as drawing a diagram, making a chart, guess-and-check, solving a simpler problem, writing an equation, and working backwards.

## Series and Parallel Circuits

**array** - a mechanically integrated assembly of modules or panels together with support structure to form a unit that produces DC power

**parallel circuit** - a type of electrical circuit in which the current is divided into two or more paths and then returns via a common path to complete the circuit

**photovoltaic cell** - the smallest, basic photovoltaic device that generates electricity when exposed to light. Cells can range in size from microscopic to 8 inches square.

**photovoltaic panel** - photovoltaic modules connected together electrically to provide a single output

**series circuit** - a type of electrical circuit in which the current passes through each circuit element in turn without branching

## Series and Parallel Circuits

The module that you have been working with is probably composed of several individual cells wired together. The output generated by an individual solar cell is too small to be useful in most applications, so several cells are connected together to create more current or voltage. In this investigation, you will look at electric circuits wired in two different ways, **series** and **parallel**, to see how wiring several cells together affects their output.

### Array Tilt Angle & Solar Azimuth

Complete the necessary background data.

Date \_\_\_\_\_ Time \_\_\_\_\_ Daylight Savings Time? \_\_\_ yes \_\_\_ no

Latitude \_\_\_\_\_

Complete the solar azimuth and optimum tilt angle using the values from a previous activity, unless it is a different time of day or more than two weeks since you calculated these angles. If so, you will need to find the angles for the current day and time, and fill them in below.

Optimum Array Tilt Angle \_\_\_\_\_ Azimuth \_\_\_\_\_

### Single Photovoltaic Cell

1. Determine the power output and plot an I-V curve for a single photovoltaic cell to use as a control in this investigation. As before, data for I-V curves should be collected under clear skies within two hours of solar noon, solar cell temperature should be allowed to stabilize before taking measurements, and I-V curve data points need to be taken quickly to minimize the effect of changes in irradiance level.
  - Using a single cell, variable resistor (rheostat) and wires with alligator clips, assemble the test circuit as you did in previous activities, leaving the positive lead to the PV cell disconnected. As before, ask your instructor to check your circuit before continuing.
  - Determine the amount of solar irradiance using an insolation meter and record this value in the data chart.
  - Place your cell on the piece of cardboard, tape a thermometer next to it and place the cardboard unit so that the cell is in the optimum position both for tilt angle and the solar azimuth.
  - Record the beginning temperature in the data sheet.



- Connect the positive lead to the PV cell. Adjust the variable resistor to zero ohms (voltage reading should be zero), and record the short-circuit current  $I_{sc}$  in the data table.
- Increase the resistance until the voltage reading is approximately 1/4 of the estimated  $V_{oc}$ . Record the current and voltage readings. Increase the resistance to 1/2 and then 2/3 of the estimated  $V_{oc}$ , recording the current and voltage readings.
- As before, continue with smaller increases in resistance, recording the current and voltage for each, until the maximum resistance setting is reached or the current is zero.
- Disconnect the resistor from the test circuit (current becomes zero). Record the open-circuit voltage,  $V_{oc}$ .
- Record the ending irradiance and temperature readings.

	Irradiance (W/m <sup>2</sup> )	Cell Temperature (°C)
<b>Initial Measurement</b>		
<b>Final Measurement</b>		
<b>Average</b>		

Voltage (Volts)	Current (Amps)	Power (Watts)
<b>0</b>	$I_{sc} =$	
$V_{oc} =$	<b>0</b>	

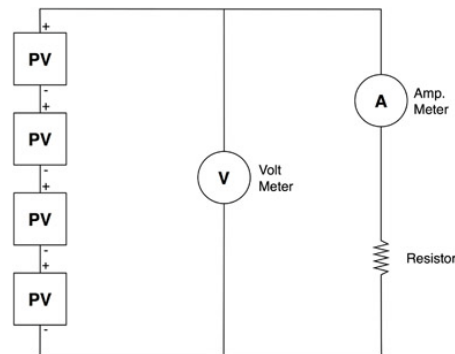
- Using the data you collected, plot the I-V curve on graph paper. Graph your power curve and use it to find the x-coordinate for the maximum power point ( $P_{mp}$ ) on the IV curve. Make sure to label both axis and title your graph. Your title should include the average temperature and irradiance reading you measured today.

3. Determine the power, voltage, and current at the maximum power point for the single cell I-V curve.

Single Cell:  $P_{mp} =$  \_\_\_\_\_  $V_{mp} =$  \_\_\_\_\_  $I_{mp} =$  \_\_\_\_\_

### Series Circuits

4. Hypothesis. What do you expect will happen when four individual cells are wired together? For the first trial, you will wire together the cells in series circuit--that is, with the positive lead from one cell connected to the negative lead of the next, and so on, alternating positive and negative connections in a circle.



Formulate a hypothesis estimating the possible voltage, current and power output of this series wired 'module'. Write your hypothesis below.

5. To test your hypothesis and determine the power output you need to plot an I-V curve for a 'module' of four cells wired in a series circuit. Complete the following procedure:
- Connect the four cells in series by connecting the positive end of one cell to the negative of another as explained above. Your multimeter is the final link in this chain. Using this assembly, and a variable resistor assemble this test circuit as in the single cell test above, leaving the positive lead at one end of your circuit disconnected.
  - Place your cells on the piece of cardboard. All cells should be at the same level, forming a 'module'. Tape a thermometer to the cardboard and place the cardboard unit so that the cells are in the optimum position both for tilt angle and the solar azimuth.
  - Connect the positive lead and collect your data in the same manner as you did with the single cell test and record your data below.

	Irradiance (W/m <sup>2</sup> )	Cell Temperature (°C)
<b>Initial Measurement</b>		
<b>Final Measurement</b>		
<b>Average</b>		

Voltage (Volts)	Current (Amps)	Power (Watts)
<b>0</b>	<b>I<sub>sc</sub> =</b>	
<b>V<sub>oc</sub> =</b>	<b>0</b>	

- Plot the data you collected in this trial plus the data from the single cell trial, creating a multiple line I-V curve on graph paper. Label or color code each curve. Graph the new power curve along with the single cell power curve, and use this graph to find the x-coordinates for the maximum power points ( $P_{mp}$ ). Make sure to label both curves, both axis and title your graph. Your title should include your average temperature and irradiance reading of the combined trials.
- Transfer the single cell data from the previous trial below and determine the power, voltage, and current at the maximum power point for the series I-V curve.

Single Cell:  $P_{mp} =$  \_\_\_\_\_  $V_{mp} =$  \_\_\_\_\_  $I_{mp} =$  \_\_\_\_\_

Series Circuit:  $P_{mp} =$  \_\_\_\_\_  $V_{mp} =$  \_\_\_\_\_  $I_{mp} =$  \_\_\_\_\_  
(Four cells)

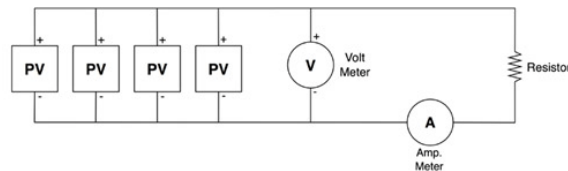
### Analysis

- What happened to the voltage when you changed from one cell to multiple cells connected in the series circuit?

9. What happened to the current when you changed from one cell to multiple cells in the series circuit?
10. Write a formula that you could use to figure the approximate ( $\approx$ ) current,  $I_{\text{total}}$ , and the approximate ( $\approx$ ) voltage,  $V_{\text{total}}$ , of a series circuit given the single cell voltage,  $V_A$ , single cell current,  $I_A$ , and number of cells in the series,  $X$ .
11. How did your test results compare with your hypothesis? If your results did not support your hypothesis, explain why.

### Parallel Circuits

12. Hypothesis. What do you expect will happen when the four individual cells are wired together in parallel—that is, with all the positive ends wired together in one branch and all the negative ends wired together in another branch?



Formulate a hypothesis concerning the voltage, amperage and power output of this parallel wired ‘module’ wired in a parallel circuit, and write it below.

13. To collect the data needed for your parallel wired ‘module’ as you did in the previous investigations:
  - Connect the four cells in a parallel circuit by connecting the positive ends together (clip one on top of the other) and all the negative ends together. Using this assembly, and a variable resistor set up the test circuit as in the single cell test above, leaving the positive lead of your circuit disconnected.
  - Place your cells on the piece of cardboard. All cells should be at the same level (or as close as possible with the wire length that you have), forming a ‘module’. Tape a thermometer to the cardboard and place the cardboard unit so that the cells are in the optimum position both for tilt angle and the solar azimuth.

- Connect the positive lead, collect your data in the same manner as you did with the previous trials and record it below.

	Irradiance (W/m <sup>2</sup> )	Cell Temperature (°C)
<b>Initial Measurement</b>		
<b>Final Measurement</b>		
<b>Average</b>		

Voltage (Volts)	Current (Amps)	Power (Watts)
<b>0</b>	<b>I<sub>sc</sub> =</b>	
<b>V<sub>oc</sub> =</b>	<b>0</b>	

- Using the data you collected in this trial plus the data from single cell trial, plot a multiple line I-V curve on graph paper. Graph the parallel power curve, and use it to find the x-coordinate for the maximum power point (P<sub>mp</sub>) on the parallel circuit IV curve. Make sure to label both curves, both axis and title your graph. Your title should include your average temperature and irradiance reading of the combined totals.
- Transfer the single cell and series circuit data from the previous trials and determine the power, voltage and current at the maximum power point for the parallel circuit I-V curve..

Single Cell: P<sub>mp</sub> = \_\_\_\_\_ V<sub>mp</sub> = \_\_\_\_\_ I<sub>mp</sub> = \_\_\_\_\_

Parallel Circuit: P<sub>mp</sub> = \_\_\_\_\_ V<sub>mp</sub> = \_\_\_\_\_ I<sub>mp</sub> = \_\_\_\_\_  
(Four cells)

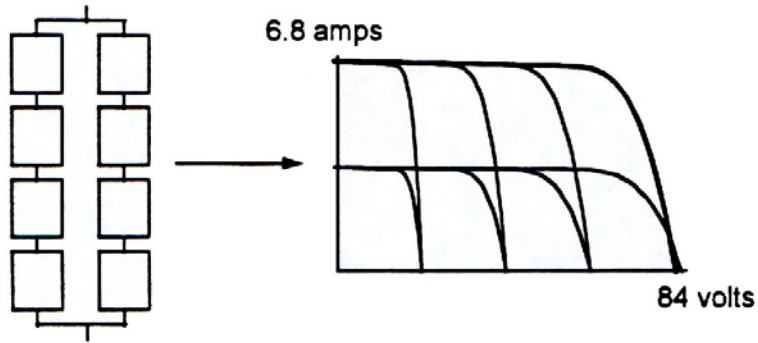
Series Circuit: P<sub>mp</sub> = \_\_\_\_\_ V<sub>mp</sub> = \_\_\_\_\_ I<sub>mp</sub> = \_\_\_\_\_  
(Four cells)

### Analysis

16. How did the voltage change from the single cell to the parallel circuit?
17. How did the current change from the single cell to the series connection?
18. Write a formula that you could use to figure the approximate ( $\approx$ ) current,  $I_{\text{total}}$ , and the approximate ( $\approx$ ) voltage,  $V_{\text{total}}$ , of a parallel circuit given the single cell voltage,  $V_A$ , single cell current,  $I_A$ , and number of cells in the series,  $X$ .
19. How did your test results compare with your hypothesis? If your results did not support your hypothesis, explain why.
20. When would it be useful to connect the photovoltaic cells in series?
21. When would it be useful to connect the photovoltaic cells in parallel?

### Combining Series and Parallel Circuits

If more voltage or current is needed than one module can produce is needed, modules can be connected in a combination of series and parallel circuits to achieve practically any final voltage and current. For example, in the diagram below, there are eight modules with a individual output of 3.4 amps and 21 volts each. Two sets of four modules are connected in series to make two 84 volt strings, and then the two strings are connected in parallel to increase the current output to 6.8 amps. A sketch of the composite curve for the entire 8-module array is also illustrated.



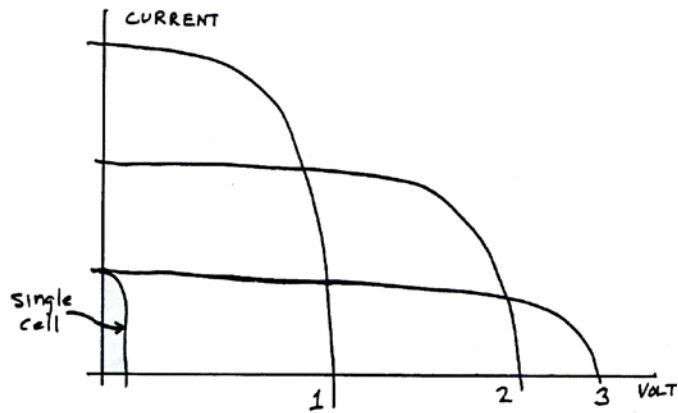
22. Sketch below a composite I-V curve that represents an array of six modules, with two strings of three modules each connected in series, and then these two strings connected in parallel.
23. How is the module that you used in the last three photovoltaic activities (*Power Output, Orientation, and Irradiance/Temperature*) wired? Explain how you came to that conclusion.

## Series and Parallel Circuits

1. Wiring multiple photovoltaic cells in a series circuit will \_\_\_\_\_ and \_\_\_\_\_.
  - a. increase the current
  - b. increase the voltage
  - c. keep the current the same
  - d. keep the voltage the same
  
2. Wiring multiple photovoltaic cells in a parallel circuit will \_\_\_\_\_ and \_\_\_\_\_.
  - a. increase the current
  - b. increase the voltage
  - c. keep the current the same
  - d. keep the voltage the same
  
3. A photovoltaic panel has three modules connected in series, each module having an open-circuit voltage ( $V_{oc}$ ) of 20 volts and short-circuit current ( $I_{sc}$ ) of 5 amps. What should the  $V_{oc}$  and the  $I_{sc}$  be for the complete panel?
  - a. 20 volts, 15 amps
  - b. 40 volts, 5 amps
  - c. 40 volts, 10 amps
  - d. 60 volts, 5 amps
  - e. 60 volts, 15 amps
  
4. How does the I-V curve for multiple PV modules connected in series differ from the I-V curve for multiple PV modules connected in parallel? Draw sketches for both cases.



5. The sketch of an I-V curve for a single solar cell and for individual modules made from that cell are shown below. (Note: All curves are shown at standard conditions.)



Match the number (on the X axis as the 'curve' number ) with the questions below. A curve may be used to answer more than one question.

- Which curve has the most cells in series?
- Which curve has the fewest cells in series?
- Which curve has two strings of cells in parallel?
- Which curve has the most strings of cells in parallel?