PLANET CHANGE

Solar panel alignment:
How to optimise energy in Space

Teachers manual

Co-funded by the
Erasmus+ Programme
of the European Union

Planet change is the short name of an EU Erasmus+ project aimed at VET teachers and their students. With small activities, the idea is to create awareness about sustainability and acquire 21st century skills. All this is done in a technical context, mostly from space technology.

www.planetchange.eu

Contents:

1. General information

Purpose: *Students learn how to most efficiently operate/install solar panels and how satellites discern the direction of the Sun.*

Target group, VET schools: See Annex 3

Target group, age: 16-18Y / 18-20Y

European Qualifications Framework level: 1/2/3

Duration: ca. 60 min

Location: classroom

Software: *Virtual satellite programming environment*

Background:

To get solar panels to produce energy efficiently they need to be positioned at a perpendicular angle with the sun. Ground based solar panels are usually installed with a fixed angle. That angle mostly depends on the latitude on earth. Solar panels on satellites, however, need to constantly adjust their position in order to keep facing the sun.

Topic

Theme

Energy Efficiency

Keywords

Satellite orientation, angle, power output, programming, solar panels, solar array, photovoltaic cells, solar power, solar energy, sun sensor.

Activity

Learning Objectives

The student will get better knowledge and training about;

1. General knowledge about;
    a. the importance of solar panels on earth and in space
    b. the ideal angle to get the maximum power output of a solar panel
    c. considerations when installing a ground based solar panel
    d. why positioning is different for satellites compared to solar panels on earth
    e. explore some of the ways how to orient a satellite’s solar panels towards the sun
2. Activities:

   a. Learn how a sun sensor works. After hypothesising how satellites keep their solar panels oriented correctly, students are introduced to the workings of a Sun sensor. Student then design and build a model of a sun sensor.
   b. Introduction to programming. They'll learn how to program a virtual satellite to actively adjust the angle of its solar panels, so it keeps being perfectly oriented towards the sun as it orbits earth.
3. Students reflect on what they have learned about solar panel orientation and how to determine the position of the sun.
4. Students are shown examples of professions where this knowledge is applied (in a career in space industry).
5. Example employee solar panel mechanic/installer (using satellite data)

Summary of activity

First, students learn why solar panels need to be aligned towards the sun at a 90-degree angle to reach maximum efficiency. They'll discuss and learn some of the considerations for choosing the optimal angle for fixed ground based solar panels. They learn why solar panels on satellites adjust their angle and explore different methods to know how to do so. During the activity, students design and build a paper version/ mock-up of a Sun sensor, a device which measures the direction of the Sun. They present their Sun sensor to the class and test if they can tell the direction of light. Additionally, students can program a virtual satellite to update the orientation of their solar panels in order to get the maximum energy efficiency/power output.

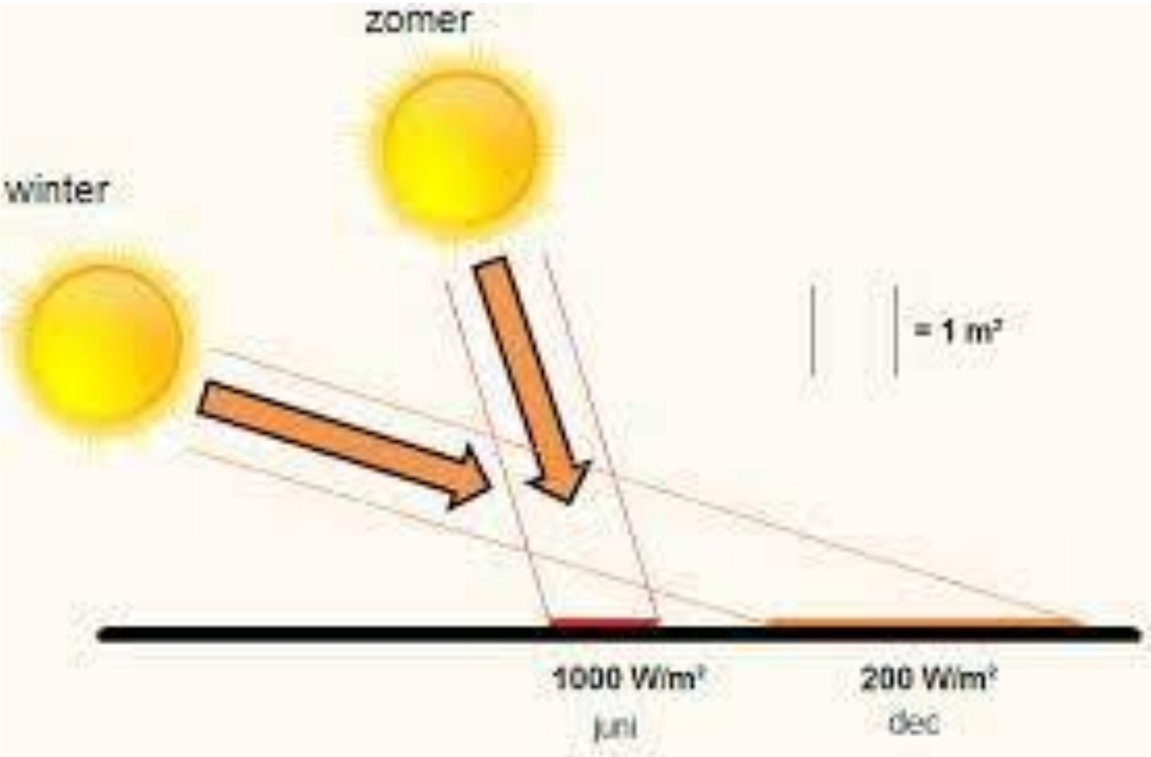
After the activities, students reflect on what they have learned about solar panel orientation and how to determine the position of the sun. The lesson can end with examples of VET students with a profession in this line of work. This lesson could be extended with an excursion / field trip to a solar energy company.

2. Introduction

Achieving sustainable development goals

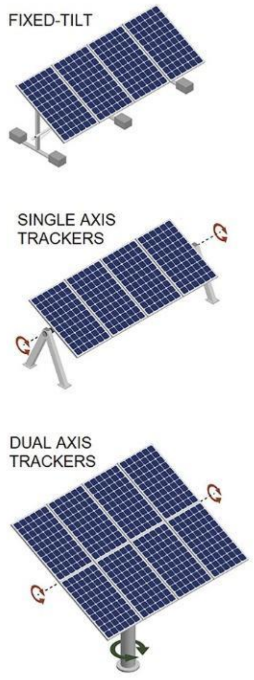
Solar panels are an increasingly popular way to generate electricity, and for good reason. They use the power of the sun to generate clean and renewable energy, which means they have less negative impact on the environment. There are many reasons why solar panels are important, including their contribution to achieving the United Nations' Sustainable Development Goals (SDGs). Firstly, solar panels help to reduce our reliance on fossil fuels, which is essential to achieving SDG 7: Affordable and Clean Energy. Fossil fuels, such as coal and oil, are non-renewable resources that contribute to climate change and air pollution. By using solar panels to generate electricity, we can reduce our dependence on these harmful fuels and move towards a more sustainable future. Secondly, solar panels can help to reduce energy costs, which is also an important aspect of SDG 7. Once installed, solar panels can generate electricity for free, meaning you can save money on your energy bills. A typical return of investment on solar panels is around 8 to 12 years, depending on the price of the solar panels, price of electricity, and how much sun they expect to receive. Additionally, many governments and utilities offer incentives and rebates for those who install solar panels, making it an even more affordable option. Thirdly, solar panels can increase the value of your home, which contributes to SDG 11: Sustainable Cities and Communities. Studies have shown that homes with solar panels sell for more than those without, making them a smart investment for homeowners. This can also help to stimulate the economy and create jobs, which is important for achieving SDG 8: Decent Work and Economic Growth. Finally, solar panels help to mitigate the effects of climate change by reducing greenhouse gas emissions, which is crucial to achieving SDG 13: Climate Action. By choosing to use solar energy instead of fossil fuels, individuals and businesses can reduce their carbon footprint and help to protect the planet for future generations. In conclusion, solar panels are not only important for reducing energy costs, increasing property values, and creating jobs, but they are also a crucial tool in achieving the SDGs, specifically SDG 7 and SDG 13. By harnessing the power of the sun, we can work towards a more sustainable, cost-effective, and climate-resilient future.

How much power a solar panel generates depends on a myriad of factors, such as the type of solar panel and its size. Still, no matter what type or size, the efficiency of a solar panel is mostly determined by the angle by which sunlight hits the surface of the solar panel. Solar panels work best if light falls perpendicular on its surface. That is, with a right (90 degree) angle. In this way, a beam of light illuminates the smallest spot and is therefore the most intense. If a beam of light falls on the solar panel at a shallow angle the same amount of light is kind of 'smeared out' over a larger surface area. Another way of to visualise this is to realise more sunbeams are able to hit the solar panels at a perpendicular angle compare to a shallow angle.



There are other factors and considerations to maximise the power output of solar panels, especially for earth-based panels. Since the sun constantly changes position and angle, solar panels that adjust their orientation to keep a perpendicular angle with the sun will be more efficient, but also more costly. To do this, you firstly need to either track the sun or know its position throughout the year. Then, the panels can be moved to keep the perpendicular angle (as much as possible). This means such systems needs sensors, process data, motors or actuators to move the panel, a more sophisticated framework on which to install the panel, and more servicing and maintenance. While these systems are getting more common and economically viable in certain situations (see ….), it's often still easier and cheaper to install more but sub-optimally angled fixed solar panels.

Installing fixed solar panels is therefore necessarily a compromise. A fixed angle must be chosen which provides the most average energy compared to all other fixed angles. To determine what that angle is, depends on several factors. Firstly, when installed on the northern hemisphere fixed solar panels should face south, while in the southern hemisphere solar panels should be directed due north. Then, the optimal angle of inclination depends on latitude. The more extreme the latitude, the higher the angle of inclination should be. On the equator, this means fixed solar panels face straight up (i.e., they lay flat on the ground). On the poles however, panels would have to be installed perpendicular with the ground.



There are some other considerations that should be kept in mind when orienting fixed solar panels. There might be objects (e.g., houses, mountains, or trees) that block the sun during certain hours. For instance, when the morning sun is blocked by a mountain. In such cases, solar panels shouldn't middle between the rising sun in the east and the setting sun in the west by facing either north or south (depending on which hemisphere) but should be oriented more towards the west. Conversely, the panels should face more eastwards if the late afternoon sun is blocked.

When is solar energy needed the most? This might be another consideration, particularly when electricity can't be stored or sold back to the power grid. Whether power consumption is generally higher in the morning or afternoon skews the optimal panel orientation to the east or west, respectively. Whether power consumption is higher during winter (e.g., heating) or in summer (e.g., air-conditioning) also skews the panels be placed at a higher or shallower inclination, respectively.

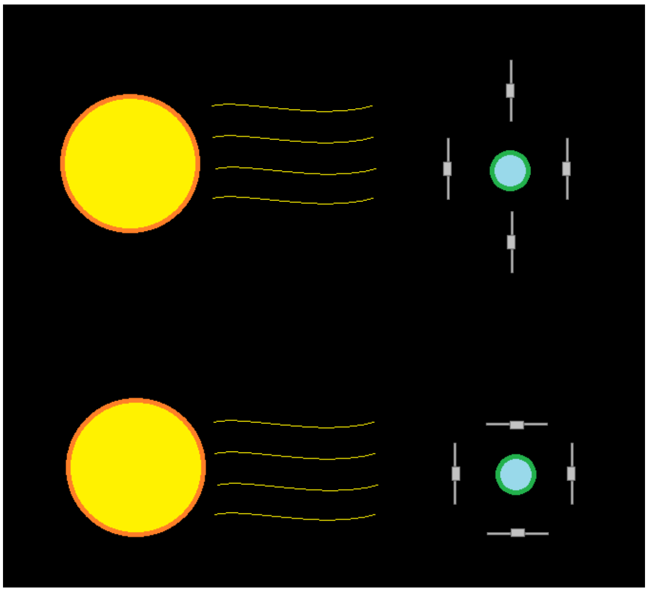
Lastly, solar panels perform best under moderate temperatures, as higher or lower temperatures can reduce efficiency. The optimal temperature for most solar panels is around 25°C. For every degree above 25°C, a solar panel's output can decrease by around 0.3% to 0.5%, affecting overall energy production. Therefore, whether solar panels are placed in a breeze versus sheltered from the wind, surrounded by objects in shadow, or bodies of water, this all affects the temperature and thus the efficiency of the solar panel.

Solar panels in space

Solar panels are one of the mayor ways satellites and space-stations provide themselves with the energy needed to be operational. Satellites need to work independently for many years. For obvious reasons you can't connect a satellite to the power grid, most batteries don't last years or couldn't provide the needed power, and you couldn't have a diesel-powered generator on a spaceship either. Luckily there is a lot of solar energy in space and no clouds to block it. However, how do you position solar panels when whizzing through space at breakneck speeds?

As we've seen, solar panels on earth usually have a fixed orientation and pitch for economic reasons. Because it very expensive to get material into space this reason doesn't hold for solar panels in space. Although prices are steadily dropping, it's still thousands of Euros to get one kilogram up into space. It's therefore cheaper to add a small and light system which can adjust the solar panel's orientation, than bringing more solar panels. This is also the reason why solar panels used in space are of the best quality. To get the maximum amount of energy per kilogram brought up to space. Moreover, when a satellite is brought into orbit, its solar panels are folded up and packed away within the payload of a rocket. So, panels on satellites already must fold out and move anyway. Another reason to adjust solar panel orientation is that the range of angles of the sun is typically much more variable in space compared to on earth. Whereas a ground based solar panel stays on the same latitude, most satellites do not. Moreover, that angle is changing fast due to the tremendous speeds at which satellites whizz around earth. Lastly, to move mass on earth is much harder than in space. Whereas such adjusting system on earth needs to move and support a lot of weight, solar panels in space are weightless due to microgravity. Solar panels in space are therefore much easier to move in any direction, and don't need any support to be kept in that position.

A satellite's orientation is most often placed/spun such that one part of the satellite, usually a sensor or transmitter, always faces earth. Satellites move in much the same way as the moon does; always facing the same side towards earth. We call such objects tidally locked. This makes the angle of the sun change more through time compared to a satellite which doesn't spin 360 degrees during a full rotation around earth.



Luckily, in orbit there is little to disturb a satellite's given angle or rotation thus its trajectory is almost completely known far in advance. However, small differences in the strength of earths gravitational field, solar winds, and the tiny bit of drag of the few molecules up there eventually do slightly change a satellites position, rotation and/or orientation. Over time such tiny disturbances can grow to be significant. So, even if the proper position of a satellite's solar array could be calculated and scheduled in advance, unknown but unavoidable tiny disturbances would still have to be checked and corrected for. Theoretically, several methods to keep the perpendicular angle could be thought of beside the scheduled way. For instance, the satellite can make tiny adjustments in any direction. Only if the adjustment results in a power increase, the adjustment is kept. In reality, most if not all satellites, use Sun sensors. These special navigational devices let in a tiny bit of light which then falls on a detector. The angle of the sun can then be determined from where light hits the detector.

Description of the activity

Part 1: Classroom introduction of solar panels on earth and in space [35 min]

a. Introduce the students to the importance of solar panels on earth (e.g., energy independence, locally produced, non-fossil/renewable, less emissions, reaching SDG's, climate change, etc.). **[5 min]**

b. *Ask the class what they think the optimal orientation of solar panel is.*

With the help of a flashlight and a sheet of graph paper, show the students why solar panels need to be oriented perpendicular towards the sun to get the maximum efficiency and therefore the highest power output. **[5 min]**

TIP: With a simple setup of a small solar cell connected to a voltmeter, fan or lightbulb you can demonstrate the optimal orientation by showing that changing the angle of light from the sun or a flashlight result in a faster/slower fan or brighter/dimmer lightbulb.

c. How to orient a fixed solar panel in order to benefit most of the power it supplies may depend on a lot of considerations. From our point of view, the sun moves through the sky from east to west. Moreover, anywhere besides the equator the sun stands high in the sky during summer but remains low during winter.

- *Ask the class why these facts about our Sun are a 'problem' when installing fixed solar panels.* **[5 min]**

d. Tell the students that solar panels on earth are mostly fixed for economic reasons. Explain that this also means we get a suboptimal power output.

- *Ask the class about any considerations when determining the optimal fixed position and angle of solar panels?* **[5 min]**

Possible considerations (mention the ones missed by the students):

Do you optimize for morning, midday, or afternoon sun? This might depend on your power consumption profile during the day. For instance, if you're only home during the morning and you use the most energy at this moment, you might want to optimize the solar panel's angle in such a way that it maximizes power output during these hours. Whether you can store energy or are able to sell it back to the grid is also relevant in this scenario.

Are there any objects blocking the sun during certain parts of the day? For instance, if a building or trees block the morning sun during most of the year, the average best angle will be skewed towards one where it gets most of the midday and afternoon sun.

Do you need/use the power more during winter or summer? If your power consumption is higher during summer (e.g., air-conditioning), you might want to angle your solar panels higher such that they are more perpendicular during summer days when the sun reaches a higher point in the sky.

e. Introduce the students to the importance of solar panels on satellites and spacecraft as an energy source (e.g., enough solar energy, no clouds, very little other viable options). **[5 min]**

- *Ask and discuss with the class why solar panels on satellites do adjust their angle.* **[5 min]**

Possible answers:

Getting materials into space is expensive. Whereas on earth it is cheaper to get more solar panels instead of actively tracking the sun, this is not true in space.

Due to the often fast-changing position of satellites in relation to the sun. [note: this is less so for geostationary satellites.]

Microgravity makes moving and supporting heavy solar panels much easier.

f. Satellites have sensors and/or communication devices that we want to aim in a certain direction, usually at earth. Therefore, with each orbit around earth, satellites also rotate 360 degrees, so their sensor remains facing the same direction. For this reason, when satellites face their solar panels towards the sun, they usually only move their solar panels and not their own (body)orientation. However, how does a satellite 'know' how to correctly orient its panels?

Potential methods:

Firstly, if the satellite's flight plan is known and on the right course, the position and angle of the sun should already be known far in advance. In space there is no wind, and no bumps in the road that can change the satellite's position/orientation. So, once up there, a satellite's flight path is very predictable. In that case, only the detailed orientation of the satellite must be known to steer its solar panels the right way. We're going to call this '*the planned way*'.

Another solution to this problem is to gradually turn the solar panel on three axes and measure its power output. If movement in a certain direction increases power output, that would indicate the solar panel is better aligned. If such movement results in less power output, then the solar panel is less aligned and should be moved back. By looping this incremental trial and error, keeping the hits and going back on the misses, eventually the solar panels are aligned in such perfect way that any change of angle will decrease power output. We're going to call this '*the trial-and-error way*'.

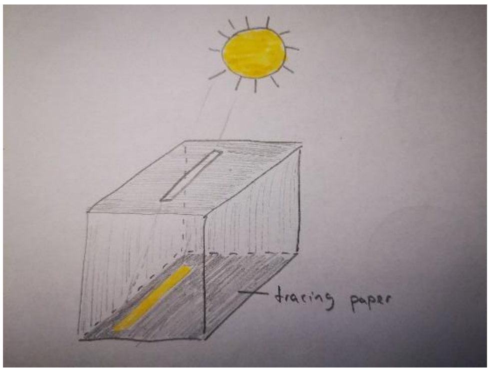
Thirdly, a satellite can 'know' where the sun is by detecting the strength of light on multiple sensors placed at different angles on the satellite. That information can be used to calculate the sun's position at that moment and align their solar panels accordingly. We're going to call this '*the measured way*'.

- *Discuss in groups of 4 how you would ensure a satellite keeps its solar panels oriented towards the sun? What would you have to know or measure? What are the benefits and downsides (drawbacks?) to each method you've come up with? Which method would you employ?* **[5 min]**
- *Ask the class which methods they have come up with and which they think would be the best one. Introduce any of the following methods if not yet mentioned by the students.* **[5 min]**

3. Part 2: Activity

a. Build a Sun sensor [20 min]

In this activity the students are to recreate the concept of a Sun sensor. A Sun sensor is a navigational instrument used by spacecraft to detect the position of the sun. However, sun sensors also find use in ground-based weather stations and sun-tracking solar array systems. In typical sun sensors, a thin slit or window at the top of a rectangular chamber allows a line of light to fall on an array of photodetector cells at the bottom of the chamber. According to where in the chamber this light is detected, the angle of the sun can be determined. A mock-up version of this can easily be crafted from a carton box and tracing paper (see picture). This gives you the Sun's direction in 180 degrees.



When multiple slits are combined perpendicular of each other you can determine the direction of the light source. The tracing paper can also be attached as half a cylinder under the slit. Pieces of an empty toilet or kitchen paper roll can be used to support and keep the cylindrical shape of the tracing paper. Doing it in this way allows one box to be used to create several slits.

Sometimes Sun sensors use one pin hole instead of a slit. When the light falls on the detector (tracing paper) below, the luminosity on each of the four quadrants of the detector will correspond invertedly with the direction of the sun. That is, when the sun is directly overhead, all four quadrants are illuminated equally. If the sun stands in the West, the two eastern quadrants are illuminated. If the sun is north, the southern two quadrants are illuminated. If the sun is north-east, the south-west quadrant will be illuminated the most, etc.

Assignment:

Prepare a darkened room with three dispersed lights that can be switched on individually (light A, B, and C). In this assignment, students will make a sun sensor with the given materials. Afterwards, they should be able to tell, by only looking inside their carton box, which of the three lights was shining.

Divide the classroom into groups of 3 to 5 students. Give each group the materials listed below. Let each group first discuss within their team what is needed to make the Sun sensor work and let them draw a simple design. Only then they should start to build a Sun sensor with the given materials. Let them think about the following aspects;

- Where would you place the slits and in what orientation?
- How many slits would you need to know the direction of a light source?
- Where and in what way would you attach the tracing paper?
- Can you use one piece of tracing paper for multiple slits?
- Could you make a workable Sun sensor with other shapes then slits?
- How would you calibrate the Sun sensor?

Rules:

1. The box should have at least one peephole through which to look.
2. When looking inside the box, the light from A, B, or C should not be seen directly. That is, it should always be detected on some other surface (i.e., the tracing paper).
3. You can only use the materials provided.

Materials per group:

- Carton box
- Tracing paper
- Tape
- Stanley knife (box cutter) and/or scissors
- Empty toilet or kitchen paper roll (optional)

Materials classroom preparation

- Darkened room
- Three spots in the darkened room with either three bright lights that can be switched on/off individually, or from where a single bright light can be held. If you use a flashlight, make sure you shine directly to the tested Sun Sensor and that it's bright enough.
- (optional) Piece of darkening cloth that can be draped over the head of the person testing/demonstrating, so they can't directly see where the light is coming from.

Presentation and demonstration

After all groups have finished building their Sun Sensor, or when time is up, let each group separately present their build to the class. Ask each group for the reasons for their design. Let each team conduct a demonstration/test where one of their team members identifies which of the three lights (A,B, or C) shines by only looking inside their Sun Sensor.

b. Program a virtual satellite (optional)

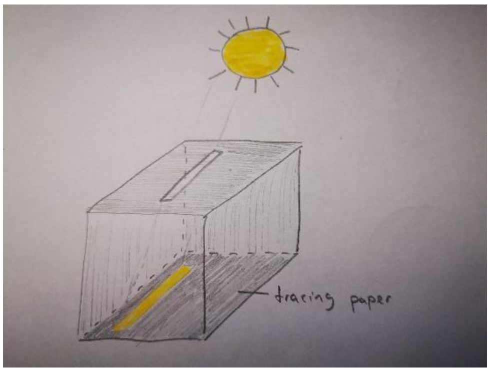
In this computer exercise students see a virtual satellite orbiting earth while the earth orbits the sun. The satellite is rotating 360 degrees during one orbit such that it's 'belly' always faces perpendicular to the earth's ground. A menu displays values from [3] optical sensors which measure light intensity from three different angles. Another menu displays power output from the satellite's solar panels. There is a text field where commands can be given to actuators on the satellite that move the solar panels. The students write code such that the optical sensor input is used to orient the solar panels and power output is constantly maximized.

4. Part 3: Worksheet

Worksheet - Build a Sun Sensor

In this activity you'll be constructing a Sun sensor in groups of 3 to 5. A Sun sensor is a navigational instrument used by spacecraft such as satellites and the International Space Station to detect the position of the sun. However, sun sensors also find use in ground-based weather stations and sun-tracking solar array systems. In typical sun sensors, a thin slit or window at the top of a rectangular chamber allows a line of light to fall on an array of photodetector cells at the bottom of the chamber. According to where in the chamber this light is detected, the angle of the sun can be determined. A mock-up version of this can easily be crafted from a carton box and tracing paper (see picture). This gives you the Sun's direction in 180 degrees. When multiple slits are combined perpendicular of each other you can determine the exact direction of the light source.

The tracing paper can also be attached as half a cylinder directly under the slit. Pieces of an empty toilet or kitchen paper roll can be used to support and keep the cylindrical shape of the tracing paper. In this way light can be detected in the full 180 degrees without falling on the sides of the box. Moreover, it allows one box to be used for several slits in different directions.



Sometimes Sun sensors use one pinhole instead of a slit. When the light falls on the detector (tracing paper) below, the luminosity on each of the four quadrants of the detector will correspond inversely with the direction of the sun. That is, when the sun is directly overhead, all four quadrants are illuminated equally. If the sun stands in the West, the two eastern quadrants are illuminated. If the sun is north, the southern two quadrants are illuminated. If the sun is north-east, the south-west quadrant will be illuminated the most, etc.

Assignment:

The teacher has prepared a darkened room with three lights that can be switched on individually (light A, B, and C), or a comparable situation. In this assignment, your group will make a sun sensor with the given materials. Afterwards, you should be able to tell, by only looking inside your carton box, which of the three lights was shining.

Rules and specifications:

1. The box should have at least one peephole through which to look.
2. When looking inside the box, the light from A, B, or C should not be seen directly. In other words, it should always be detected on some other surface (i.e., the tracing paper). It's thus not allowed to make big holes through which the darkened room and the light can be seen directly.
3. You can only use the materials provided.

Instructions:

a. First, discuss within your group what is needed to make a functional Sun sensor.

   It might help to think about the following questions:

   - Where on the box would you place the slits and in what orientation?
   - How many slits would you need to know the direction of a light source?
   - Where and in what way would you attach the tracing paper?
   - Can you use one piece of tracing paper for multiple slits?
   - Could you make a workable Sun sensor with other shapes then slits?

b. Then, draw a simple design of the Sun sensor you want to build.

c. Only then start to build a Sun sensor with the given materials.

d. When everybody has finished their Sun sensor, or when the time is up, present your build to the class. Make sure you explain your design choices. Finish your presentation with a demonstration/test where one of their team members identifies which of the three lights (A, B, or C) shines by only looking inside the Sun Sensor.

5. Part 3: Reflection

Part 3: Reflection [10 min]

Have a classroom discussion about the following questions:

a. *Knowing more about fixed solar panels, what could we do to make new housing more suitable for solar energy production?*
b. *Out of the different methods discussed in 1F (trial-and-error, planned or measured way), which one would the Sun Sensor fall into?*
c. *Where, or in which situations, do you think sun tracking solar panels would be more economically viable here on earth?*

6. Part 4: A possible future

Part 4 (optional): A possible future of working with solar panels in space

- Example of project at LiS where students made a calibration system for a sun sensor.

- Example of using satellite images to determine where and how to place solar panels are best placed.

Part 5 (optional): Excursion

This lesson can be combined with an excursion to a regional local solar panel manufacturer, supplier or installation company. In some countries it might be possible to arrange an excursion to a company involved in solar arrays for space.

- *In the Netherlands, for example, an excursion to Airborne or Airbus who manufactures solar panels for spacecraft such as ESA's JUICE mission could be an interesting field trip.*

- *In Italy, Leonardo also worked on ESA's JUICE spacecraft' solar array.*

- *In Norway, REC is a big solar panel provider, although its manufacturing facility has been moved to Singapore.*

- *In Portugal, Openplus is a big manufacturer and installer of solar panels. Also, SolarisFloat is an interesting company which makes floating sun tracking solar arrays, reducing land use and makes use of the cooling properties of the water to have increased efficiency of their solar panels. Interestingly, a floating installation covered in 180 of these moving solar panels is already operational in Oostvoornse Meer, a lake in the south-west Netherlands.*

- *In Spain, Bet Solar and Alba Renova are for instance big players in solar energy market.*

7. Annex I: Materials

Materials:

Demonstration:

- *flashlight*
- *graph paper*
- *(optional) toilet roll*
- *(optional) circuit with solar cell, fan or light, (and voltmeter)*

Activity per group:

- *carton box (minimum size of shoebox)*
- *tape*
- *tracing paper*
- *empty toilet roll*
- *scissors*
- *box cutter (optional)*

8. Annex II: Background information / tutorials / examples

Background information

Information to the teachers

VET Schools

Used, interesting or relevant sources:

https://space.stackexchange.com/questions/49398/how-many-sun-sensors-are-required-to-find-a-cubesats-orientation

https://www.bbc.com/future/article/20221116-the-floating-solar-panels-that-track-the-sun

https://www.cell.com/joule/fulltext/S2542-4351(20)30188-4?_returnURL=https%3A%2F%2Flinkinghub.elsevier.com%2Fretrieve%2Fpii%2FS2542435120301884%3Fshowall%3Dtrue

https://www.solar-mems.com/how-sun-sensors-work/

https://blog.ecoflow.com/us/effects-of-temperature-on-solar-panel-efficiency/#:~:text=The%20optimal%20temperature%20for%20solar%20panels%20is%20around%2025%C2%B0,%25%2C%20affecting%20overall%20energy%20production.

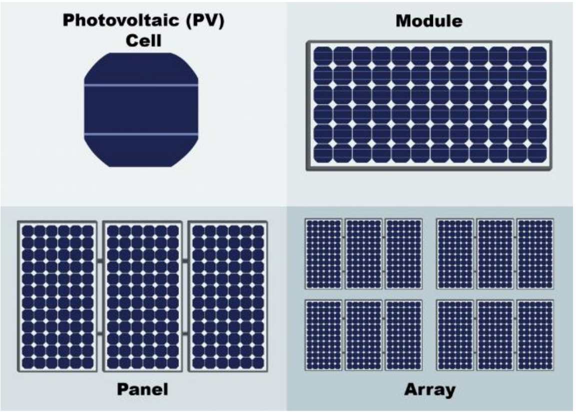


Figure 2. Differences between the terms used: An array has multiple panels, a panel has multiple modules, and module is made out of many photovoltaic cells (Bron: https://energyresearch.ucf.edu/consumer/solar-technologies/solar-electricity-basics/cells-modules-panels-and-arrays/)