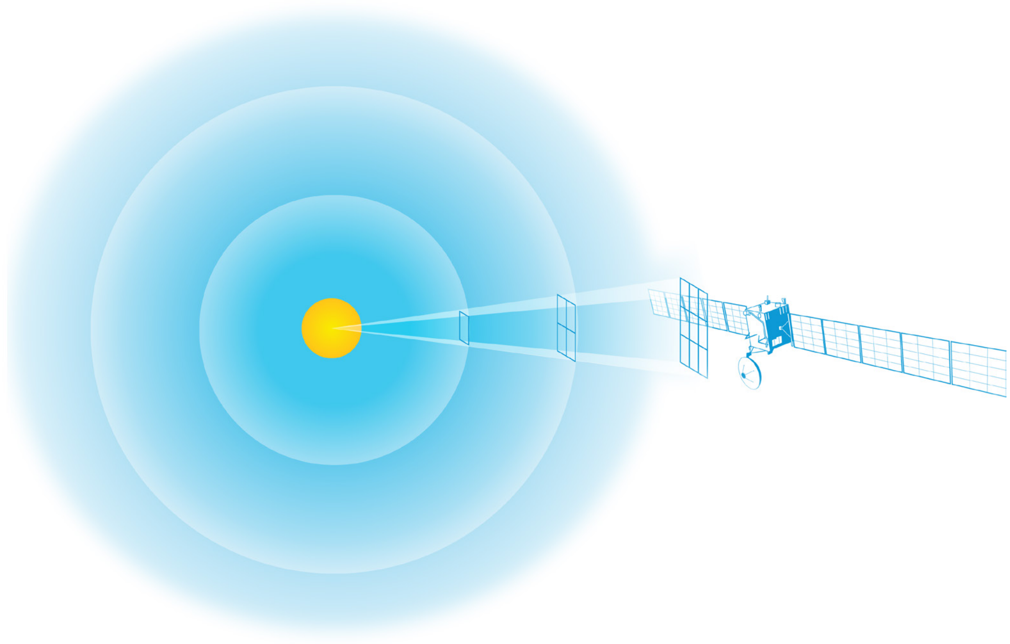
Physics | P09

teach with space

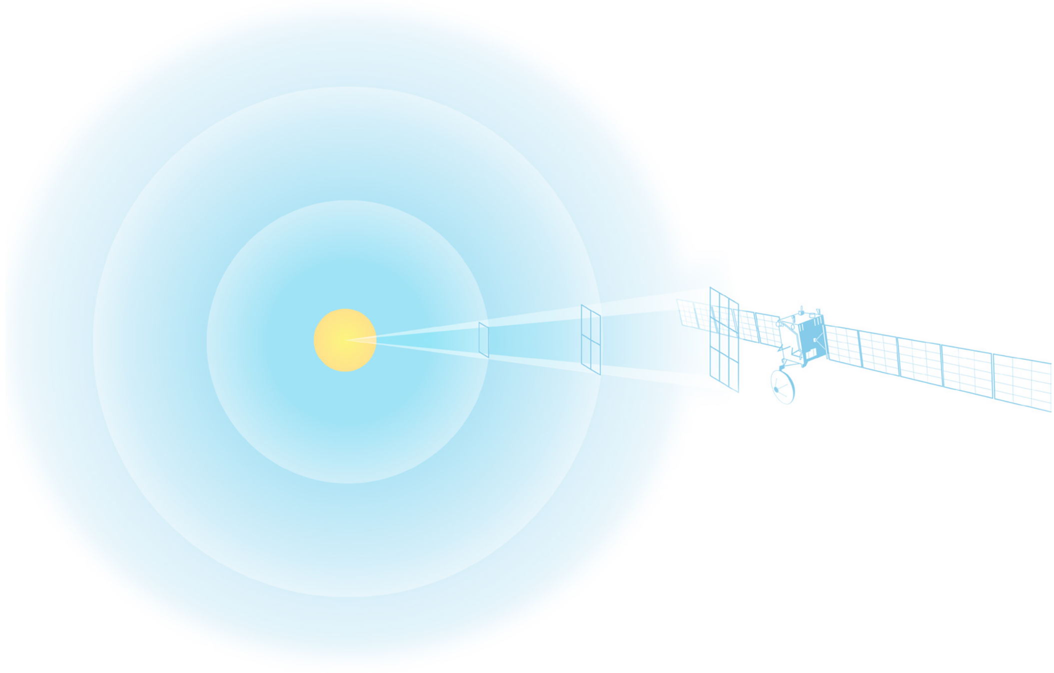
→ POWER FROM SUNLIGHT

Powering space exploration with solar energy



teacher guide & student worksheets

European Space Agency



Teacher guide

teach with space – power from sunlight | P09
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→ POWER FROM SUNLIGHT

Powering space exploration with solar energy

Fast facts

Subject: Physics
Age range: 14-18 years old
Type: student activity
Complexity: medium
Cost: low
Teacher preparation time: 1 hour
Lesson time: 1 hour and 30 minutes (plus 20 minutes to assemble the experiment)
Location: classroom
Includes use of: solar cells
Keywords: Physics, Solar power, Inverse square law, Light intensity, Angle of incidence, Solar system

Brief descriprion

In this set of activities, students will learn about two concepts that influence solar panel design for space missions: the inverse square law and the angle of incidence. Students will perform two simple investigations using a photovoltaic cell (solar cell) and a light source. First, they will measure how the power produced by the solar cells varies with distance from the light source and attempt to retrieve the inverse square law for light intensity experimentally. Students will then conduct a second experiment to investigate the dependence of the power output for the solar cell with the angle of incidence. Last, they will apply these concepts to real ESA space missions.

Learning objectives

- Understanding and calculating light intensity.
- Understanding the angle of incidence.
- Learning about solar cells.
- Perform hands-on experiments to investigate the inverse square law of light and the impact of the angle of incidence of light.
- Analysing and plotting data.
- Constructing simple electric circuits using solar cells.
- Learning about electric potential difference, electric current, power and light intensity.
- Investigating solar power requirements on space missions.

→ Summary of activities

Summary of activities					
	Title	Description	Outcome	Requirements	Time
1	The inverse square law	Studying the inverse square law of light intensity through an experiment.	Understanding the inverse square law and how it influences power output of solar cells.	None	20 minutes to construct the experiment 30 min for the activity
2	The angle of incidence	Investigating the angle of incidence through an experiment.	Understanding the angle of incidence and how it influences the power output of solar cells.	Completion of activity 1 is advised	30 minutes
3	Exploring space with solar power	Practise using the inverse square law on real ESA space missions.	Understanding advantages and disadvantages of solar power for space exploration.	Completion of activity 1 is advised	30 minutes

→ Introduction

Solar energy is often used to power space missions because it is the only source of energy that does not need to be launched with the spacecraft and can power the spacecraft for several years. In this resource, we will investigate two important factors that must be considered when designing solar panels for space missions: the inverse square law and the angle of incidence.

Inverse square law

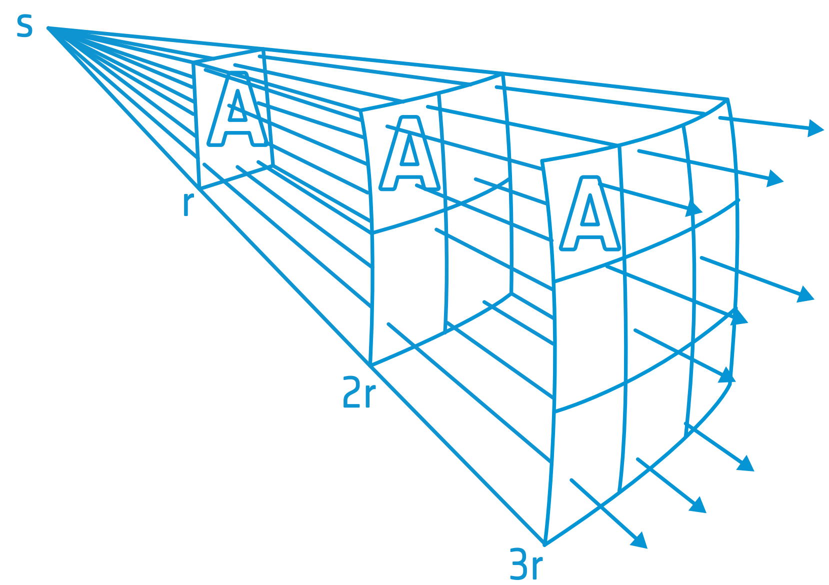
The inverse square law states that the value of a physical quantity is inversely proportional to the square of the distance from the source of that physical quantity. One of the most famous examples of this is the inverse square law of light; the flux received from a light source is inversely proportional to the squared distance from the light source. For light, the flux is the amount of power radiated through a given area. For a spherical light source, such as the Sun, the flux is the same as the **intensity of radiation** (I). The Sun emits light uniformly in all directions, and so the intensity of radiation will follow the inverse square law with distance from the Sun. The inverse square law for this case is summarised in the following equation:

$$I \propto \frac{1}{r^2}$$

I = intensity of radiation from the Sun
r = distance from the Sun

This means that, if a planet or spacecraft is twice as far away from the Sun as the Earth is, the intensity of solar radiation will be only a quarter of that measured on Earth (Figure 1).

Figure 1



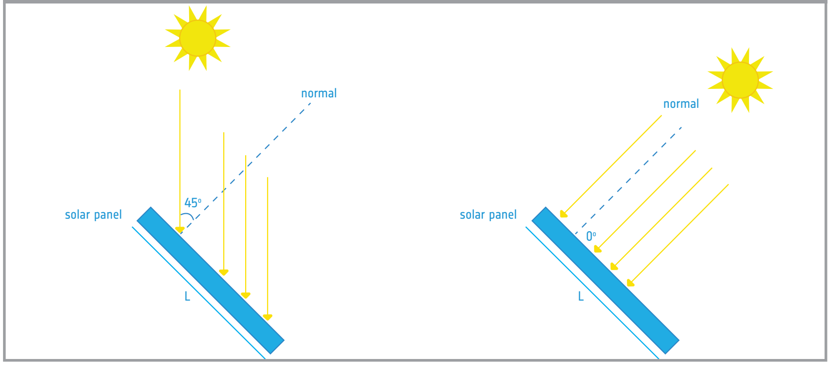
↑ The Sun at point S emits light uniformly in all directions. At a distance r the light passes through an area A, when the distance doubles (2r) the area quadruples (4A) and when the distance triples the area becomes 9A.

Understanding the inverse square law has important implications for space missions powered by solar panels. The further a solar-powered spacecraft is from the Sun, the larger the area of its solar panels must be in order to meet he same power requirements.

Angle of incidence

The angle of incidence, θ, of sunlight on a solar panel is also an important factor for power generation. A solar panel will collect solar energy most efficiently when the Sun's rays are perpendicular to the panel's surface, with a 0° angle of incidence, because it maximizes the effective collection area (see Figure 2). For a solar panel with length L, the effective collection area is equal to L*cos(θ), thus the intensity incident on the solar array is also L*cos(θ).

Figure 2



↑ An angle of incidence of 45° (left) and 0° (right). The angle of incidence is the angle between the incident Sun rays and the normal to the solar panels (with length L). When the Sun rays are perpendicular to the solar panel they have an incident angle of 0°.

For space missions, the angle of incidence of sunlight is a critical factor. Many spacecraft are equipped with rotatable solar panels to decrease the angle of incidence of sunlight and thereby maximize the power production.

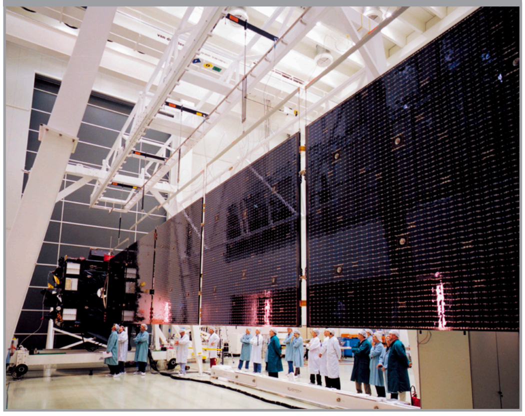
Solar power for space missions.

Examples of how the inverse square law and angle of incidence affect the engineering of space missions.

Rosetta

ESA's Rosetta mission travelled for more than 10 years to meet with Comet 67P/Churyumov-Gerasimenko. At the furthest point of its journey, Rosetta was at 800 million kilometres from the Sun, where levels of sunlight are only 4% of those received by Earth. It is the first mission to journey beyond the main asteroid belt relying solely on solar cells for power generation. Its solar panels spanned 32 metres and had a total surface area of 64 m^2(see Figure 3).

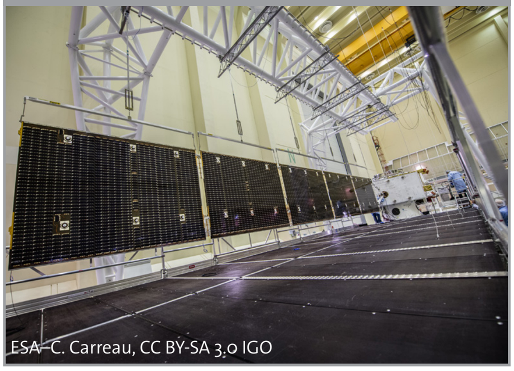
Figure 3



↑ Rosetta spacecraft with one of its two solar wings fully deployed.

BepiColombo

Figure 4



↑ BepiColombo Mercury Transfer Module solar wing deployment.

A large part of the incoming light that reaches the solar panels is converted into heat. ESA's BepiColombo mission to Mercury will fly close to the Sun and therefore the heating effect will be very large. If the solar panels of BepiColombo point directly at the Sun for more than a few seconds, the materials would be damaged and the solar panels would stop working. In order to keep the solar panels cooler (around 200°C) they are tilted away from the Sun. To produce the electric energy needed for BepiColombo, the solar panels have to be much bigger than if we calculated the area using only the inverse square law. For BepiColombo the solar panels have to be 42 m^2 (see Figure 4).

→ Activity 1 - The inverse square law

In this hands-on activity, students will calculate the power output of a solar panel by measuring the electric current and electric potential difference and try to retrieve the inverse square law from their experimental measurements.

Equipment

- Student worksheet and Annex 1 printed for each group
- A dark box (open in one end)
- Electric cables
- Sellotape
- Light source (small light bulb, 4.5V, 0.3A)
- Ruler
- 30 cm rod (for example a wooden stick)
- Material to block light (for example a sponge, cloth)
- Ammeter and voltmeter (or a multimeter)
- Crocodile clips

Exercise

Divide the students into groups of 3 to 4 students. Distribute the student worksheet and Annex 1 to each group. Before starting the experiment, introduce the students to the concept of intensity of radiation.

Set-up of the experiment

First, the students will have to set up the experiment. Ask them to complete steps 1 to 9, of Annex 1. In step 9, make sure students mark the distance zero when the light source is touching the solar cell. After completing the set up phase, students should make sure all of the equipment is working and connected properly.

Experiment

Students should take their measurements of electric potential difference (U) and electric current (I), following steps 10 to 12 in Annex 1, and record their data in Table 1 in the student worksheet.

Before taking the first measurement, students should retract the rod at least 5 cm. For each subsequent measurement, students should retract the light source 1 cm until reaching approximately 30cm. Ideally students should measure 20 to 30 different distances. It is possible to use larger intervals, but the drop in power output can be too quick to observe the inverse square law, the variation is dependent of the light source and the solar cells. We advise to test the optimal distances before doing the experiment with your students.

Students should repeat their measurements twice more and calculate the average. Discuss reliability of results and scientific process with the students.

Ask the students to complete Table 1 of their student worksheet by calculating the output power:

$$P(W) = I\,(A) * U\,(V)$$

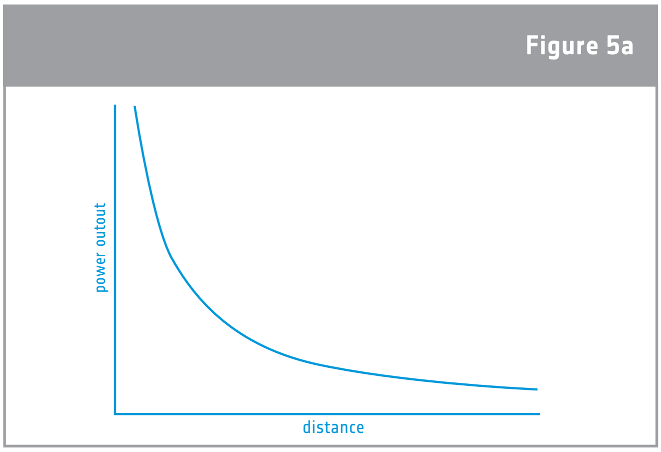
Results

In analysing these results, we assume that the power produced by the solar cells is directly proportional to the power that is received by the solar cell (power produced = power received x efficiency of cell). The power received is proportional to the light intensity from the light source (because intensity = power/area, and the area remains the same throughout the experiment). Therefore, we can say that the power produced by the photovoltaic cell is proportional to the intensity of light.

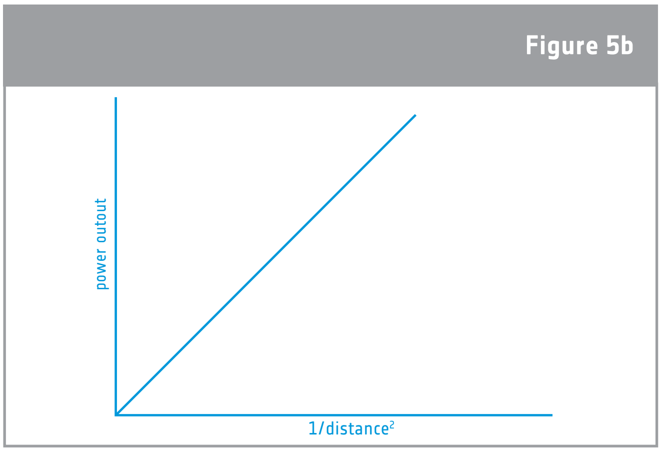
To obey the inverse square law, the power produced by the solar panel (P) should be proportional to the inverse of the distance squared (r).

$$P \propto \frac{1}{r^2}$$

To analyse their data, students should plot power as a function of distance (Figure 5a), and power as a function of 1/distance² (Figure 5b); the second plot should yield a straight line.



↑ Expected graph for power output against distance.



↑ Expected graph for power output against 1/distance2.

The students may not retrieve exactly an inverse square law. These are some of the factors that may influence the results:

- The box may not be completely dark and fluctuations from outside light influence the measurements.
- In this set up, the measurement of the distance can have a large error.
- There might be internal light scattering.
- The internal resistance of the solar cell may vary throughout the experiment.
- The measurements close to the solar cell may not follow the inverse square law because the light source cannot be approximated to a point source.

As a conclusion, students should identify that if we double the distance to the light source, we need to have solar panels 4 times larger to generate the same amount of energy.

→ Activity 2: The angle of incidence

In this activity, students will learn about the importance of the angle of incidence and the benefits of optimally positioning solar cells. Through an experiment, they will measure how the angle of incidence influences the power output.

Equipment

- Student worksheet and Annex 2 printed for each group
- Experimental setup from activity 1 (see Annex 2)
- Stick to rotate the solar cell (BBQ stick for example)
- Protractor

Exercise

For this activity, students should again be in groups of 3 to 4. Distribute the student worksheet and Annex 2 to each group.

Before starting the experiment, introduce the students to the concept of angle of incidence.

Set-up of the experiment

Activity 2 is a continuation of Activity 1. Students will have to update their experimental setting so that they can tilt the solar panel to a specific angle. Students should adapt the experiment from Activity 1 following step 1 to 7 in Annex 2[1]. Before starting the measurements, students should make sure all of the equipment is working and connected properly.

Experiment

Students should take the measurements as described in steps 8 to 10 in Annex 2 and record them in Table 2 of the student worksheet. Students should repeat the measurements two more times, making sure they keep all of the conditions similar and calculate the mean power for each angle of incidence.

[1] If students have not done Activity 1 previously they should follow the instructions in Annex 1 to assemble the experiment, from steps 1 to 7 skipping step 5, and then follow the instructions in Annex 2.

Results

Ask the students to plot the mean power as a function of the incidence angle.
Students should retrieve, from their data, that the power output is largest when the solar panel is perpendicular to the light rays (angle of incidence = 0°).

Although the expected reading when the solar cell is parallel to the light source (angle of incidence = 90°) should, in principle, be zero, this will not be retrieved, mainly due to the light scattering inside the box.

Even if the light lamp is switched off, a measurable residual current in the circuit (dark current) may still exist. When performing scientific experiments that require precision measurements, the values should be corrected by subtracting this error from the readings.

If the students tilt their solar cells to have angles of incidence = -30°, -60° and -90°, they should retrieve similar values, because the system is symmetric. Experimentally, this will depend of how well the system is aligned.

Some of the sources of error have already been mentioned in Activity 1. In this activity, we must also consider uncertainty in the measurement of the angle, and the alignment of the solar panel in the box as potential sources of error.

To conclude, students should answer question 9 in the student worksheet, finding that to maximize the solar panel's power output, the angle of incidence should be close to 0°. They can propose a sun-tracking mechanism with solar panels that rotate and tilt according to the Sun's apparent movement.

In these experiments the heating effect is negligible, as the total energy of the light bulb is only a few watts. For spacecraft flying close to the Sun, such as BepiColombo, the heating effect is large and has a major impact on the design of the mission. Another aspect to consider is that solar panels on Earth can be cooled by air, which is not the case in the vacuum of space.

→ Activity 3: Exploring space with solar power

In this activity, students practise using the inverse square law in application to real ESA space missions. Students will discover how the properties of the inverse square law affect how large the solar panels have to be and how the angle of incidence is of critical importance for missions venturing close to the Sun.

Results

1. The light intensity received at Earth's average distance from the Sun(I_{Earth}) can be calculated using the inverse square law and the values provided on the student worksheet:

$$I_{Earth} = \frac{3.828 * 10^{26} W}{4\pi(1.5 * 10^{11} m)^2} = 1354 \frac{W}{m^2}$$

2. At a distance of 45 million km from the Sun the light intensity is calculated as:

$$I_{BepiColombo} = \frac{3.828 * 10^{26} W}{4\pi(4.5 * 10^{10} m)^2} = 15043 \frac{W}{m^2}$$

$$I_{BepiColombo} = 11\, I_{Earth}$$

At this distance from the Sun the light intensity is 11 times larger than at Earth's distance. The heat damage caused to the solar panels will be significant, implying that they need to be tilted away from the Sun permanently. This means that the real surface area of the solar panels, $42m^2$, is much larger than if it would be possible to have the solar panels facing the Sun directly.

3. ESA's Rosetta spacecraft followed a trajectory that took it 800 million km away from the Sun. At this distance the light intensity is calculated as:

$$I_{Rosetta} = \frac{3.828 * 10^{26} W}{4\pi(8 * 10^{11} m)^2} = 47.6 \frac{W}{m^2}$$

Compared to I_{Earth}:

$$I_{Rosetta} = 0.035\, I_{Earth}$$

The intensity of light at 800 million km from the Sun is approximately 3.5% of the intensity of light at the distance of Earth from the Sun.

4. Although powered by highly-efficient solar cells, Rosetta's solar panels had varied efficiency between 18% and 26%. Combined with the low light intensity at its furthest point in the orbit, Rosetta's solar panels had to have a very large surface area of $64m^2$.
Assuming the only variable would be the difference of light intensity if Rosetta had been orbiting at the Earth's distance, the area of the solar panels would be only:

$$A_{Earth} = 0.035 * 64\, m^2 = 2.24\, m^2$$

5. Using the inverse square law the light intensity at the distance of Saturn is given by:

$$I_{Saturn} = \frac{3.828 * 10^{26} W}{4\pi(1.4 * 10^{12} m)^2} = 15.5 \frac{W}{m^2}$$

Similar to the calculation for the Earth's distance: $I_{Rosetta} = 3.1\, I_{Saturn}$
This means that the solar panels would have to be 3.1 times bigger, at a distance of 1.4 billion km, compared to 800 million km from the Sun.

$$A_{Saturn} = 3.1 * 64\, m^2 = 198.4\, m^2$$

6. Cassini-Huygens power requirements are 2.2 times bigger than Rosetta's (885 W /395 W= 2.2) and therefore it used a nuclear power source called a radioisotopic thermoelectric generator. If it had used solar arrays instead, the area of the solar array would have had to be 2.2 times larger than the value calculated in question 4.

$$A_{Cassini\text{-}Huygens} = 2.2 * 198.4\ m^2 = 436.5\ m^2$$

7. The solar panels have a mass per square metre of:

$$\frac{51.2kg}{64m^2} = 0.8\,kg\ m^{-2}$$

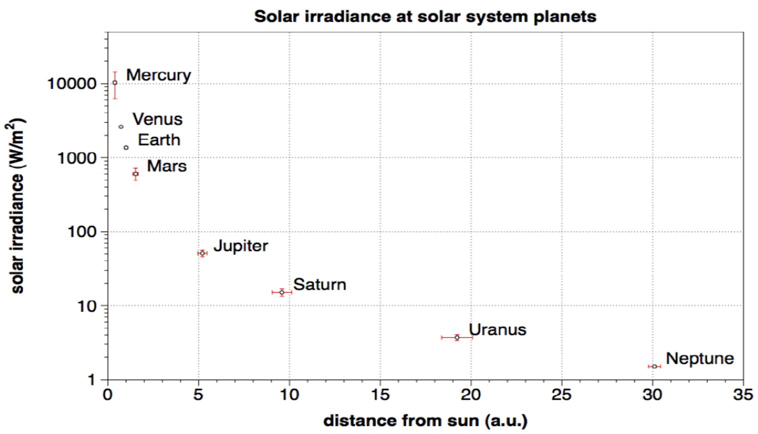
The total mass of the solar panels required to power Cassini would therefore be approximately:

$$0.8\ kg\ m^{-2} * 436.5\ m^2 = 349.2\ kg$$

The radioisotopic thermoelectric generators weighed 56.4 kg
The increase in mass would be of 292.8 kg.

8. Solar power is very important because it is a renewable power source and because it is not launched with the spacecraft. Due to the inverse square law, the intensity of light decreases rapidly with distance from the Sun (see Figure 6). This means that larger solar arrays are needed to provide the necessary on-board power requirements further away from the Sun and that at distances beyond Jupiter it is effectively too dark to use solar power.

Figure 6



	Distance from Sun, AU	Solar radiation W/m^2	Approx array temp, degC
Mercury	0.4	9014	238
Venus	0.7	2645	101
Earth	1.0	1371	45
Mars	1.5	593	-15
Jupiter	5.2	51	-134
Saturn	9.5	15	-170
Uranus	19	4	-200
Neptune	30	2	-215
Pluto	39	0.9	-222

↑ Solar irradiance (light intensity) at solar system planets.

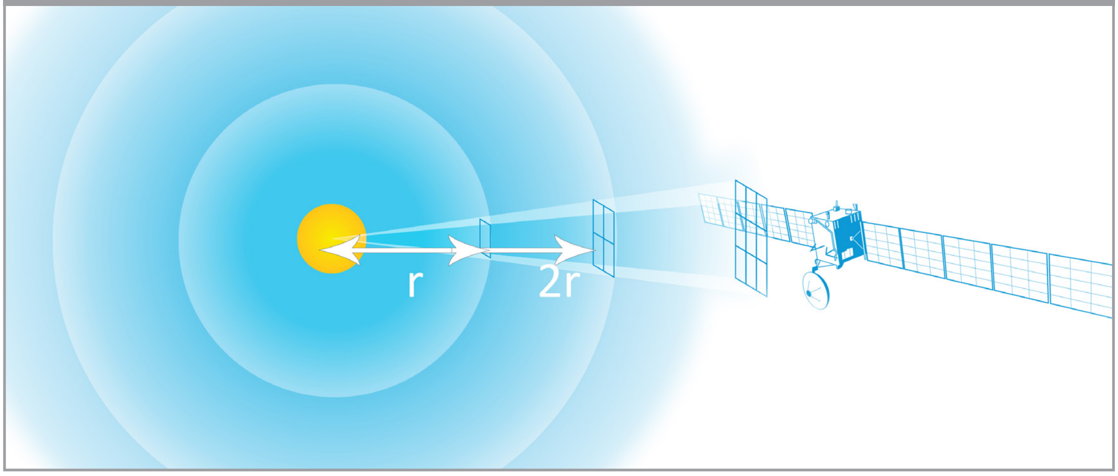
As calculated in question 6, if Cassini-Huygens would need to have solar panels, they would have a mass more than six times the mass of the radioisotopic thermoelectric generators! Consideration of mass is very important for space exploration, because for every additional kilogramme, more fuel is required to escape earth's gravity. Safety and security constraints associated especially with nuclear power must however be considered.

→ POWER FROM SUNLIGHT

Powering space exploration with solar energy

→ Activity 1: The inverse square law

Figure A1



↑ The Sun emits light uniformly in all directions. At a distance r light passes through an area A, when the distance doubles (2r) the same amount of light will cover an area four times bigger (4A).

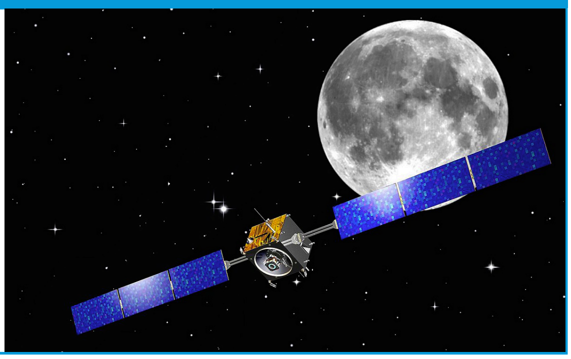
The Sun emits light uniformly in all directions (see Figure A1), and so light intensity (I) at a given distance (r) will equal the total power emitted from the Sun, distributed on a sphere of radius (r) with surface area $4\pi r^2$.

$$\text{Intensity of radiation from the Sun } (W/m^2) = \frac{\text{Power emitted from the Sun (W)}}{4\pi r^2 (m^2)} \qquad (1)$$

Depending on their distance from the Sun, spacecraft in the Solar System experience huge differences in the amount of sunlight they receive.

Did you know?

Launched in September 2003, SMART-1 became the first ESA mission to the Moon. It was the maiden mission to leave Earth's orbit solely using solar power, albeit slowly, setting a 13 month record for the longest journey to the Moon. SMART-1 broke the lowest fuel consumption record per km for any Moon voyage, drawing most of its electric power from its solar panels wings, each of which was about 7m long.



Experiment

In this experiment, you will try to retrieve the inverse square law for the power output of a solar cell.

- Set up the experiment following the instructions provided in Annex 1, from step 1 to step 10.
- Confirm that all of the equipment is connected and working properly.
- Start taking the measurements. Follow instructions in step 11 and 12.
- Take note of your measurements of electric potential difference (U) and electric current (I) readings in Table 1.
- Repeat the measurements two more times.
- Calculate the power output of the solar cell and complete Table 1.

$$P(W) = I\,(A) * U\,(V)$$

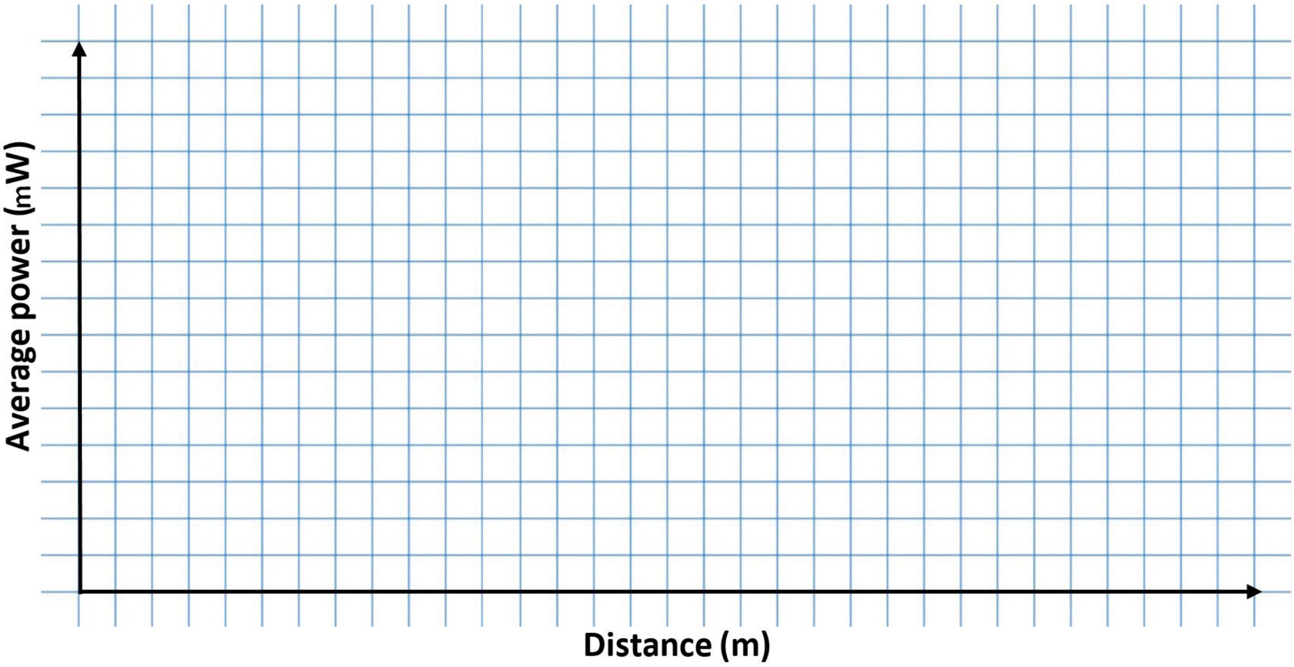
- Calculate the average power for each distance.

Table 1

Distance	Experiment 1			Experiment 2			Experiment 3			Mean
	U (V)	I (mA)	P (mW)	U (V)	I (mA)	P (mW)	U (V)	I (mA)	P (mW)	P (mW)

↑ Table for recordings of Electrical Potential Difference (U), current (I) and corresponding power output (P)

1. Plot the average power output as a function of the distance of the light source:



2. Does the power output from the solar cell follow the inverse square law? Explain.

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3. What uncertainties are there in your experiment? How do they influence your result?

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4. If we double the distance to the light source, how big do the solar panels have to be in order to produce the same power?

   ☐ They should be smaller

   ☐ They should be 2 times as big

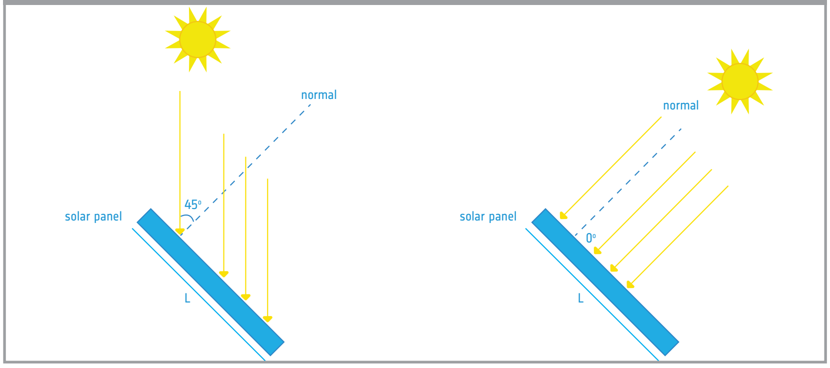
   ☐ They should be 4 times as big

   ☐ They should be 9 times as big

→ Activity 2: The angle of incidence

The angle of incidence of sunlight on the solar panels is an important factor. The angle of incidence is the angle between the incident Sun rays and the normal to the solar panels. When the Sun's rays are perpendicular to the solar panel they have an incident angle of 0°.

Figure A2



↑ Representation of an angle of incidence of 45° (left) and 0° (right).

1. Before starting the measurements, predict which angle of incidence will generate the largest power. Explain your guess.

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____

Experiment

In this experiment, you will measure how much the angle of incidence influences the power output of your solar cells.

- Adapt the experimental setup from Activity 1 by following step 1 to step 7 in the instructions provided in Annex 2.
- Perform the experiment following the instructions in steps 8 to 10 Annex 2. Take note of your measurements of electric potential difference (U) and electric current (I) for different angles of incidence in Table 2 bellow.
- Repeat the measurements two more times.
- Calculate the power output of the solar cell and complete Table 2.

$$P(W) = I\ (A) * U\ (V)$$

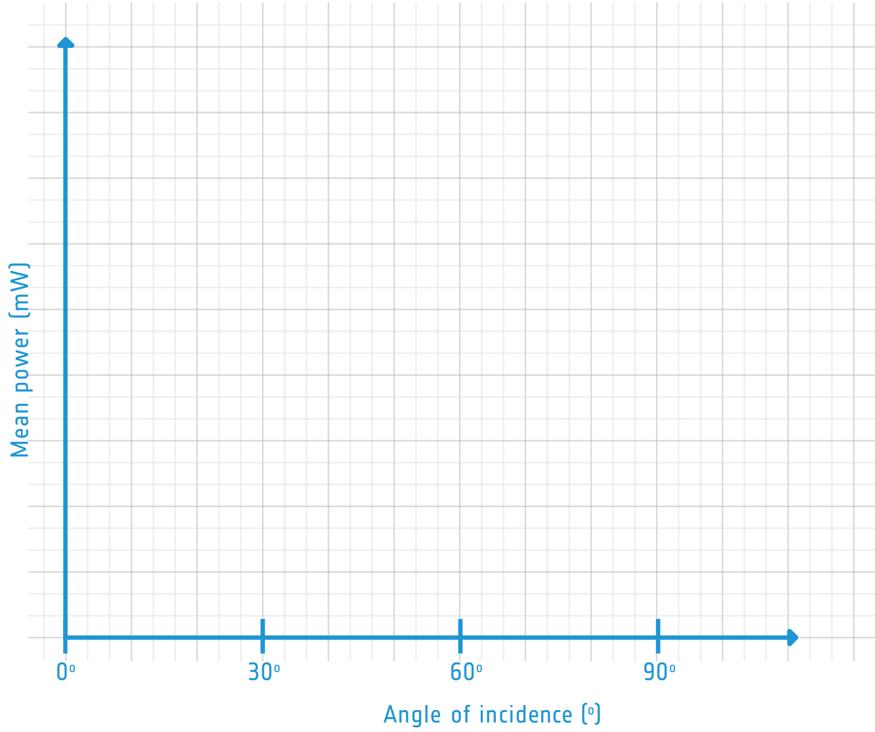
- Calculate the average power for each angle of incidence.

Table 2

Distance	Experiment 1			Experiment 2			Experiment 3			Mean
	U (V)	I (mA)	P (mW)	U (V)	I (mA)	P (mW)	U (V)	I (mA)	P (mW)	P (mW)
0°										
30°										
45°										
60°										
90°										

↑ Recordings of electrical potential difference (U), electric current (I) and power output (P) for different angles of incidence.

2. Plot the mean power as a function of the angle of incidence:



3. Which angle of incidence generates the largest power output? ______________________

4. Was your prediction in question 1 correct? If not, can you explain why it was different?

____

____

____

5. Why do you think the power output is not zero when the solar cell is parallel to the light source? (Angle of incidence = 90°)

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6. Do you expect to have any power output if you preform the experiment with the lamp switched off? Test your guess and explain your findings.

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____

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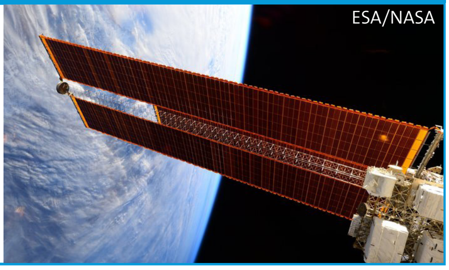
7. What power values would you expect if you performed the experiment with the angle of incidence at -30°, -45°, -60° and -90°? Explain your answer.

8. What are the main uncertainties in the experiment? Are there any errors on your measurements?

9. You have measured how power depends on the angle of incidence. How would you construct your solar panels to maximize power output?

Did you know?

The International Space Station (ISS) is powered by solar panels. The image on the right shows some of the solar panels on the ISS, which is home to up to six astronauts at a time. As the ISS orbits Earth, the solar panels can be rotated to point more directly at the Sun. The panels span an area of 2500 m^2 – that is equivalent to the size of half of a football field!


ESA/NASA

→ Activity 3: Exploring space with solar power

When is it a good idea to use solar power for space exploration and how can we use our knowledge of the inverse square law and angle of incidence to our advantage?

ESA's Rosetta mission, travelling 800 million km away from the Sun, required enormous solar panels to produce enough power to sustain its on-board systems. In contrast, **ESA's BepiColombo mission** to Mercury, is travelling so close to the Sun that will receive huge amounts of radiation that can be very damaging for the solar panels.

Exercise

1. The Earth is at an average distance of approximately 150 million km from the Sun. The average power emitted by the Sun is $3.828 * 10^{26}$W. Use equation (1) in activity 1 to calculate the light intensity at the distance of Earth(I_{Earth})

2. BepiColombo's minimum distance to the Sun will be around 45 million km. To minimise damage to the solar panels by the intense heat they have to be tilted away from the Sun. Calculate the light intensity($I_{BepiColombo}$) at this distance. Compare it to I_{Earth}.

3. Rosetta's maximum distance from the Sun was of 800 million km. Calculate the light intensity($I_{Rosetta}$) at this distance. Compare it to I_{Earth}.

→ STUDENT WORKSHEET

4. Considering the need for power in combination with the low light intensity at its furthest point in the orbit, Rosetta's solar panels had to have a very large surface area, of $64 m^2$. What would be the required size of the solar panels if Rosetta was at Earth's distance instead? Take into account only the difference in light intensity and assume all other variables remain constant.

5. Now imagine that Rosetta goes to explore Saturn, at 1.4 billion km from the Sun. What would be the required size of the solar panels at this distance? Take into account only the difference in light intensity and assume all other variables remain constant.

6. The last mission to Saturn, Cassini-Huygens, was powered using radioisotope thermoelectric generators (RTGs). Cassini-Huygens needed 885 W of power, while Rosetta only needed 395W. Calculate the size of the solar panels that would be required to power Cassini-Huygens (at the distance of Saturn), assuming they would be similar to Rosetta's solar panels.

7. The radioisotopic thermoelectric generators used for Cassini-Huygens had a mass of 56.4 kg. Rosetta's solar panels had a mass of 51.2 kg. How much would Cassini-Huygens' mass increase if the mission had used solar panels, as calculated in question 5?

8. What are the advantages and disadvantages of using solar power for space exploration?

→ Links

ESA resources

Moon Camp Challenge
esa.int/Education/Moon_Camp

Moon animations about Moon exploration
esa.int/Education/Moon_Camp/Making_a_Home_on_the_Moon

ESA classroom resources:
esa.int/Education/Classroom_resources

ESA space projects

ESA Rosetta mission
esa.int/rosetta

ESA/JAXA BepiColombo mission
esa.int/Our_Activities/Space_Science/BepiColombo_overview2

Cassini-Huygens mission
esa.int/Our_Activities/Space_Science/Cassini-Huygens

Technical information relating to the questions

Information on the mass of the Rosetta solar panels (page 10)
lpi.usra.edu/opag/nov_2007_meeting/presentations/solar_power.pdf

Effective power generated at 5.25 AU by Rosetta (395 W, 64 m^2)
esa.int/Our_Activities/Space_Science/Rosetta/The_Rosetta_orbiter

Specifications for the Cassini spacecraft
fas.org/nuke/space/bennett0706.pdf

Information about the mass of solar panels estimated from slide 10
lpi.usra.edu/opag/nov_2007_meeting/presentations/solar_power.pdf

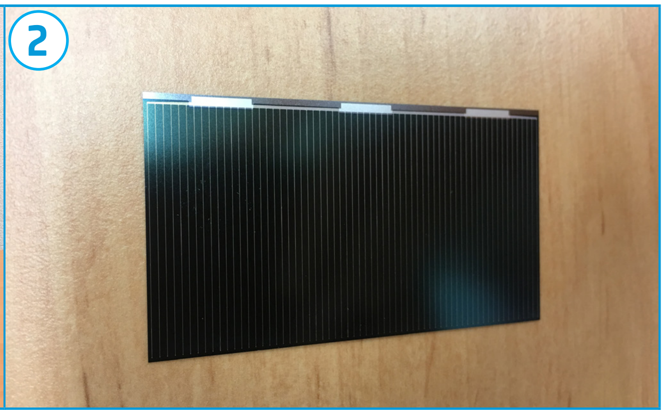
BepiColombo solar wing deployment
youtube.com/watch?v=Lhw4aojbkvs

→ Annex 1 - Inverse square law

1

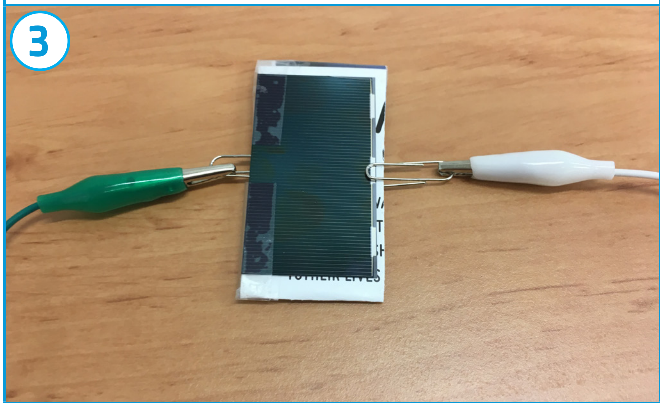
You will need a dark box (20-30 cm in length is sufficient for a small light bulb).

2



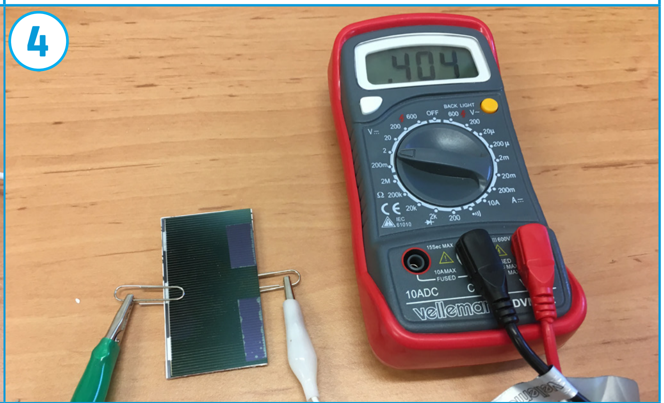
You will also need a solar cell.

3



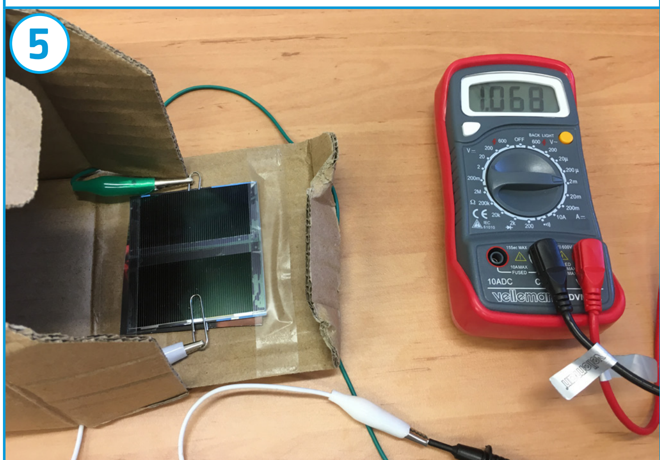
Connect crocodile wires to the solar cell. Depending on which solar cell you have you might have to create connection points for the crocodile wires. A simple way to do this is by using paper clips.

4



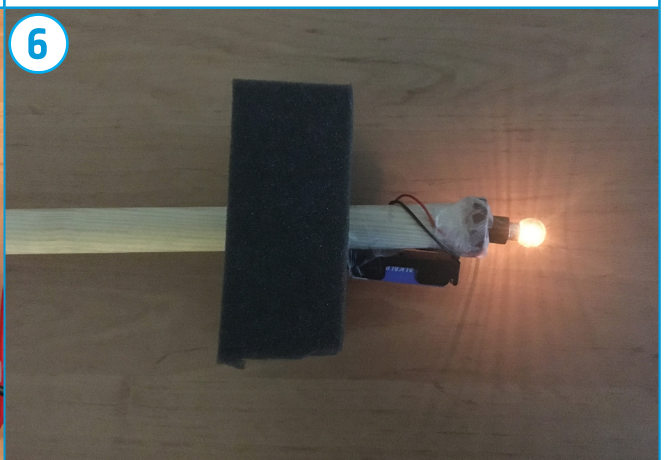
Test that your solar cell is working properly by connecting an ammeter in series and a voltmeter in parallel (or by connecting a multimeter). You should have readings of current and electric potential difference.

5

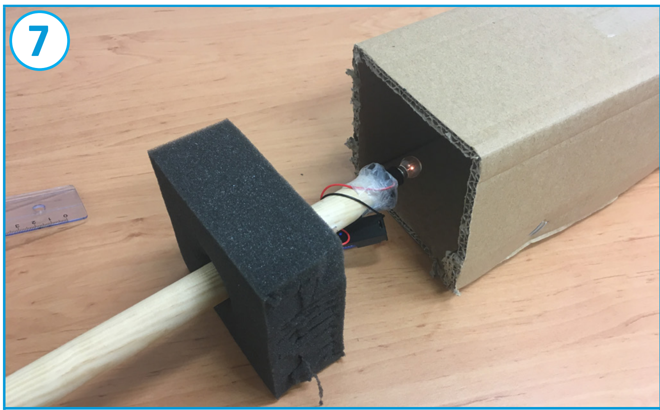


Attach the solar cell to the inside of the box as shown in the image. Close the box.

6



Place the small light with a battery at the end of a rod. Cut out a piece of material in the dimensions of the cross-section of the box to block any light coming in from behind the light source as shown in the image.



Turn on the light source and insert the rod in the box. Have the dark foam fit the box as tight as possible, if needed light-insulate the box with dark sellotape or perform the measurements in a dark room.

Carefully insert the rod into the box until the light source is touching the solar cell. Be careful not to break the solar cell.

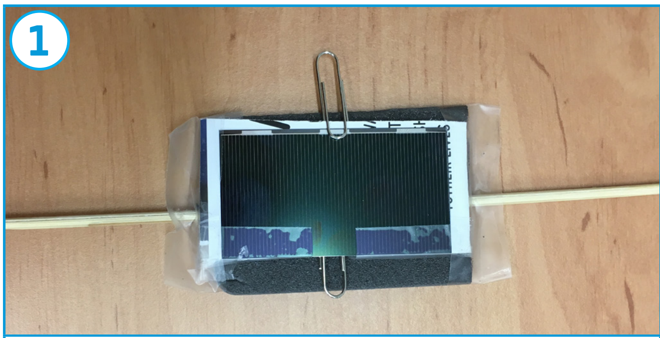
Take note of this initial position on the rod with a marker or attach a measuring tape to the rod and take note of the value.

You have finished the setup of the experiment. Make sure all the equipment is working and connected properly.

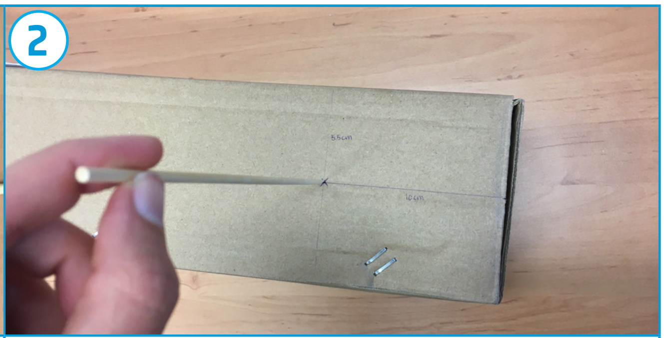
Move the light source away from the solar cell by 5 cm. Record the measurement of current and electric potential difference in table 1 on your worksheet.

Move the light source away from the solar panel by 1 cm at a time until the light source is at the end of the box. Record the electric potential difference and current at each position. Repeat the measurements twice with the same conditions and distances.

→ Annex 2 – Angle of incidence

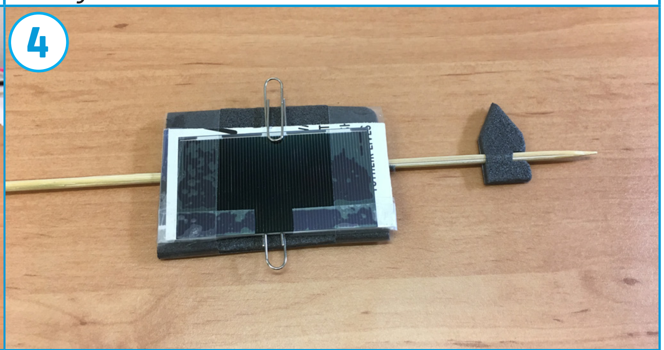


Use the equipment from activity 1. Attach the solar cell to a small stick. This will allow it to be rotated inside the box. The rotation axis should be in the centre of the solar cell.



Use the box from activity 1. Mark a point on the side of the box for the stick to go through the box. Make sure it is centred vertically with the same distance to the top and bottom. Make sure the solar cell has enough space to freely rotate.

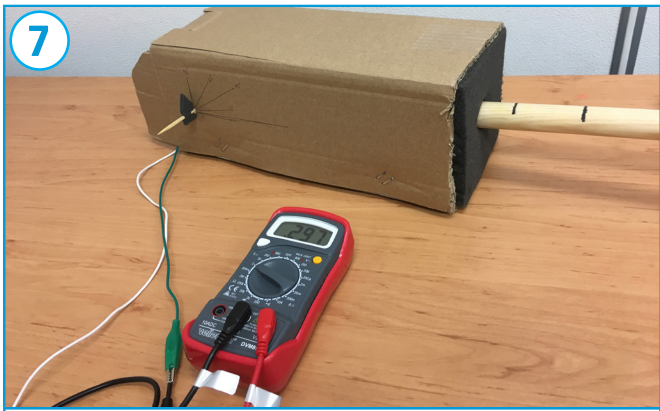
Mark the angles 0°, 30°, 45°, 60° and 90° degrees with the vertical axis on one side of the box (or attach a protractor).



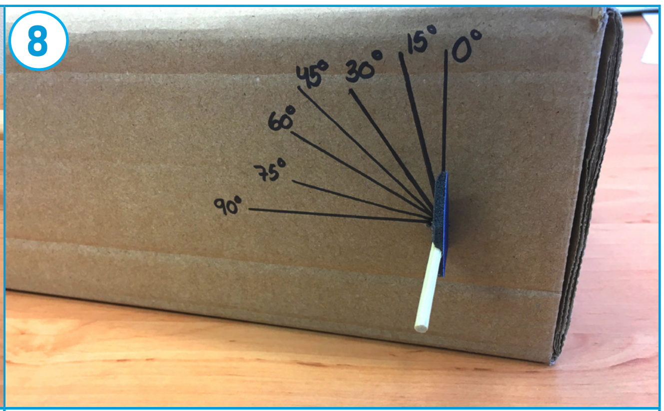
Attach a piece of cardboard on the stick with the same orientation as the solar cell. This will sit on the outside of the box and indicate the angle of the solar cell inside the closed box.

Insert the solar cell in the box and connect an ammeter in series and a voltmeter in parallel (or connect a multimeter). Close the box.

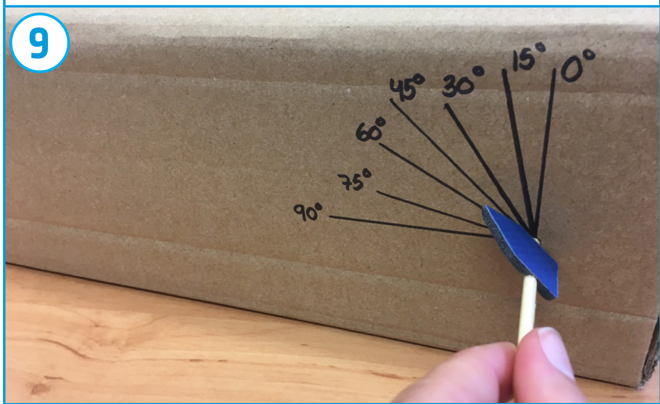
Turn on the light source and insert it into the box. The distance between the light source and the solar cell should be approximately 10 cm. This distance should be constant throughout the experiment (the rod should not be moved).



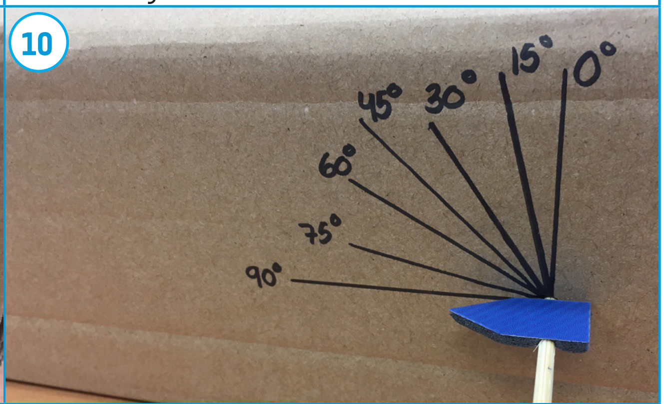
Test that it is working.



Take measurements of current and electrical potential difference when the solar cell is perpendicular to the light source (angle of incidence 0°). Record your measurements in table 2 in your student worksheet.



Tilt the solar cell gradually by twisting the small stick and reading the angle on the side. Take measurements of current and electrical potential difference at each angle and record them in table 2 in your student worksheet.



Twist the solar cell until it is in parallel with the light source (angle of incidence 90°). Take measurements of current and electrical potential difference at this position and record them in table 2. Repeat the experiment two more times