SOLAR CELLS
From light to electricity

This guide provides as accurate an explanation as possible of the complex phenomena behind the transformation of light into electricity. It also includes exercises on energy and light.

In addition, at the end of this guide is an experiment that demonstrates the effect of light on the generation of electricity in a photobattery. The experiment is delicate and takes at least one week to work, but it is a good illustration of the impact of light on electric current and is simple to carry out.

Please note that the "BATTERY" guide presents the means of storing energy produced using solar panels to ensure Solar Impulse's energy supply at night. That guide includes instructions to build a small battery.

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Concepts covered

Science

- Light and energy

Physics

- Wavelengths and frequencies
- Solar cells and semiconductors
- Battery voltage

Activity duration

Theory: 2 periods
One period to present light and light energy, and one for photovoltaic panels.

Exercises: 2 periods
The exercises are appropriate for all levels.

Experiment: 4 periods
The experiment is only appropriate in the context of a lab session in a science course that takes place over two weeks, as it takes one week for the device to work.

This guide is an opportunity to present students the link between light and electricity and to introduce some topics from the history of science and technology.

HISTORICAL SIDEBAR

The history of solar panels is one of a reaction that plays out at the atomic scale. This reaction is called the photovoltaic effect. The photovoltaic effect is a physical phenomenon that occurs in particular materials known as semiconductors, which produce electricity when they are exposed to light.

The photovoltaic effect was discovered in 1839 by Edmond Bequerel, a French physicist. He observed that certain materials such as platinum could produce a weak voltage when exposed to light. Albert Einstein later took up the subject. In 1905, he published an article on the potential of producing electricity from sunlight. That document explored the photovoltaic effect, the technology that solar cells are based on. In 1913, William Coblentz submitted the first patent for a solar cell, which he was never able to get working. In 1916, Robert Millikan became the first person to produce electricity using a solar cell. Over the next 40 years, little progress was made in developing the technology; the efficiency of solar cells was too low to make transforming sunlight into electricity pay off.

Despite the many advantages of this clean energy source, the 20th century was powered by thermal energy derived from oil. Oil was abundant and cheap, and came to be considered a strategic raw material, leading to the geopolitics of oil. Solar energy was considered to be less attractive, and projects and discoveries were few and far between.

Bell Labs built the first solar panel in1954. It was called a “solar battery,” just for impact. It was, however, much too expensive to produce at a large scale. Research into solar energy really took off during the “space race.” Satellites needed a reliable and renewable source of energy, and solar energy seemed just right: it is constantly available for orbiting satellites, at least when they are exposed to the sun’s light. Consequently, the space industry started investing heavily into the development of solar panels. This became the first major application of the technology.

In 1958, the first satellites fitted with solar panels were sent into space. Around the same time, a solar cell with an efficiency of 9 % was developed (for comparison: today, efficiencies on the order of 20 % are the norm).

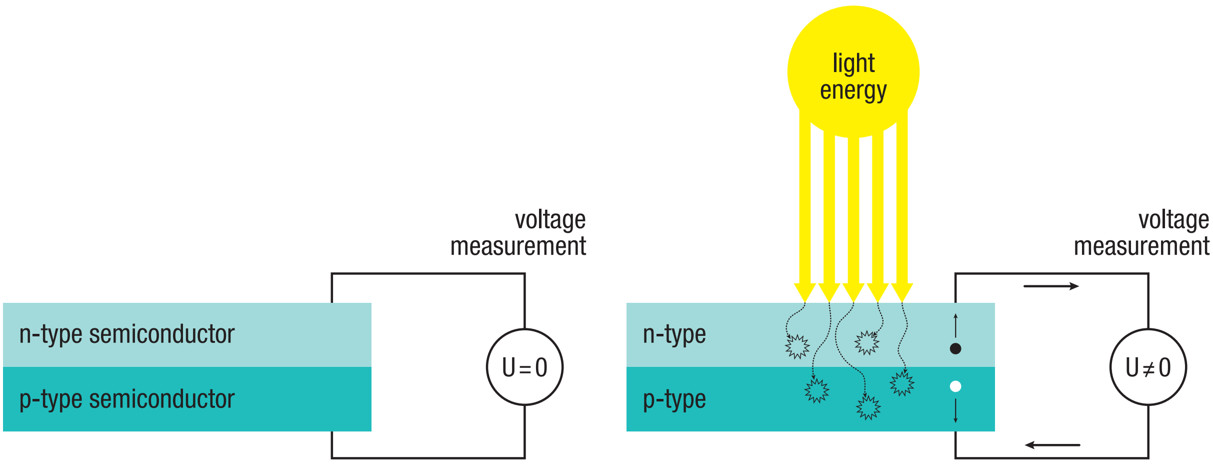
The space race gave solar panels a chance to prove themselves and bring down the cost of production. Solar energy got a second wind during the energy crisis in the 1970s, when the price of oil soared, and solar panels started to be used in domestic applications. Since then, photovoltaic panels have developed slowly. For many years, they were considered a source of alternative energy. Today, solar energy is booming because of predictions of a coming oil shortage, concern for global warming, and high energy prices. With today’s technology, commercial solar panels typically achieve efficiencies around 17 - 20 %. The efficiency of the cells in a solar panel corresponds to the percentage of incoming solar radiation that is converted into electricity. This means that the cells in a solar panel can transform a maximum of 17 - 20 % of the incoming solar energy into useable electricity.

SOLAR PHOTOVOLTAIC PANELS OR SOLAR CELLS

Semiconductors have become quite important in our society. They are the basis for all the electronic and optoelectronic [1] components used in computers, telecommunications, televisions, cars and household appliances. It's been said that we are currently living in the silicon age.

The electrical conductivity of a solid is a property that is derived from the presence of electrons, which are free to move in the environment and thus generate electric current. Electric current is just the simple flow of free electrons. The study of pure crystallized bodies shows that crystals separate into two main families in the vicinity of absolute zero (-273 °C): metals that conduct electricity, which contain many free electrons, and insulators, in which all the electrons are involved in chemical bonds and are thus strongly bonded. Certain insulators become conductors at higher temperatures, particularly if they contain impurities or defects; these are referred to as semiconductors. A semiconductor is thus a crystal that is an insulator near absolute zero and whose electrical conductivity is caused by thermal agitation, impurities, or other kinds of defects. When solar cells are illuminated, the photons captured by the cell increase the thermal agitation in the silicon and allow it to become a conductor.

But that's not all: thermal agitation of electrons is not sufficient to create electric current. For that, the electrons must all circulate in the same direction. This is why there are two kinds of semiconductors used in different layers that make up a photovoltaic cell. In the first layer, a deficit of electrons is created by introducing boron atoms, which have one less electron (p-type semiconductors). In the second layer a surplus of available electrons is introducing by adding phosphorous atoms, which have a surplus electron (n-type semiconductors). Thanks to these differences, the electrons can now circulate in the cell. Like in a battery, we have a positive (+) terminal (with an electron deficit) and a negative (–) terminal (with an electron surplus).



We quantify the electric tension (or electromotor force) that a battery or photovoltaic cell can produce using volts [V].

[1] Composants optoélectroniques : composants électroniques qui émettent ou interagissent avec la lumière..

ALL THIS IN NUMBERS…

Exercise 1

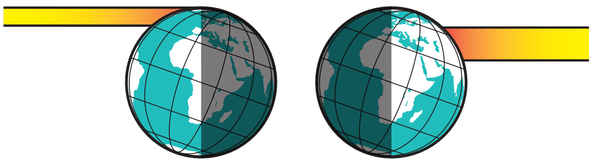
a) 40 % to 50 %, i.e.: $0.4 \cdot 0.5 = 0.2 = 20\,\%$

b) 20 % of 170,000,000 GW, i.e.: $1.7 \cdot 10^8 \cdot 0.2 = 3.4 \cdot 10^7 = 34{,}000{,}000\,\text{GW}$

c) 40 % to 50 % of 170,000,000 GW, i.e. 20 % of 170,000,000 GW,
thus: $0.4 \cdot 0.5 \cdot 1.7 \cdot 10^8 = 3.4 \cdot 10^7 = 34{,}000{,}000\,\text{GW}$

d) Mean radius of the Earth is 6,371 km, therefore its surface area is: $4 \cdot \pi \cdot (6{,}371 \cdot 1{,}000)^2 = 5.1 \cdot 10^{14}\ \text{m}^2$
Thus, we have: $1.7 \cdot 10^8 / 5.1 \cdot 10^{14} = 3.3329 \cdot 10^{-7}\ \text{GW/m}^2 = 333.29\ \text{W/m}^2$
As energy is given by $E = P \cdot t$, therefore daily energy per m^2 is: $E = 333.29 \cdot 24 \cdot 60 \cdot 60 = 2.879 \cdot 10^7\ \text{J}$

e) To obtain the energy, we assume that all the radiation emitted by the sun in the direction of the earth arrives on the planet's surface. To do this, the sunlight must hit our atmosphere perpendicularly so that there is no reflection, which is obviously not the case. In addition, the inclination of the light varies depending on the hemisphere, the season, the hour, and the time of day.



f) $140\,\text{km}^2 = 140 \cdot 1{,}000 \cdot 1{,}000 = 1.4 \cdot 10^8\,\text{m}^2$
Which gives a total energy of: $1.4 \cdot 10^8 \cdot 1'200 = 1.68 \cdot 10^{11}\,\text{kWh}.$
However the efficiency is only 20 %, thus the energy produced is: $1.68 \cdot 10^{11} \cdot 0.2 = 3.36 \cdot 10^{10}\,\text{kWh}$

g) $3.36 \cdot 10^{10}$ kWh (= $3.36 \cdot 10^7$ MWh) of energy is potentially produced by solar panels, which represents $3.36 \cdot 10^7 / 2{,}400{,}000 = 14$ times more than the Grande Dixence.

Leibstadt produces: $1{,}200 \cdot 10^6 \cdot 365 \cdot 24 \cdot 60 \cdot 60 = 3.78 \cdot 10^{16}\,\text{J}$
Since 1 kWh = $1000 \cdot 60 \cdot 60 = 3'600'000$ J, Leibstadt produces: $3.78 \cdot 10^{16} / 3{,}600{,}000 = 1.05 \cdot 10^{10}\,\text{kWh}$

So the solar panels could potentially produce $3.36 \cdot 10^{10} / 1.05 \cdot 10^{10} = 3.19$ times more than Leibstadt.

Exercise 2

The 200 m^2 would intercept: $200 \cdot 250 = 50{,}000\,\text{W}$
but with an efficiency of 12 %, the panels would only produce: $50{,}000 \cdot 0.12 = 6{,}000\,\text{W}$

These 6 kW correspond more or less to the power of the Wright Brothers' plane's motor (9 kW), which completed the first motorized flight in 1903.

TECHNOLOGY: BUILD A PHOTOBATTERY

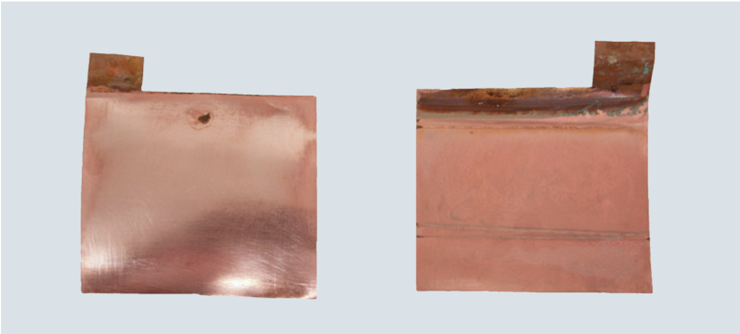
This experiment was performed in 1839 by Edmond Becquerel (the father of Henri, who discovered radioactivity). He was also the first to experiment on photobatteries.

He mainly studied the effects of light on electric current: depending on the case, it can modify the re- sistance of a conductor while electricity is flowing, or it can create an electric potential, resulting in the direct conversion of light into electricity. The first phenomenon, photoconduction, is what is used in cameras and photographic devices, and the second phenomenon is used in solar cells. What is less well known is that the discovery of photoelectric effect led to thorny theoretical problems. And it was in trying to get around these problems that Einstein came up with his theory of photons (1905) by applying quantum theory to light energy. He won the Nobel Prize in Physics for his explanation of the photoelectric effect.

Practical information

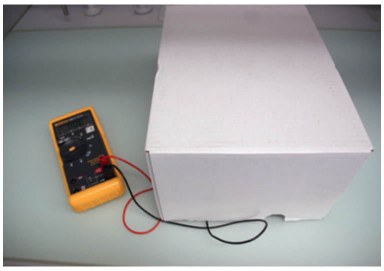
Over time, the exposed sheet will be covered in a layer of copper oxide (Cu_2O: a semi-conductor) and will play the role of a solar cell.

Electrode apparatus after 15 days of oxidation.

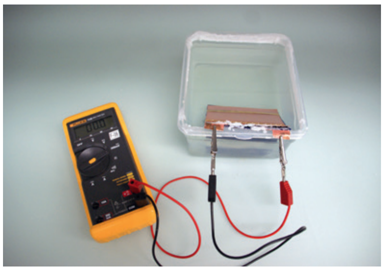


Difference between the “dressed” (left) and “naked” (right) sheet covered with copper oxide after 15 days in the salt solution.

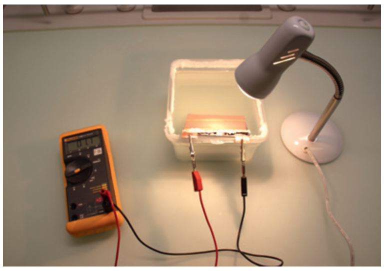
Measurements are taken like this:



Measurement without light



Measurement in ambient lighting



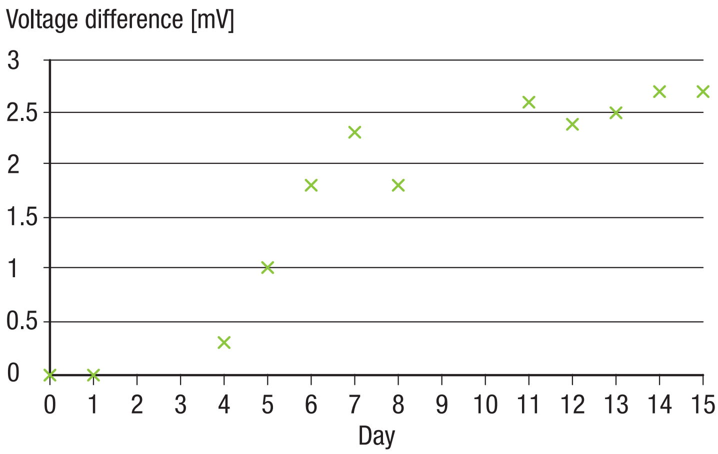
Measurement with a 36 W bulb

Measurements with and without ambient lighting are both on the order of 0.1 - 0.2 mV. This is why the measurement in ambient lighting was selected as the initial voltage.

Over time, the exposed tabs on the sheets will be covered with salt. They should be cleaned before attaching the paper clips. When doing this, avoid agitating the solution as much as possible, as this could cause effects such as an inversion of the polarity in the sheets. Ideally, you could solder two electric wires to the sheets to avoid the problem altogether.

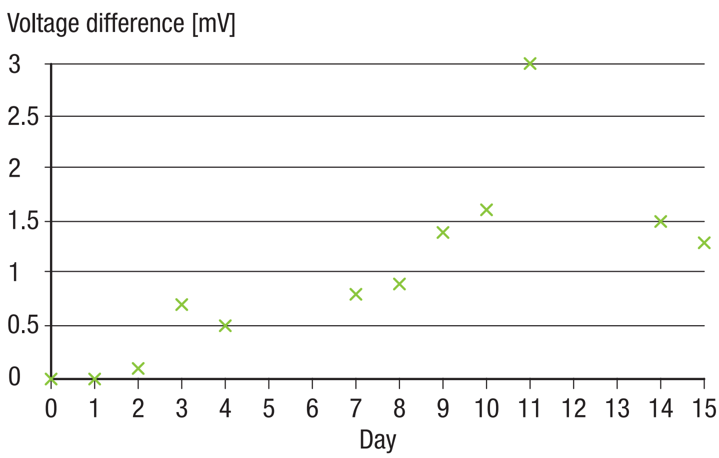
Over 15 days of the experiment, the following results were collected:

Day	Voltage without light U_1 [mV]	Voltage with light U_2 [mV]	Voltage difference U_2-U_1 [mV]
0	4.3	4.3	**0**
1	1.3	1.3	**0**
2			
3			
4	2.0	2.3	**0.3**
5	2.2	3.2	**1.0**
6	2.4	4.2	**1.8**
7	1.1	3.4	**2.3**
8	1.6	3.4	**1.8**
9			
10			
11	2.1	4.7	**2.6**
12	2.8	5.2	**2.4**
13	2.5	5.0	**2.5**
14	1.8	4.5	**2.7**
15	2.2	4.9	**2.7**



The experiment was repeated and these are the results:

Day	Voltage without light U_1 [mV]	Voltage with light U_2 [mV]	Voltage difference $U_2 - U_1$ [mV]
0	2.3	2.3	**0**
1	0.4	0.4	**0**
2	1.8	1.9	**0.1**
3	1.2	1.9	**0.7**
4	0	0.5	**0.5**
5			
6			
7	0.8	1.6	**0.8**
8	0.7	1.6	**0.9**
9	0.8	2.2	**1.4**
10	0	1.6	**1.6**
11	0.2	3.2	**3.0**
12			
13			
14	0.2	1.7	**1.5**
15	-0.2	1.1	**1.3**



In the beginning, the voltage difference that was measured when the sheet was illuminated was not more than 1 millivolt, but in any case this photoelectric effect is evident, and the goal attained. The more UV radiation the light carries (in full sun, on a mountaintop) the larger the voltage difference.

In effect, UV radiation is the shortest wavelength in the electromagnetic spectrum (which also makes it the most energetic), violet and blue are quite energetic, and yellow and red have wavelengths that are too long to produce enough energy to cause electrons to move.

It is sometimes observed that stirring up the solution in the container or moving the electrode apparatus can flip the polarity, causing a "–" to appear on the multimeter. Interestingly, illuminating the active sheet will cause the potential to fall; this "anti-photoelectric effect" deserves additional study. It takes an hour or two for things to settle back to normal.