MODULE V

Topic 1

Summary

Lesson title	
Solar cells efficiency	
Duration	90 min
Proposed student's age range	10 – 14

Lesson summary

The aim is to test how much sun energy a solar cell can capture. It will be placed under the sunlight, and voltage and current measurements will be taken to calculate the maximum power and the power provided to a small fan.

Learning outcomes

Purpose/Learning Objective

- Students are taught how sun energy is transformed into electricity.
- Understand the concept of solar cell efficiency and how to measure it.
- Verify how solar cells are arranged to increase the power they provide.

Intersecting objectives

- Understanding how photovoltaic modules work
- Learn how to measure voltages and currents in an electrical circuit

Connection to SDGs

This lesson is aligned with ODS 7: “It´s about ensuring access to clean and affordable energy, which is key to the development of agriculture, business, communications, education, healthcare and transportation.”-Target 7.2 By 2030, substantially increase the share of renewable energy in the global energy mix.

Implementation

Facilitation

- A day with a clear and very sunny sky should be selected, and the activity in the central hours (with the sun at the zenith) or 100-watt incandescent lamps should be available indoors.
- It is recommended that groups of 4 or 5 be formed to carry out this activity.
- Before the lesson, it should be ensured that all materials are ready (solar cells, fans with wires, banana plugs, etc.; soldering may be necessary to connect the plugs).
- To make the measurements outside, tables or a suitable place to set up all the materials will be needed.

Resources required

Materials for each group of students (see Figure V.1.1):

- Two solar cells (better with wires already laid out) (like that)
- One multimeter to measure volts and amps (DC)
- Sunlight or other strong light source, such as a 100-watt incandescent bulb
- One small USB fan (run on 5 volts) or any small motor 5 volts DC as used with Arduino, with red and black wires to connect it (soldering may be necessary)
- Banana plugs or alligator clips (three red and three black) for the wires of solar cells and fan
- Metric ruler
- Calculator, paper, and pen.
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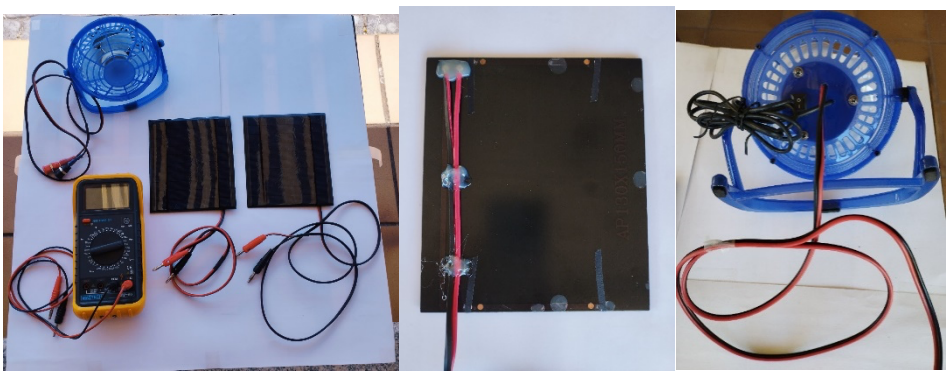


Figure V.1.1. Materials for each group of students

Ideas for follow-up

- Test the effect of shading on solar cells by measuring their voltage and current with different portions of the cells shaded.
- Visit a photovoltaic installation and check how much electricity it produces.

Source / Materials & class preparation

- This activity is based on https://www.exploratorium.edu/snacks/output-solar-cell, created by Exploratorium Teacher Institute, licensed under Creative Commons Attribution-Noncommercial-ShareAlike 4.0. (https://creativecommons.org/licenses/by-nc-sa/4.0/)

To learn about solar photovoltaic

- Energy Kids is a student-friendly website hosted by the U.S. Department of Energy, Energy Information Administration (EIA). The site includes a variety of information and activities about energy.

To learn about voltage and current

- BBC Bitesize is a free online study support resource designed to help with learning, revision, and homework. Bitesize supports learners aged 5 to 16+ across various school subjects.

Lesson Outline

Timing	Instructions step-by-step
20 min	**Introduction** What is a solar cell, how does it work, what is voltage and current, and how can we measure them?
15 min	**Voltage and current measurements (Voc, Isc)** Place one solar cell in direct sunlight and measure its voltage (V) and current (I) with a multimeter. Place the solar cell upside down (avoiding sunlight) and measure the voltage and current. Orient the solar cell until you obtain the maximum voltage value, at which point the sun's rays hit the cell's surface perpendicularly. Now, measure the voltage value; this value is called Voc. Repeat the same procedure to measure the current, and this value is called Isc. Calculate maximum power (Voc x Isc)
15 min	**Voltage and current measurements with a load (Vload, Iload)** Connect the two wires of the solar cell to the two wires of the fan Flip the solar cell face-up and notice how the fan spins in the sun. Tilt the solar cell to maximise motor speed. Measure the voltage across the motor as it runs at maximum speed. Then, set the multimeter to measure current and connect it in a single loop with the motor and solar cell Calculate power delivered to the load (Pload=Vload x Iload)
10 min	**Calculate the solar cell's efficiency** Use a ruler to measure the active area, A, of your solar cell Calculate the solar power arriving at the solar cell by multiplying the intensity of the sun (1000 W/m^2) by the area of the solar cell Calculate the maximum efficiency and the actual efficiency with the fan connected.
15 min	**Maximise the power. Two cells in a series** Connect the positive terminal of one cell with the negative terminal of the other. Measure the voltage using the other two terminals of the cells. The total voltage should be approximately the sum of the voltages of each cell. With this arrangement, change the terminals of the multimeter to measure current. The series's current should be approximately equal to the current of one cell. With this arrangement, you will get double the power because you get double the voltage.

15 min	**Maximise the power. Two cells in parallel** Connect the positive terminal of one cell to the positive terminal of the other, and do the same with the negative terminals. Then, connect the multimeter in parallel to measure the voltage. The voltage of the parallel should be approximately the same value we had with only one cell. With this arrangement, the terminals of the multimeter are changed to measure current. The current of the parallel should be the sum of the current of the two cells. With this arrangement, you will get double the power because you get double the current.

Formative assessment
Methodologies to be used: Classroom observations and questionnaires.

Feedback

Net Promoter Score (NPS) is a widely used metric to gauge the loyalty and satisfaction of customers or, in an educational context, students. It measures the likelihood of the students recommending the lesson or course to others. Here is how you can describe and implement NPS:
Develop the NPS Question:

- Primary Question: "On a scale of 0 to 10, how likely are you to recommend this lesson to other students?"
- Follow-up Questions: "Why did you choose that score?" and "How can we improve this lesson?"

Collecting Responses:
A template for collecting feedback using paper surveys is shown in the Annexes.

- Digital Surveys: Use online tools like Google Forms, SurveyMonkey, or Typeform to distribute the NPS questions to students.
- Paper Surveys: Hand out paper questionnaires at the end of the lesson for students to fill out.
- Interactive Applications: Utilize interactive apps like Quizziz, Mentimeter, or Kahoot! to gather real-time responses.

Classifying Responses:

- Promoters (Score 9-10): Students who are highly satisfied and likely to recommend the lesson.

- Passives (Score 7-8): Students who are satisfied but not enthusiastic can switch their opinions easily.
- Detractors (Score 0-6): Students who are dissatisfied and unlikely to recommend the lesson; may provide constructive criticism.

Calculating the NPS:

- Formula: NPS = % of Promoters - % of Detractors.
- Interpreting the Score: NPS ranges from -100 to +100. A positive score (above 0) is generally good, and a score above 50 is excellent.

Analysing and Using Feedback:

- Review additional comments to understand the reasons behind the scores.
- Identify patterns and specific areas for improvement from detractors and passives.
- Use positive feedback from promoters to reinforce successful aspects of the lesson.

Annexes

QUESTIONNAIRE TO COLLECT FEEDBACK ON THE LESSON

On a scale of 0 to 10, how likely are you to recommend this lesson to other students?

0	1	2	3	4	5	6	7	8	9	10

Not likely at all — Extremely likely

Why did you choose that score?

How can we improve this lesson?

QUESTIONNAIRE TO COLLECT MEASUREMENTS OF SOLAR CELLS

Fill in Table V.1.1 with the voltage and current measurements on a cell.

	Full sunlight	Poor light
Voc		
Isc		

Table V.1.1. Voltage and current measurements in a cell

Fill in Table V1.2. With the voltage and current measurements on a cell connected to the fan

	Full sunlight
Vload	
Iload	

Table V.1.2. Voltage and current measurements on a cell connected to the fan

Fill in Table V.1.3 with the power calculations

$$Power = VxI$$

	V	I	Power
Power max			
P actual			

Table V.1.3. Results of power calculations

Fill in Table V.1.4 with the efficiency calculations

$$Efficiency(\%) = \frac{Pout}{Psun} x100$$

	Area (A)	Psun	Pout	Efficiency (%)
Efficiency max				
Efficiency actual				

Table V.1.4. Results of efficiency calculations

Fill in Table V.1.5 with voltage and current measurements on two cells in series and parallel.

	Voc	Isc	Power
Series			
Parallel			

Table V.1.5. Results of voltage and current measurements on two cells in series and parallel

Supporting guide for teachers

Voltage measurement

Measure the open circuit voltage (Voc) across the solar cell. This is the voltage when no current is flowing through the cell. Since no current flows, a voltmeter measures the open circuit's voltage.

Set the multimeter to the DC voltage (V ⎓) scale to measure a few volts. Connect the common (COM) terminal of the meter to the negative terminal of the solar cell. Then, connect the meter's positive terminal to the solar cell's positive terminal.

Tilt and orient the solar cell until the maximum possible voltage value is obtained. Figure V.1.2 shows how to connect the multimeter. In this case, for example, we had a V = 5,68 volts in full sunlight.

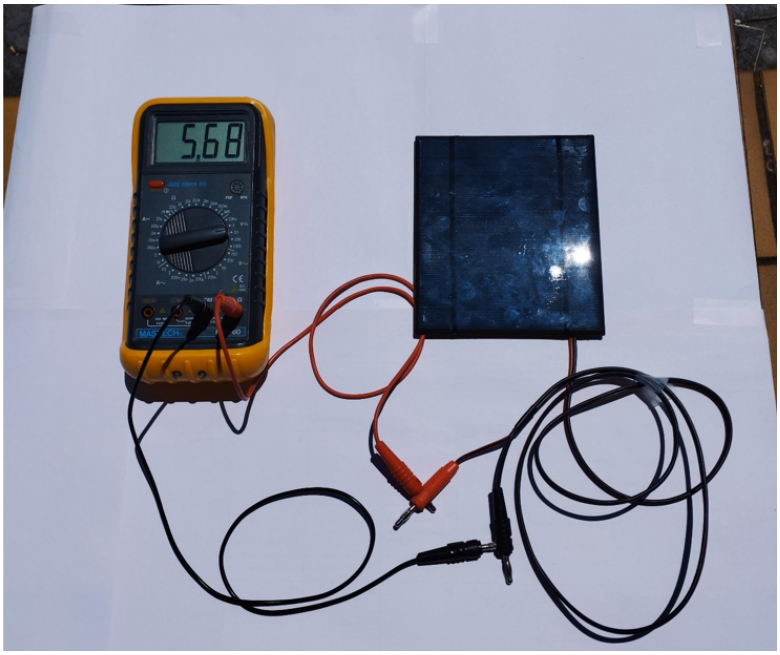


Figure V.1.2. Voltage Voc measurement

If we place the cell upside down, when it receives hardly any sunlight, the voltage measured in our case is 3.80 volts (Figure V.1.3)

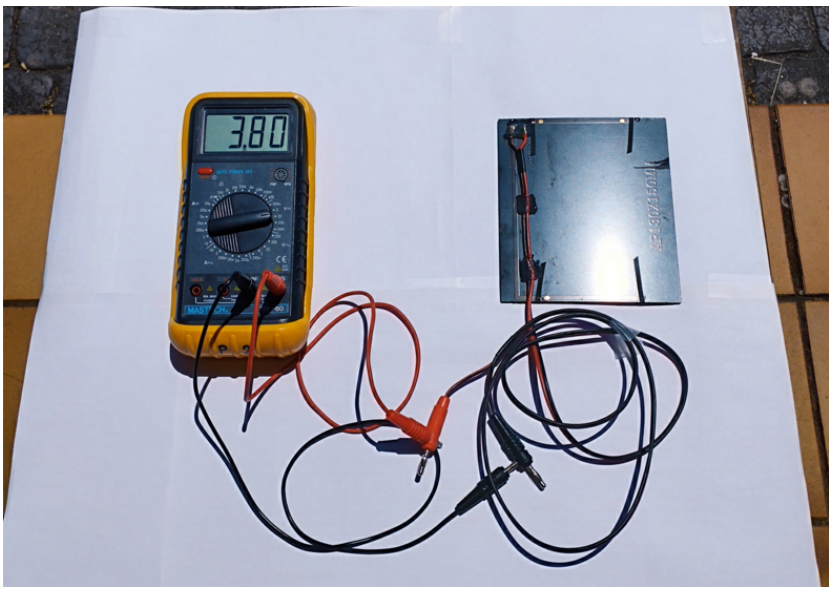


Figure V.1.3. Voltage measurement in poor light

Current measurement

Flip the solar cell face-up again so the light hits it directly and set the meter to “DC amperes” on a scale that will measure a few amperes of electrical current. Connect the common (COM) terminal of the meter to the negative terminal of the solar cell. Then connect the meter's positive terminal to the solar cell's positive terminal. Note that we need to move the positive terminal of the meter to a separate terminal for measuring amperes.

The maximum current that a solar cell can produce occurs when a wire is connected across the terminals. This is called the short-circuit current, or Isc. Like a wire, an ammeter has very low resistance, so it will register a measurement like a short circuit.

See Figure V.1.4 for the Isc through the solar cell. In our setup, the solar cell measured Isc = 0.508 amps in full sunlight (your results may vary).

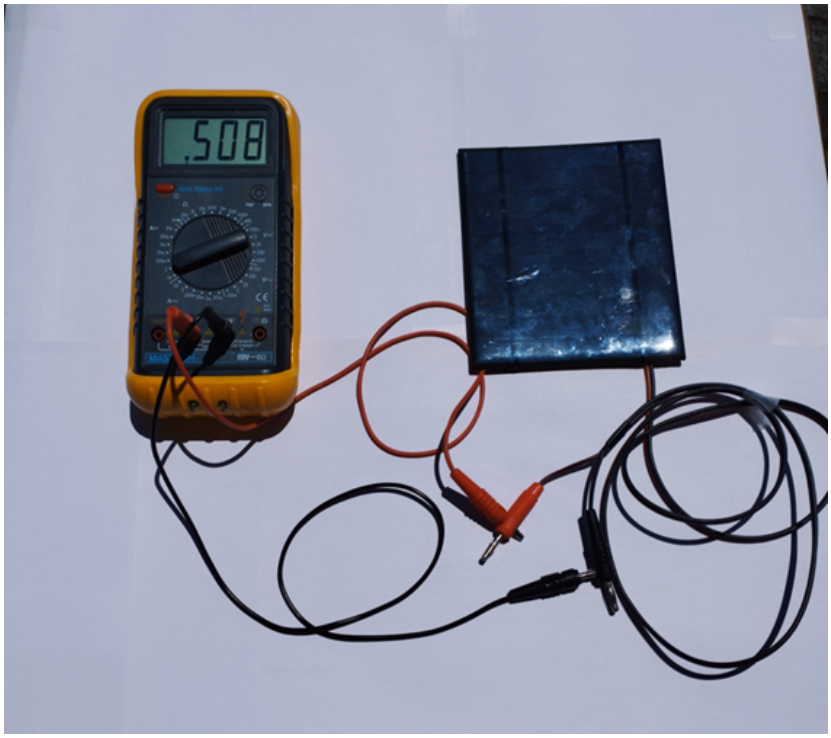


Figure V.1.4. Current Isc measurement

Try tilting the solar cell. How does the current change? See Figure V.1.5.

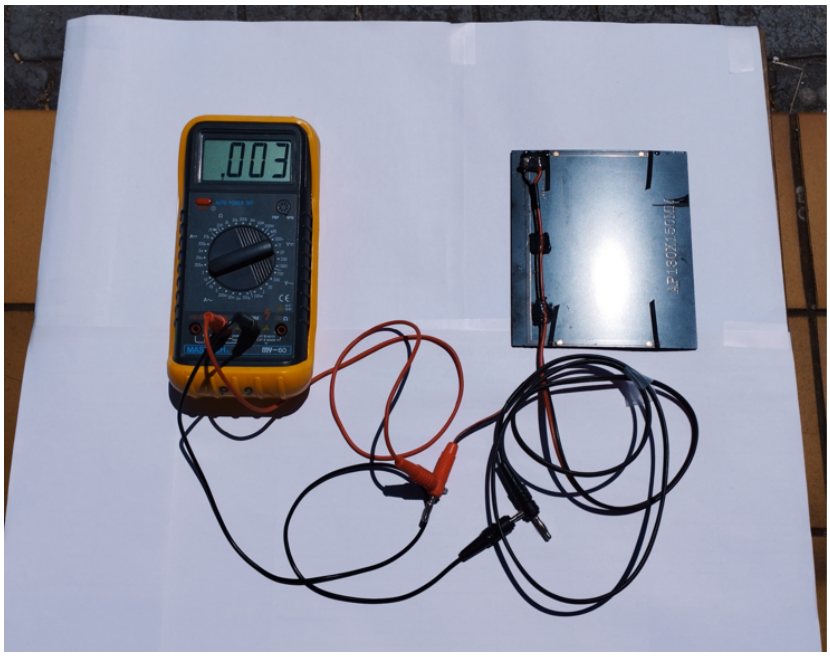


Figure V.1.5. Current measurement Isc in poor light

Power calculation

Connect the solar cell's two terminals to the fan's two terminals as shown in Figure V.1.6. Flip the solar cell face-up and notice how the fan spins when it's in the sun. Tilt the solar cell to maximise fan speed, then tilt it away from its maximum orientation. (Be careful not to shade the solar cell as you hold it.) Notice that the fan speed is greatest when the solar cell is oriented perpendicularly to a line from the sun to the solar cell.

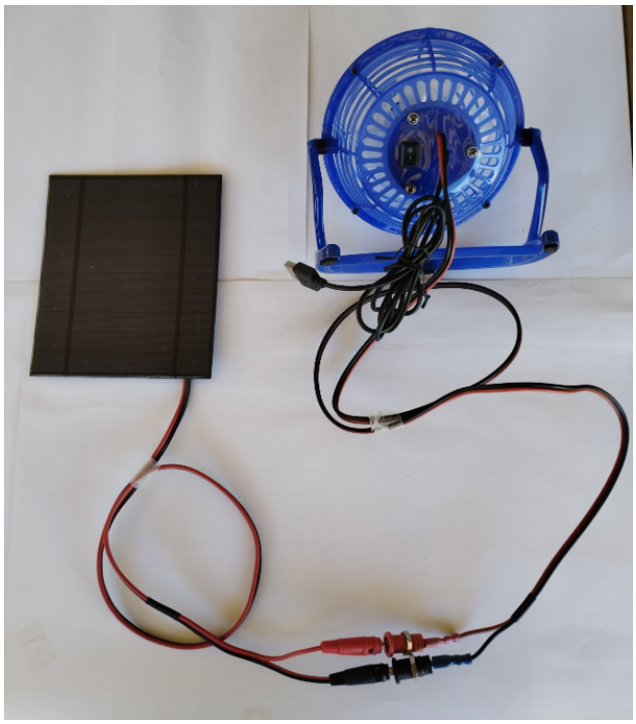


Figure V.1.6. Connection of the cell to the fan

Measure the voltage across the motor as it runs at maximum speed by connecting the meter as you did to measure voltage voc. This arrangement is referred to as having the meter in parallel, as shown in Figure V.1.7.

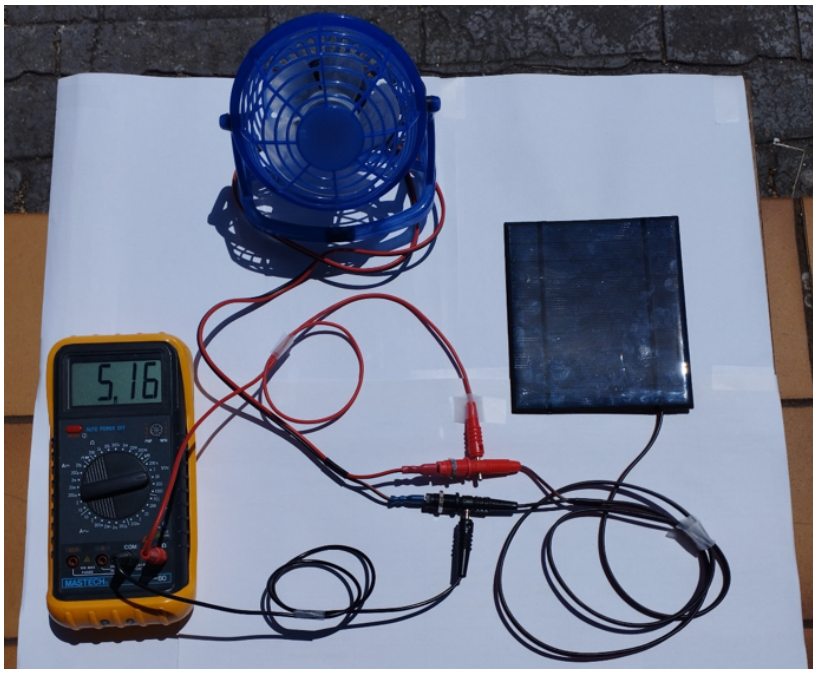


Figure V.1.7. Voltage V with the cell connected to the fan

Then, set the multimeter to measure current and connect it in a single loop with the fan and solar cell. This arrangement is called having the meter in series (see Figure V.1.8.)

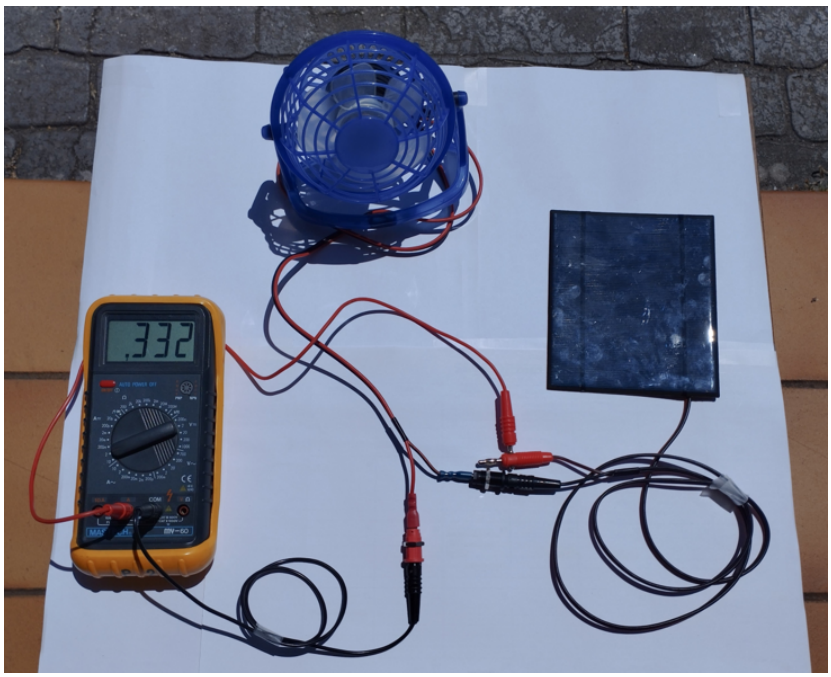


Figure V.1.8. Current I with the cell connected to the fan

Power calculations

The power of a solar cell is the product of the voltage across the solar cell times the current through the solar cell.

$$Power = VxI$$

The maximum theoretical power from our solar cell, Pmax, is the product of the Voc and Isc.

Pmax = 5,68 x 0,508 = 2,9 W

In practice, the actual power, Pactual, delivered by the solar cell to the fan, is equal to the voltage across the fan, Vload, times the current through the fan, Iload.

Pactual = 5,16 x 0,332 =1,7 W

Calculate the solar cell's efficiency.

The efficiency of the solar cell is the ratio of the electrical power obtained at its output to the solar power received at its input.

$$Efficiency(\%) = \frac{Pout}{Ps} x100$$

Here's how to calculate the efficiency of the solar cell:

First, calculate the solar power arriving at the solar cell by multiplying the sun's intensity by the area of the solar cell.

The solar intensity from the sun, Si, over a given area on the earth's surface, is different depending on the time of day and the state of the sky. In the central hours of the day with clear skies, it can be approximately 1000 watts/m2. This is the value that is used to define the efficiency and power of solar modules.

Use a ruler to measure the active area, A, of your solar cell (see Figure V.1.9).

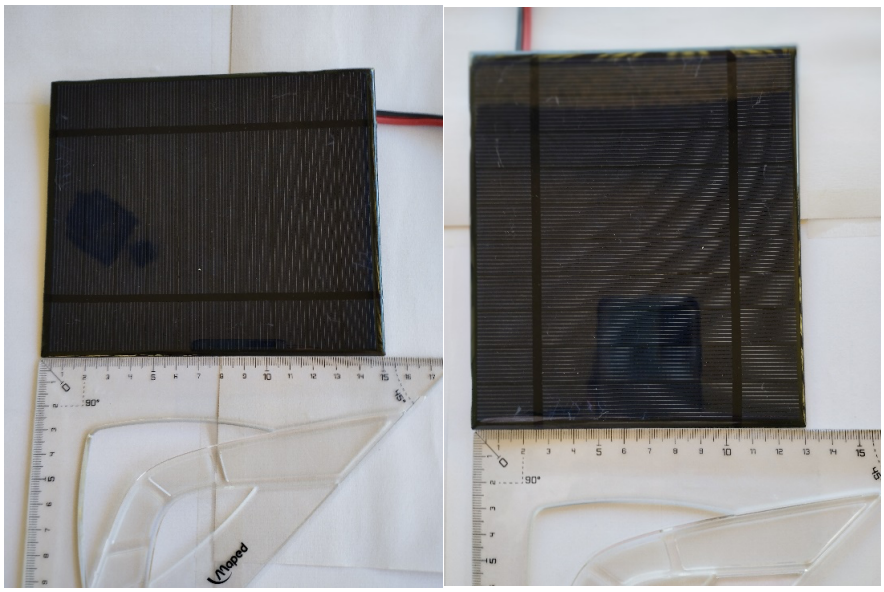


Figure V.1.9. Solar cell size

The cells in this experiment measured 13 cm by 15 cm.

$$A = 13\ cm \times 15\ cm = 195\ cm^2 = 0{,}0195\ m^2$$

The solar power, P_s, intercepted by a cell this size is

$$Ps = 1000\ W/m^2 \times A\ (m^2) = 1000 \times 0{,}0195 = 19{,}5\ W$$

The maximum theoretical efficiency of the solar cell is estimated to be

$$Efficiencia(\%) = \frac{Pmax}{Ps} x100 = \frac{2{,}9}{19{,}5} x100 = 14{,}9\%$$

The actual efficiency of the solar cell when providing power to the fan was:

$$Efficiencia(\%) = \frac{Pactual}{Ps} x100 = \frac{1{,}7}{19{,}5} x100 = 8{,}7\%$$

Maximise the power

An important engineering challenge is to maximise the power delivered to the fan using solar power. One way to do this is to combine two solar cells in series or parallel. This is done in a solar module, combining several cells to obtain more power.

Two cells in a series

Connect the positive terminal of one cell with the negative terminal of the other. Measure the voltage using the other two terminals of the cells (see Figure V.1.10).

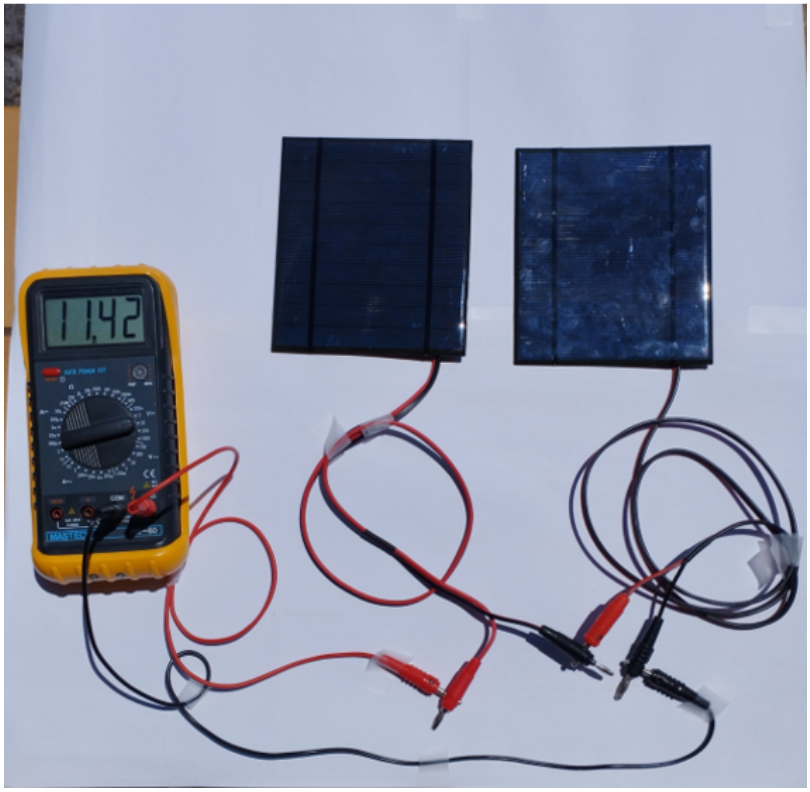


Figure V.1.10. Voltage measurement of 2 series-connected cells

The total voltage is the sum of the voltages of each cell; in this case, we had 11,42 volts. Remember that the voltage measured before from one cell was 5,68 volts.

With this arrangement, change the terminals of the multimeter to measure current. The current of the series is equal to the current of one cell. In this experiment, we had 0,527 amps, only a bit more than the Isc current, because of better sunny conditions (Figure V.1.11).

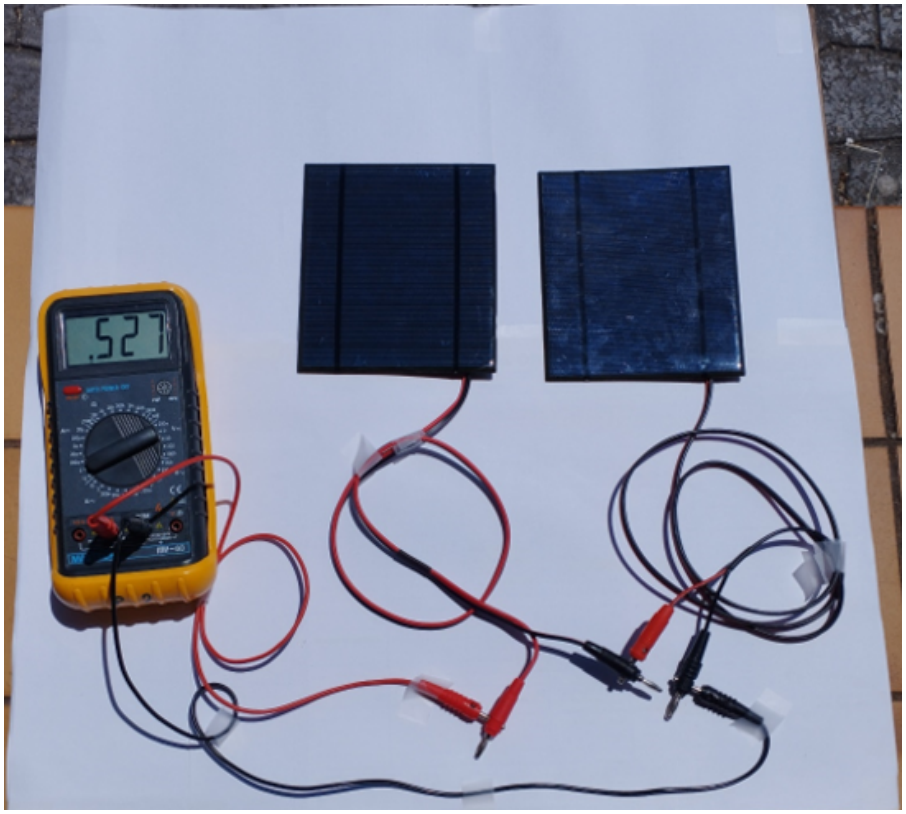


Figure V.1.11. The current measurement of 2 cells connected in a series

The power of the two cells connected in series was therefore:

Power series = 11,42 x 0,527 = 6 W

Since we have twice the voltage, we get twice the power.

Two cells in parallel

Connect the positive terminal of one cell to the positive terminal of the other, and connect the negative terminal of one to the negative terminal of the other. Then, connect the multimeter in parallel to measure the voltage (see Figure V.1.12).

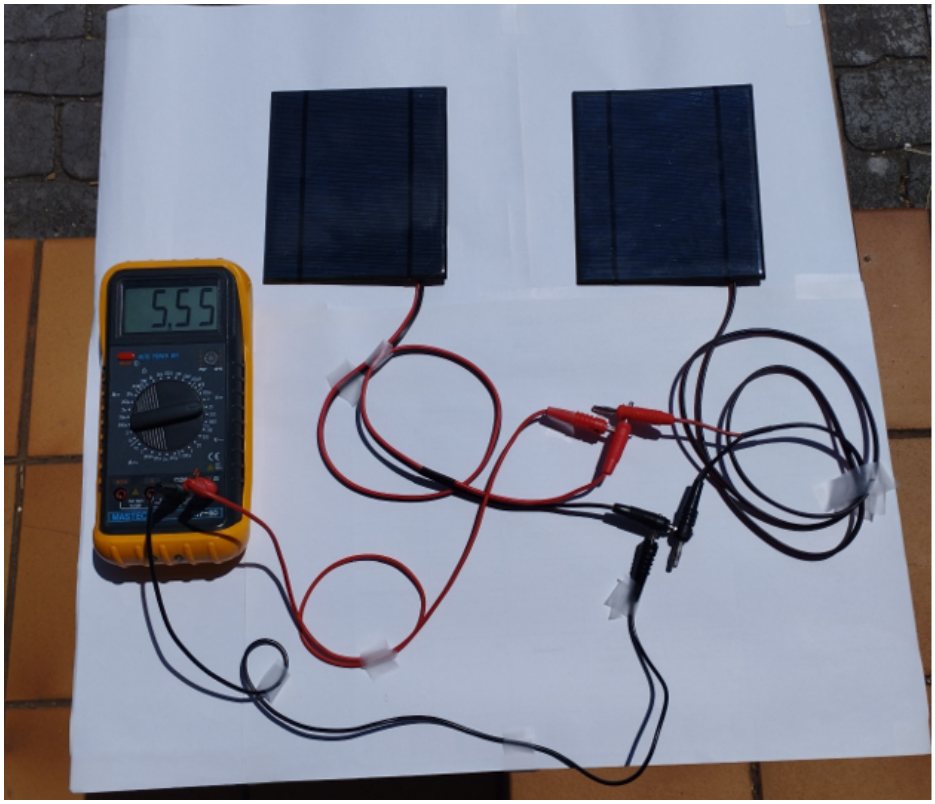


Figure V.1.12. Voltage measurement of 2 cells connected in parallel

The voltage of the parallel was 5,55 volts, approximately the same value we had with only one cell. With this arrangement, change the terminals of the multimeter to measure current. The current of the parallel is the sum of the current of the two cells. In this experiment, we had 1,1 amps (Figure V.1.13).

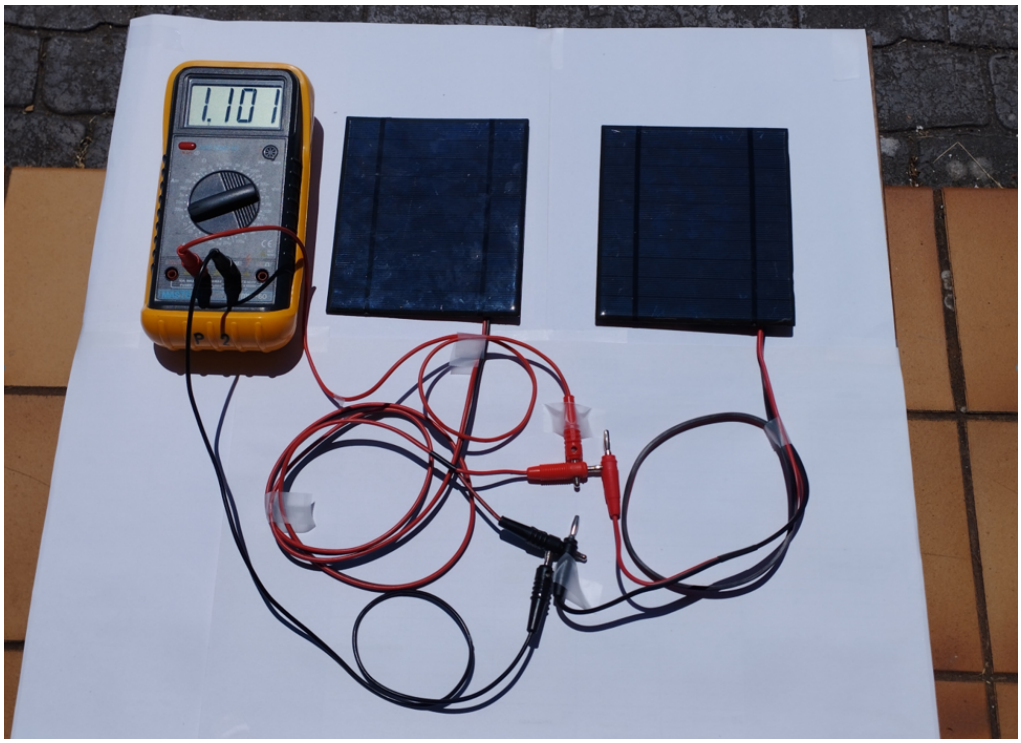


Figure V.1.13. The current measurement of 2 cells connected in parallel

The power of the two cells connected in parallel was therefore:

Power parallel = 5,55 x 1,1 = 6,1 W

With this arrangement, you will get double the power again.