schoolgen
Power to the next generation

INVESTIGATING THE PERFORMANCE OF PHOTOVOLTAIC CELLS

Teacher-led Activity

In this activity, the students will investigate the effects of load resistance on power output, estimate the efficiency of conversion of solar energy to electrical energy, and look at the variations in output.

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1. LEARNING AREAS:

Science, Physics, Technology

2. CURRICULUM LEVELS: 7–8

3. AIM OF THE ACTIVITY

The students will investigate the performance of photovoltaic cells. In particular, they will:

- Investigate the effects of load resistance on power output and to plot a current-voltage (I-V) curve
- Estimate the efficiency of conversion of solar energy to electrical energy
- Use the photovoltaic module to investigate the inverse square law of radiation from a light source
- Look (qualitatively only) at the variation in output with inclination of the photovoltaic module to incoming light.

4. INTENDED LEARNING OUTCOMES

The students will be able to:

- Explain the effects of various parameters including distance from source, load resistance and orientation on the output of a solar cell
- Design and connect a simple electrical circuit and use a multimeter to measure the potential difference (voltage) across a component (in this case a resistance)
- Make measurements and record data with appropriate uncertainties, and analyse and evaluate the data collected.

5. WHAT YOU NEED

- A small photovoltaic module e.g. a 100 mm diameter module. Try www.solarworld.com for solar modules and educational kits.
  It can be mounted on a wooden block with a hinge to enable adjustment of the angle to the horizontal (See Figure 1)
- A multimeter (a mains operated one is fine indoors, but a battery operated portable meter is easier if the experiment is taken outdoors)
- A set of resistors or decade resistance box, ideally from 1–200 Ω
- Incandescent light bulbs of different powers e.g. 45, 60, 75, 100, 150 W

Figure 1
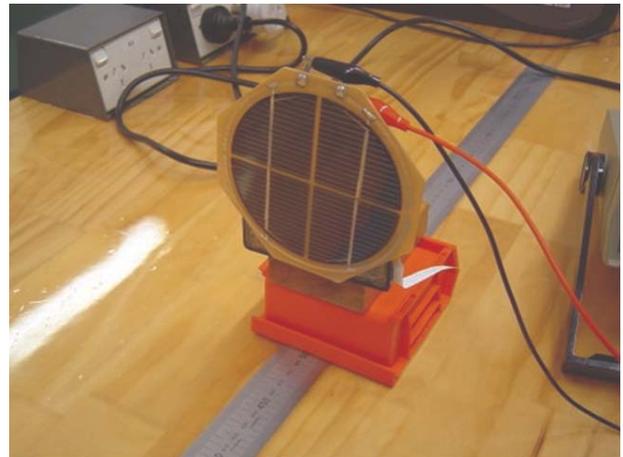
- A bulb holder and/or angle poise or similar adjustable lamp
- Connecting wires and plugs
- A meter rule
- A ruler and protractor.

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The results using the photovoltaic module described above are compiled in the [Teacher's Answer Guide and Sample Data](#). This guide also contains answers to the activities in each experiment.

The students may also want to refer to [Keywords and Glossary Terms](#).

6. FOCUS

A photovoltaic cell converts light energy to electrical energy. Ask the students questions like:

- How is energy carried by light (photons)?
- How is light absorbed in absorbed in conventional silicon-based photovoltaic cells?
- How does an electrical current flow?
- What happens to the light energy that is not transformed to electricity?

7. MANAGING THE ACTIVITIES

Experiment 1: Power Output vs Load Resistance and Current-Voltage Curves
The manufacturers specify the short circuit current and open circuit voltage of photovoltaic cells/modules: these refer to the hypothetical situations of the photovoltaic cell in circuits with zero and infinite resistance respectively.

Ask the students to find out the quoted short circuit current and open circuit voltage for your photovoltaic cell or module.

Part A: Variation of Output Power with Load Resistance
When the photovoltaic cell is placed in a real circuit, with finite "load" resistance, R, its output varies with R. For a given illumination (incident power) the output power is maximum for some optimum value of R.

Ask the students to:

(i) Place the 100 W bulb in the bulb holder or lamp, and position it 50 cm from the photovoltaic module (see Figure 2)
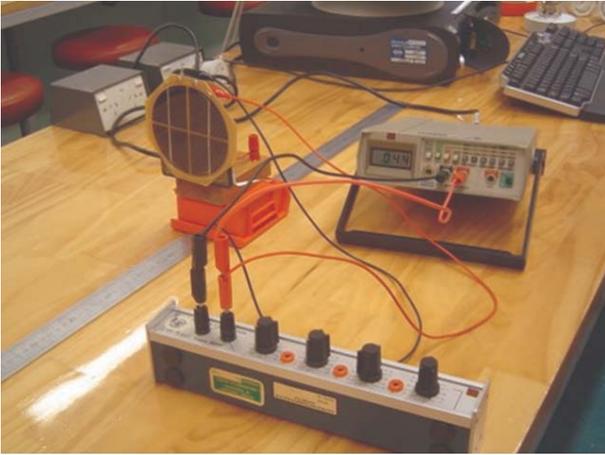
Figure 2
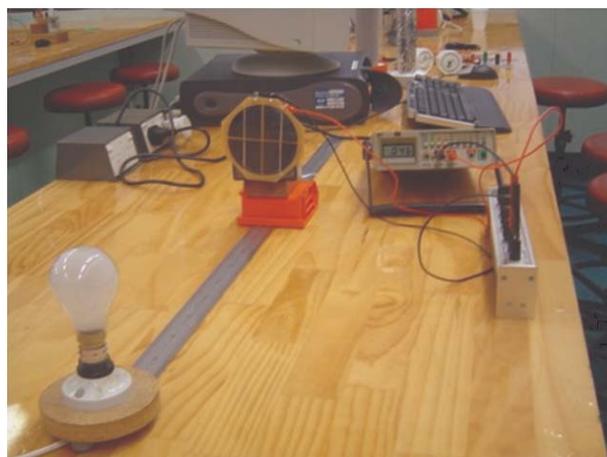
(ii) Set up a circuit with the solar cell driving a current through a resistance R. Use the multimeter, on the voltage setting, to measure the voltage (potential difference) developed *across* R (see Figure 3)

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Figure 3

(iii) Make up a table like the one below to record values of R and V, and to calculate (using Ohm's Law) the current, I, through R and the power, P, dissipated in R

R (ohms)	V (volts)	I (amps)	P (watts)
5			
6			
7			

(iv) Make and record measurements of V, for R = 10, 20, 30 ... 200 Ω

(v) Complete the calculations of I and P for each value of R

(vi) Plot a graph of power output, P, against load resistance, R

(vii) Use the graph to determine the maximum power output, P_{max}, and the load resistance, R_{opt}, at which maximum power is obtained

(viii) Estimate the precision (uncertainty) with which they can determine P_{max} and R_{opt}.

Part B: I-V Curves

For many common types of power supply the optimum load resistance is constant and is equal to the internal resistance of the supply (it is a nice exercise to prove this). However, with a photovoltaic cell, R_{opt} varies with the input power (= power of the incident light). The characteristics of a particular photovoltaic cell or module are usually described in terms of a set of I vs V curves for different input powers or levels of illumination.

Ask the students to:

(i) Plot a graph of current, I (vertical axis) against output voltage, V (horizontal axis) for the results they have just obtained. Add a legend noting the power rating of the light bulb they used and its distance from the photovoltaic cell/module

(ii) Plot a second graph of power, P against voltage, V

(iii) Repeat the experiment above with a different light bulb (say 60W), keeping the distance between the light bulb and the photovoltaic module the same as before

(iv) Plot the P-R, I-V and P-V curves for this second experiment on the same graphs, using the same axes, scales etc, as before

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(v) Estimate, with uncertainties, the optimum resistance and maximum power output for this illumination. Are the results significantly different from their first results?

Part C: Estimate of Efficiency
Ask the students to:

(i) Estimate the efficiency with which the photovoltaic cell converts energy from the incident light into electrical energy, at the load resistance corresponding to maximum power output for each of the sets of data you have collected

$$\text{Efficiency} = \frac{output\ power}{input\ power} \times 100\%$$

Estimate the power falling on the cell from the lamp:
(a) calculate the energy radiated per second, assuming that the light bulb converts its input energy entirely to electromagnetic radiation
(b) calculate how much of this energy is incident on the photovoltaic cell, if it radiates uniformly in all directions.

(ii) Consider the assumptions made in this estimate, and assess whether the assumptions are reasonable

(iii) Consider differences to the experiment if the students had used sunlight. Would they expect a similar efficiency in sunlight? Why or why not? (To answer this the students will need to understand a bit about how the solar spectrum and the solar cell works, see student fact sheet: Photovoltaic System Technology.)

Experiment 2: Operation in Sunlight
To test the solar cell in sunlight the students will need to take the solar panel, multimeter and appropriate load resistance outdoors on a cloudless, sunny day.

Part A: Estimate of the Solar Power Flux
Ask the students to:

(i) Position the solar panel so it is approximately facing the sun, then adjust its orientation carefully to maximise the output voltage
(ii) From the voltage, calculate the corresponding output power
(iii) Calculate the incident power on the module if the efficiency was the same as that calculated in Experiment 1
(iv) Use this to estimate the power flux (power per square metre) reaching the surface of Earth today
(v) Compare this with the Solar Constant, 1415 W/m2, which is the power flux incident at the top of Earth's atmosphere.

Part B: Effect of Orientation of the Solar Module
Investigate how the output voltage and power vary with the orientation of the module with respect to the incident solar radiation. (For various reasons, it is difficult to make this into a meaningful, quantitative experiment. However, it is well worthwhile demonstrating that the voltage and power output are maximum for normal incidence and decrease

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monotonically as the module is rotated so as to present a smaller cross sectional area to the solar radiation.)

Experiment 3: An Investigation of the Inverse Square Law of Radiation
The photovoltaic module can be used to construct an experimental investigation of the inverse square law of radiation from a light bulb.

Part A: Test of Hypothetical Linear Relationship Between Output Voltage and Incident Power for a Chosen Load Resistance
First, it is necessary to test the hypothesis that there is an approximately linear relationship between output voltage and incident power. (This is counterintuitive: one might expect the output *power*, rather than voltage, to vary linearly with input power, for example, constant efficiency; however, as we have demonstrated, the characteristics of a photovoltaic cell change as the incident power is varied, and this means that the efficiency (output power/ input power) is not necessarily a constant.)

Ask the students to:
(i)   Connect up the circuit they used in Experiment 1, with R set to the optimum value R_{opt} that was determined for a 100 W light bulb at 50 cm away
(ii) Measure and record the output voltage, V, for each of the light bulbs available. For this experiment the light bulb should be in a lamp holder, so that it radiates uniformly in all directions. Keep the distance between the light bulb and the

photovoltaic module at 50 cm, and make sure that the module is always facing directly towards the light bulb, so the light strikes it at 90° (normal incidence)
(iii) Plot a graph of output voltage, V, against light bulb rating (45, 60, 75, 100 W etc)
(iv) Evaluate the linearity of data. This is readily done in Excel, where a linear regression facility is available, which includes the calculation of the "R2" parameter. (Students should be familiar with the interpretation of R2.)
This evaluation assumes that the power incident on the photovoltaic module is proportional to the rating of the light bulbs. Is this reasonable? Why or why not?

Part B: Investigation of the Variation of Incident Power with the Distance Between the Photovoltaic Module and the Light Source
(i)   For a given light bulb (say 100 W), and keeping R as above, measure and record V as the distance of the photovoltaic module from the light bulb is increased from 20 to 100 cm at 10 cm intervals
(ii) Make up a table of d, V, $\log_{10}d$ and $\log_{10}V$, as shown below:

d (cm)	V (volts)	$\log_{10}d$	$\log_{10}V$
20			
30			
40			

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(iii) Plot a graph of $\log_{10}V$ (vertical axis) against $\log_{10}d$ (horizontal). Does the data lie on a straight line? Would the linearity be improved by ignoring some of the data? If so, which and what is a reason why these points might be unreliable?

(iv) Calculate the gradient of the best line fitted to the reliable data points

(v) Estimate an uncertainty in the gradient

(vi) Consider whether the experiment supports the inverse square law of radiation. (Ask the students to explain their reasoning carefully!)

8. REFLECTION
Different photovoltaic modules have different characteristics. If using a different module from the one tested, you may need to vary the resistances etc used in these experiments.

9. EXTENSION
Get the students to research the development of new photovoltaic technology. Try these websites to get them started:
 www.pvresources.com/en/
www.epia.org - European Photovoltaic Industry Association

10. SAFETY GUIDE
The electrical voltages and currents generated in this experiment are very small and pose no safety hazard. Nevertheless, all electrical equipment should be treated with care.

11. RESOURCES
- Student fact sheet: Photovoltaic System Technology
- Teacher's Answer Guide and Sample Data

The following are defined in Keywords and Glossary Terms: current, efficiency, electrical energy, incident power, inverse square law, linear regression, load resistance, multimeter, Ohm's law, open circuit voltage, photons, photovoltaic (PV) cell, photovoltaic module, power, power dissipated in resistor, resistance, short circuit current, solar constant, voltage

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Relevant Equations

Ohm's Law: $V = IR$

Power dissipated: $P = VI = \dfrac{V^2}{R}$

$\text{Efficiency} = \dfrac{Output\ Power}{Input\ Power}$

$\text{Power flux} = \dfrac{Incident\ Power}{Area\ Perpendicular\ To\ Radiation}$