Determining the power and efficiency of a solar cell

By: Irina Bichele, 2020

Solar radiation

The sun is our main source of energy. Green algae and higher plants use blue and red light to synthesise organic substances from inorganic substances in the course of photosynthesis, thereby forming the first link of all food chains. Coal, oil, natural gas and oil shale contain solar energy, stored in fossilised plants.

In the case of a clear sky, dissipation and absorption weaken the total radiation flux by approximately 20%. Clouds weaken the total radiation by another 20–30%. Thereby, only 50–60% of the radiation at the top of the atmosphere reach the ground (1360 W/m^2 of area that would be incident on a plane perpendicular to the rays). At midday, on our latitude, the average power level of solar radiation at sea level in the case of a clear sky is 600 W/m^2 (power of an oil radiator), 400 W/m^2 in the case of partly cloudy weather and 50-100 W/m^2 on a cloudy winter day.

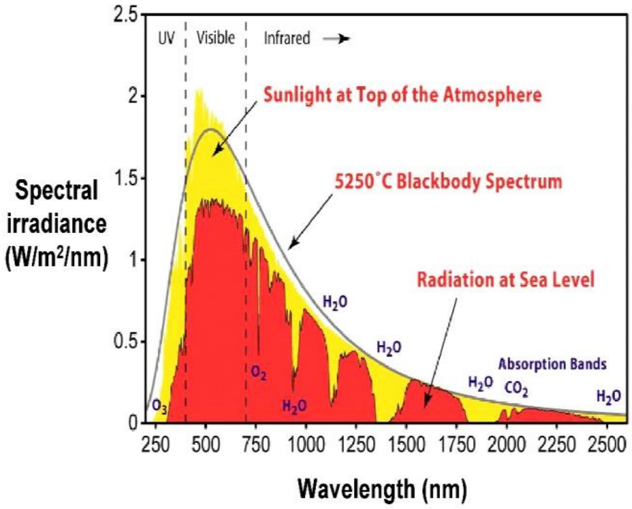


Figure 1. The correlation between the solar radiant flux and photon wavelength

Solar radiation (like radiation from other sources) is characterised by a spectrum. **A spectrum is** a correlation between any parameter tied to electromagnetic radiation (intensity of radiation, photon flux density) and the wavelength or frequency of the radiation, and it is shown using a graph, where the x axis shows either wavelength or frequency. When speaking of the visible radiation (light), it can be said that it depends on the colour of the light. Radiation with a wavelength of 0.7…10 μm is called thermal radiation or infrared radiation, **a range of 380…750 nm the visible radiation or light**, (the range of 700...750 nm is also called far-infrared radiation), and the range of 100…380 nm ultra-violet radiation.

The most common solar radiation spectrum is shown in Figure 1. It can leave a careless viewer with a deceptive impression – does the Sun radiate mostly blue (~450 nm) and considerably less red light (~650 nm)? When we examine the *y* axis, then the unit Wm^{-2} (W = J/s) shows that this is the radiation <u>energy</u> flux on different wavelengths (nm). The Joule (J) is an energy unit, therefore the spectrum shown on the figure shows how much solar energy is brought every second into the atmosphere (Figure 1, yellow spectrum) or the ground (Figure 1, red) by the photons of different wavelengths falling on one square metre. Out of that energy, approximately 53% is infrared radiation, 42%—visible light 5%–ultraviolet radiation energy. If the spectrum of the radiation reaching the ground were to be standardised by the energy quantity of the photons (e.g., the average

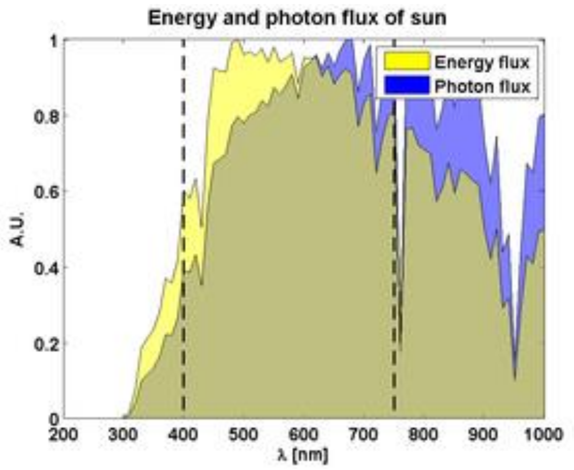


Figure 2. Relative correlations between solar radiation energy and photon flux, and the radiation wavelength

energy quantity of a blue photon is 2.8 eV and red a mere 1.8 eV) it is revealed that photons with a short wavelength actually reach the ground in slightly smaller numbers than those of red and infrared ones (Figure 2, blue graph).

The energy radiated by the sun which reaches the ground is more than enough to cover the needs of humankind more than 10,000 times over. Green plants and algae absorb 32% of the solar energy that reaches the Earth, about 8% of it (0,3*0,08 => 2.5%) is used for photosynthesis (synthesising organic matter) (http://galspace.spb.ru/index115.html). Humankind could cover all of its needs if it used only 2%. Then, coal, gas and oil could all remain in the earth. The energy of the future will undoubtedly be linked to solar or photovoltaic cells, or PVCs, which convert luminous energy directly to electricity.

The photovoltaic effect (creation of free charges upon exposure to light) was demonstrated experimentally by a French physicist named Alexandre-Edmond Becquerel in 1839. The Russian physicist Alexander Stoletov constructed the first photoelectric element in 1888, based on the photoelectric effect discovered by Heinrich Hertz. In 1905, the German physicist Albert Einstein explains the nature of the photoelectric effect—the energy of the photon hitting a metal surface is used to eject an electron, and to give kinetic energy to that electron. This earned A. Einstein the Nobel Prize in physics in 1921.

The first silica-based solar element was constructed after World War II. US and USSR space crafts were already equipped with solar elements in 1958. From that time, silica refinement technologies have developed and the solar cell efficiency coefficient has grown from 6% in 1958 to 20%, their production is growing at an ever-increasing pace, and yet humankind converts an insignificantly small amount of solar energy to electricity. Figure 3 lists the countries where solar power use finds most widespread national and popular support.

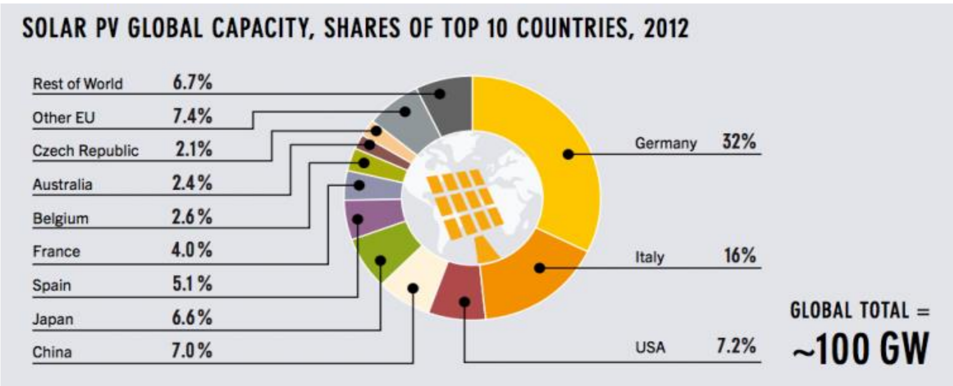


Figure 3. Energy produced using soar cells by

How a solar cell works

In order to understand how a solar element converts sunlight directly to electricity, we must remember the properties of semiconductors.

Semiconductors are mostly crystalline solids, which means their atoms or molecules are arranged in a highly ordered manner, forming a crystal lattice. These include some pure elements (silicon, germanium, selenium, tellurium, arsenic, phosphorus and others), many oxides, sulphides, selenides and tellurides, some alloys, many minerals etc. Electric properties make them widely used in modern industry. In all conductors, semiconductors and many insulators, the **electronic** conductivity is of utmost importance.

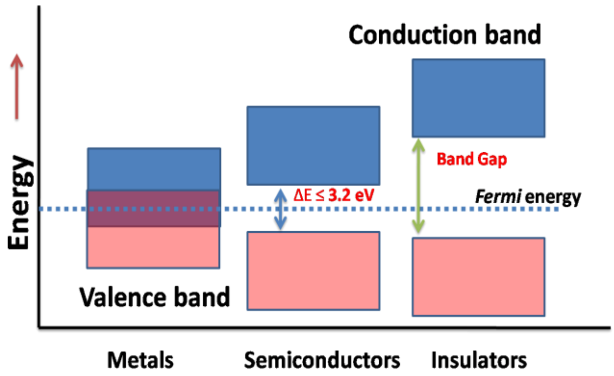


Figure 4. In **metals,** the valence band (pink) and the conduction band (blue) can partially overlap and there is no band gap. In **insulators,** electrons lack the same type of free mobility as the valence band and the conduction bands are divided by a hopelessly large gap (up to 10 eV). In **semiconductors,** the band gap is significantly narrower (1...3 eV). Elecrtons can jump to the conduction band and leave behind a „hole" in the valence band.

Under normal circumstances, semiconductors and insulators lack free charge carriers. The valence band (pink band in Figure 4) is filled with electrons and there is no overlap between the valence band and the conduction band (blue band on Figure 4). The valence band and the conduction band are isolated from each other by a band gap (an energy range where no electron can exist). Insulators and semiconductors simply differ in the size of their band gaps. In insulators, the band gap size is usually such that electrons don't possess enough energy to be excited across the band gap. In semiconductors, however, the band gap is narrower and additional energy from radiation can excite an electron, i.e. provide additional energy for that electron to cross the band gap and leave behind a vacant position in the valence band**. A vacant position like this acts as a positively charged particle and is called an electron hole.** A hole has an identical but opposite charge to an electron ($+1.6\times10^{-19}$ C). Thus, holes and electrons move in opposite directions in an electric field. In an electric field, this place lacking an electron may move within the crystal lattice by being filled with an adjacent electron. This kind of electric conductivity in semiconductors composed of one chemical element is called **intrinsic conduction.**

It differs from **extrinsic conduction**, where additional charge carriers are generated artificially by adding impurities (such as electron acceptors or donors) to the intrinsic (pure) semiconductor in a process called **doping**.

Dopants can be added to semiconductors by thermal diffusion or ion implantation. Hereby it is important to mention that a very small amount of dopant atoms are needed to significantly increase the conductivity of a semiconductor. For example, 1µg of phosphorus in 50mg of silicon reduces its electrical resistivity 100,000 times.

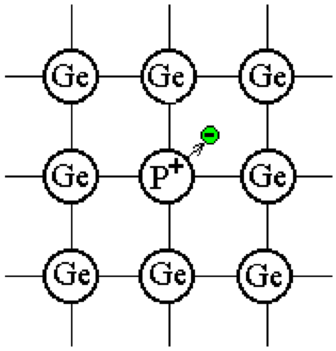


Figure 5. n-type semiconductor
(doped with donor impurities).
The phosphorus atom intoduced to the crystal lattice has one additional valence electron compared to adjecent atoms, this electron will be free to move about in the crystal.

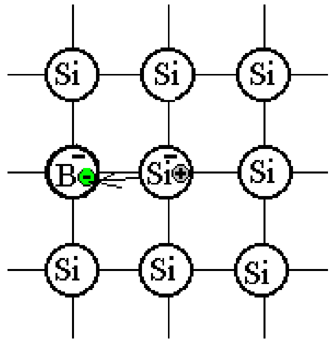


Figure 6. p-type semiconductor
(doped with acceptor impurities).
The dopant (boron) has one fewer valence electon compared to silicon, thus creating a hole that can accept an elecrton from an adjecent silicon atom.

When inserting dopants into a crystal lattice of a semiconductor consisting of atoms that have four valence electrons (for example Si or Ge), we can create two distinct types of semiconductors. When we use an element with more valence electrons (such as P or As) we end up with a situation where there are free valence electrons that can act as a charge carrier. These are called **n-type** semiconductors (Figure 5). Alternatively, when an element with three valence electrons is used as a dopant (such as Al or B), electron holes are created and these, acting as positive charges, can move around the lattice and function as charge carriers. This type of material is known as a **p-type** semiconductor (Figure 6). The diversity of electrical properties and a strong dependence on external parameters makes semiconductors an ideal material for the construction of electronics. Combining p- and n-type semiconductors, we can create a wide array of electronic appliances (light emitting diodes, transistors, thyristors, etc.).

p–n junction

If we create two zones with different types of conductivity in the same semiconductor by doping, then the boundary or interface between the two types (p- and n-type) of semiconductor materials is called a p–n junction. A transition of positive and negative charges takes place at the p–n junction (Figure 7). In the n-type part with donor impurities there is a number of electrons with no suitable place in the lattice. However, the adjacent p-type zone can harbour these electrons due to the electron holes in its structure. Therefore, electrons start moving to the free spaces in the p-zone by diffusion which causes the previously neutral p-zone to acquire a negative charge and the n-zone, having lost electrons, now acquires a positive charge (Figure 7). The diffusion of charge carriers can take place only at the p–n junction, as it is hindered by a forming electrical field E. This electrical field facilitates the transfer of electrons back from the p-zone to the n-zone and the movement of holes back to the p-zone. If we connect the p- and n-zones into

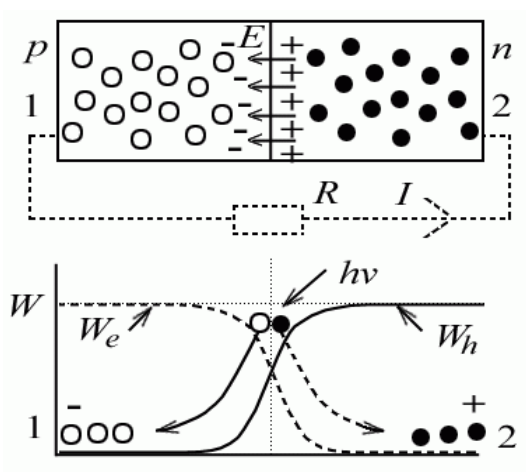


Figure 7. The distribution of charges, the formation of an electrical field E and potential barriers W_e and W_h in the p–n junction. Charges created by light travel towards the lowering of potential.

an electrical circuit we get a direct electrical current. Manipulating various environmental factors, such as radiation or temperature, we can increase the amount of free charge carrier pairs and under the influence of the forming electrical field the electron holes will move into the p-zone and the free electrons into the n-zone, respectively increasing the voltage.
A **solar cell**, also known as a photovoltaic cell, is in essence a device consisting of p- and n-type semiconductors where short wavelength radiation (such as sunlight) can produce current without the cell being connected to an external power source.

Structure of a solar cell

A **solar cell** actually consists of many photovoltaic elements that are connected either in a parallel or a series circuit, depending on the desired current and voltage. These elements can be manufactured from different materials, thus the different classifications:
First generation or conventional cells are made using **crystalline silicon** (can be further divided into monocrystalline and polycrystalline silicon cells) and are currently more available and used more often commercially. Their efficiency is typically between 11% and 17% and a 10 square metre cell can produce up to 1 kW of power and lasts up to 30 years. Monocrystalline cells are black in colour, whereas polycrystalline cells are blue.
Second generation solar cells, also known as **thin film solar cells** use primarily cadmium telluride (CdTe) or amorphous silicon (a-Si) which is deposited in layers using chemical vapour deposition. This allows the production of both thicker yet stiff as well as very thin and flexible solar cells. The efficiency for these cells is somewhat lower compared to crystalline silicon, with production models ranging between 3% and 11%. A 10 square metre cell would be able to produce around 500W of electricity with an average lifespan of 10 years. These cells are uniformly grey in colour.

A solar cell resembles a card, where different layers are stacked and laminated under a press (Figure 8). The layers consist of the following materials:

- glass cover
- anti-reflective coating
- the front electrode (on the illuminated side) is in the form of a mesh or thin strips
- a thinner layer of n-doped semiconductor (so the light could pass through to the p–n junction)
- a thicker layer of p-doped semiconductor
- back electrode

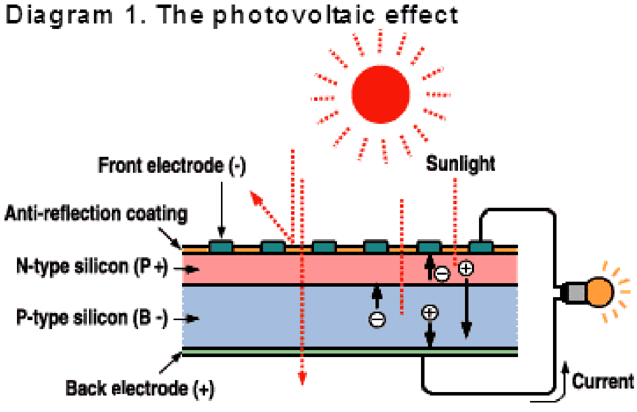


Figure 8. The layered structure of a solar cell.

When all the layers have been laminated together, an aluminium frame is attached around it and cables are connected. The end result is a structure where the illuminated n-doped side acquires a negative charge and the p-doped side a positive charge, like in a battery resulting in an electrical potential difference (voltage). If we connect the two sides of a solar cell into a circuit, then electrons from the illuminated n-doped side will start flowing to the p-doped side, where they recombine with electron holes. Usually within the circuit we would also have either a lamp, a heating source or any other appliance consuming the electricity produced where the electrical current would do work producing power. To harness solar energy effectively, single solar cells are assembled into modules or so called “solar panels”.

Solar cell efficiency

The efficiency of transforming solar energy into electrical energy by a solar cell depends on the quality of the crystalline or amorphous material used, the surface area of the p–n junction, losses suffered due to reflection, temperature, spectral sensitivity and the absorption of radiation within the material. The spectral sensitivity of a cell based on silicon (Figure 9) is greater in the longer wavelength part of the spectrum. In the visible light part of the spectrum, the absorption spectrum of silicon is similar to the photon flux coming from the Sun (see Figure 2).

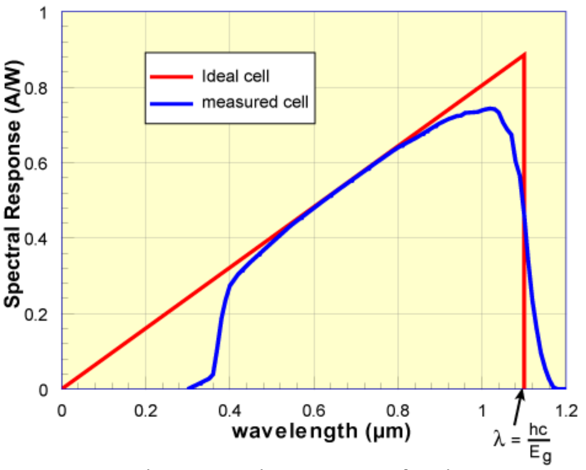


Figure 9. The spectral sensitivity of a glass covered silicon cell. Silicon absorbs less blue light and more red light. The glass absorbs UV-light.

The electrical properties of a solar cell are described using a current–voltage characteristic or I–V curve (current–voltage curve, Figure 10). In an electrical circuit consisting of a solar cell, a voltmeter, an ammeter and a load resistance R (Figure 11), the voltage and current are measured at different resistance values at a constant temperature and light intensity. The maximum current corresponds to R = 0 Ω and is called the short circuit current (I_{sc}). By gradually increasing the resistance we get the I–V curve, at the other end of which the current drops to zero and the voltage is equal to the open circuit voltage (U_{oc}) – the highest voltage produced by the solar cell without an electrical current. I_{sc} and U_{oc} depend on environmental factors (Figure 12). The higher light intensity is, the more electron–hole pairs are formed and therefore a higher current I_{sc} is achieved. The conductive properties of a solar cell as a semiconductor is strongly dependent on temperature. Electrons that gain energy from heat may jump to the conduction band from the valence band more easily, but equally will recombine with holes at a much higher frequency. The electrical field at the p–n junction is weaker at higher temperatures, therefore resulting in a lower potential difference between electrodes. Hence, the lower the temperature, the higher the voltage U_{oc}.

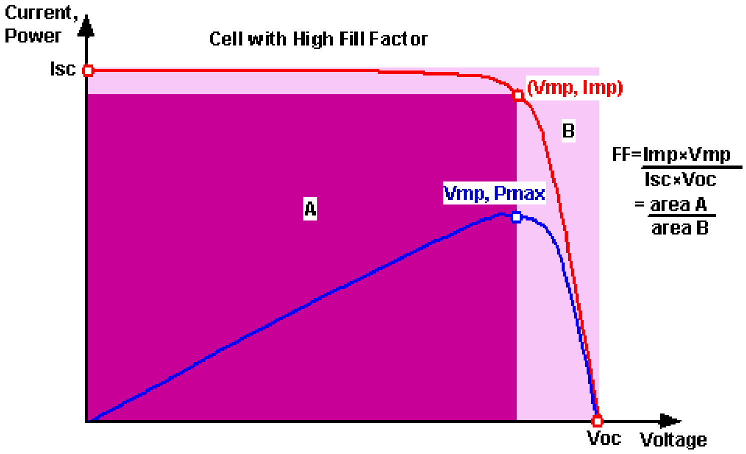


Figure 10. Current–voltage (red) and power–voltage (blue) characteristics of a solar cell.

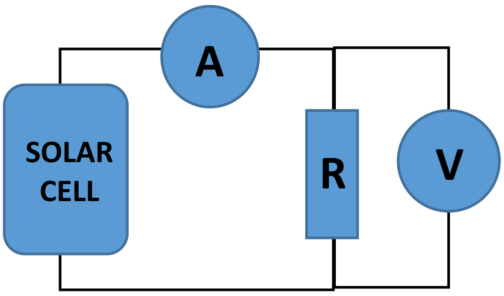


Figure 11. Electrical circuit diagram for measuring the current–voltage characteristic of a solar cell.

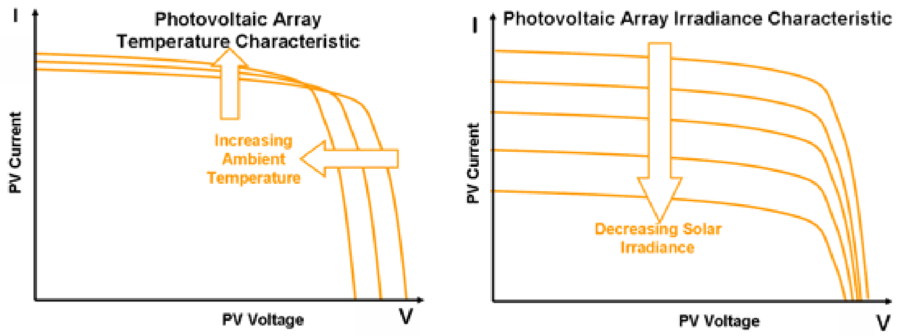
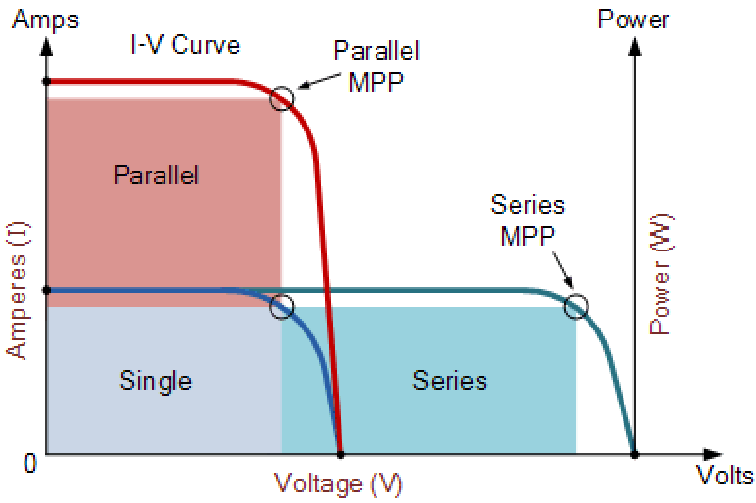


Figure 12. The I-V curve shape depends on the temperature and irradiance.

Short circuit current and open-circuit voltage are the maximum current and voltage values that can be produced by the solar cell. However, at these points on the I–V curve, power is equal to zero (as P = I×U). However, consumers are interested specifically in power. The theoretical maximum power output of a solar cell would be equal to $P_{max} = I_{sc} \times U_{oc}$ which is the area of the light pink rectangle B in Figure 10. When we use the data from the I–V curve to calculate the power of the electrical current, we can see that power is maximal at the kink of the curve (the blue curve in Figure 10) and the actual maximum power $P_{mp} = I_{mp} \times U_{mp}$ is equal to the area of the dark pink rectangle A (about 80% of the theoretical maximum).

If we connect the points (0;0) and (U_{mp};I_{mp}) we get a line where the slope (I_{mp}/U_{mp}) is equal to the conductance of the solar cell (a reciprocal value of internal resistance). From this, we can make an important conclusion: when resistance R is equal to the internal resistance of the solar cell, then the resulting power output is maximal at a given temperature and irradiation. However, changes in temperature and irradiation values in turn bring about changes in the shape of the I–V curve I_{sc}, U_{sc}, I_{mp}, U_{mp} as well as the resistance at maximum power (R_{mp}, Figure 12). As mentioned above, depending on our needs, we can connect solar cells in series or in parallel. A series circuit gives a higher open-circuit voltage, whereas a parallel circuit gives a higher short circuit current (Figure 13).



Joonis 13. The I–V curve shape depends on the way solar cells are connected (in series or parallel)

<u>**Practical tasks**</u>

Materials: solar cell, LED light fixed to a stand, lux-meter (a tool for measuring illuminance), 2 multimeters, resistance box, wires.

LED-light

Lux meter.

Resistance box, correct connection at 1.5 kΩ

Practical task 1. Solar cell short circuit current dependence on illuminance.

ATTENTION! The light emitted by the LED is very bright, do not look directly into the lamp!

1. Measure and note down in the protocol the surface area of the solar cell.
2. Connect the solar cell and multimeter, used an ammeter to the resistance box. Choose the 20 mA direct current (DC) measuring range (sockets COM and mA);
3. Bring the light source to the highest possible position on the stand.
4. Place the solar cell under the light source and next to it place the detector of the lux meter.
5. In the protocol prepare the following table: (for at least 6-7 mesurements)

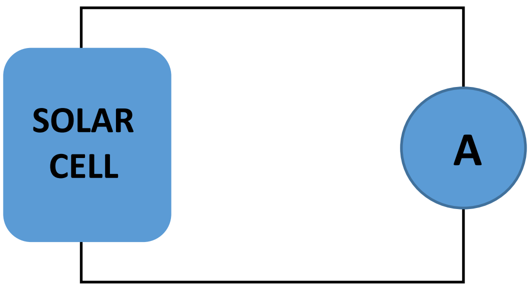


Figure 14. Circuit diagram for measuring short circuit current

Table 1.
Surface area of the solar cell S = ………… cm^2

Illuminance E, lx	Power of light P_v, W	Short circuit current value, mA
(measured)	(calculated according to, formula (2))	(measured)
1.		
2.		

6. Turn on the lux meter (bottom switch, middle position). For measuring weak light choose the lowest setting (2000, upper switch, lower position). You should see “**x1**” written at the bottom of the screen. Measure the first short circuit value at ambient light conditions.
7. Plug in the AC adapter of the lamp and continue measuring the illuminance **E** and the corresponding current **I**. Repeat the measurements by lowering the lamp in 6-7 cm increments up to 10-12 cm distance between lamp and solar cell. At some point you will need to choose a higher measurement range for the lux meter. The text at the bottom of the screen reading “**10x**” means you have to multiply the reading by 10, when it reads “**100x**” you will need to multiply the reading by 100.
8. **When you have finished your measurements, switch off the lamp and the lux meter.**

Practical task 2. The current–voltage characteristic and the energy conversion efficiency of a solar cell.

Fig. 15.

1. Build an electrical circuit according to the photo in Figure 15. set one multimeter to the 20 mA DC range (sockets COM and mA) and the other to the 2V DC range (later on 20V; sockets COM and V)
2. Set the initial resistance R = 0 on the resistance box
3. Set the height of the lamp so that the illuminance underneath it would be approximately **3000 lx**. Note down the exact value as it will be necessary for determining the energy conversion efficiency! Place the solar cell in place of the lux meter detector and make sure that the cells position and illumination remains the same during the experiment.
4. In the protocol prepare the following table:

Illuminance ……….. lx = ……………W Table 2.

Resistance R, Ω	Voltage U, V	Current I, mA	Power P_e=I·U, W	Efficiency Pe/Pv
(given)	(measured)	(measured)	(calculated)	(calculated)
0				
500				
1000				
2000				
3000				
5000				
8000				
20000				
50000				
∞				

5. Measure the I-V curve with one solar cell.

Practical task 3 (teamwork). Connecting single solar cells into a solar panel.

Put together a team of 2-3 people who have finished the previous experimental tasks roughly at the same time.

1. Connect the solar cells of your team (2-3 cells) into a parallel and a series circuit (electrical diagrams at the end of manual, Fig 16 a, b) and measure the I–V characteristics of the circuits at a similar light intensity as you did for a single cell (**around 3,000 lx**). Note down the results in two separate tables.

Number of solar cells …… Circuit type: series/parallel

Illuminance ……….. lx =………W

Table 4.

Resistance R, Ω	Current I, mA	Voltage U, V	Power P_e=I·U, W	Efficiency Pe/Pv
(given values)	(measured)	(measured)	(calculated)	(calculated)
0				
As in Table 2.				

Calculating the energy conversion efficiency

The energy conversion coefficient shows how much of the radiation energy hitting the solar cell surface is being converted into electrical energy. The efficiency is presented in per cent and calculated using the following formula:

$$\eta = \frac{P_e}{P_v} \times 100\% \qquad (4)$$

Finalising the report (see example)

Every report must contain the title of the practical task, the name of the author, tables with data and calculations, formulas used for calculations and graphs. Important results must be highlighted and be accompanied by comments (conclusions). **The questions must be answered in written form.**

Results

Summarize your results in the table

Number of cells	Connection	Power of light	Short circuit current **Isc**	Open circuit voltage **Uoc**	Theor. max power **Pmax = Isc·Uoc**	Effective power of electrical current **Pmp**	Max solar cell efficiency **η**	Relation of effective power to theoretical **Pmp/Pmax**
tk.		mW	mA	V	mW	mW	%	%
1								
1								
2-3	parallel							
2-3	series							

Questions

1. Does a solar cell work with UV-radiation? What about heat radiation (infrared)?
2. What does the short circuit current value depend on?
3. How do semiconductors differ from metals?
4. What is semiconductor doping?

Conclusion

Comment on your results. Compare single and connected solar cells parameters.

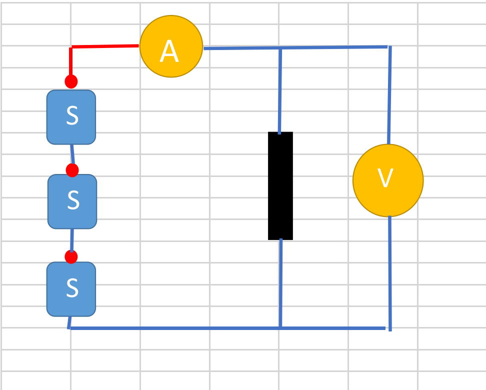


Figure 16a. Electrical circuit diagram for measuring the current–voltage characteristic of a solar cells in series circuit.

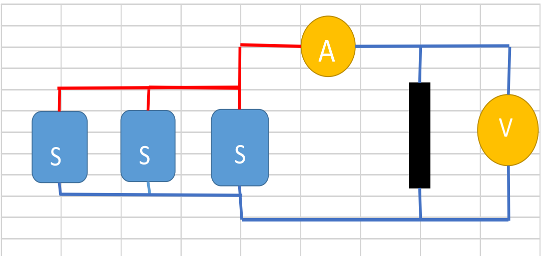


Figure 16b. Electrical circuit diagram for measuring the current–voltage characteristic of a solar cells in paralleel circuit.

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