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LABORATORY INSTRUCTION NO. 8-OS a

CHARACTERISTIC OF SOLAR CELLS

1. Purpose & range of the exercise

The exercise aims to familiarize students with the following topics:
• Measuring the current-voltage characteristic of solar cells,
• Calculating parameters of electric photovoltaic cells in constant lighting conditions.
• Series- and parallel-connected photovoltaic cells.

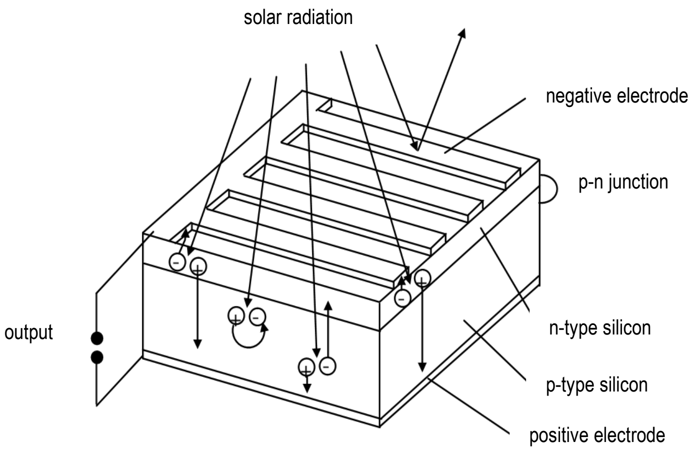
2. Scope of exercise

The basic construction block of any photovoltaic system is a solar cell (photovoltaic). When exposed to sunlight, it produces direct voltage.

Solar cells can be grouped and connected with each other to create photovoltaic modules.

A photovoltaic cell includes the following elements:

- a silicone plate, mono- or polycrystalline, in which a p-n junction has been created,
- electrical contacts (front and rear electrode - the front electrode should be shaped in such a way that it enables the maximum amount of radiation to reach the junction area, the depth of which is limited by radiation penetration depth in silicon),
- anti-reflective layer coating the cell's front.



Principle of photovoltaic conversion is illustrated in Figure 1.

Absorption of light in semiconductors is achieved through releasing electrons from atomic chemical bonds. To produce a free electron within a certain semiconducting material, a portion of energy at least equal to the energetic gap energy E_g must be provided (for silicon in 300 K, E_g = 1,12eV). When an electron is set free, it leaves behind a hole, which, having a positive charge, can move (through diffusion or under the influence of an electric field).

Fig. 1. Scheme of photovoltaic conversion in a silicon solar cell (not in scale)

If the p- and n-type areas of a semiconductor form a p-n junction, in the moment of connection, a very large electron & hole concentration gradient will exist at the border of both areas. This gradient drives electron diffusion from n- to p-area, as well as hole diffusion in the opposite direction (from p- to n-area). As a result of diffusion, a space charge is formed next to the junction line. On the n-area side, the charge is positive, because electrons have moved from this area, leaving behind uncompensated positive charges of donor ions, but also because positively-charged electron holes have shifted into the area; on the p-area side, the charge is negative, because - through a similar diffusion process - an area of negatively-charged, immobilized acceptor ions has been created, but also because of the electrons, which shifted towards this area from the n-area. This way, in the p-n junction area, a region of space charge is formed (dipole space charge region). Within this region, a potential barrier and an electric field, directed from n- to p-area, is created. The field counteracts further diffusion and limits the diffusion current to a certain value. Aside from majority carriers, botch areas of the junction contain minority carriers, forming as a result of generating thermal electron-hole pairs. A potential barrier, created through majority carrier diffusion, encourages the flow of minority carriers from both areas. Movement of these carriers is known as dark current. Its direction is opposite to the direction of diffusion current.

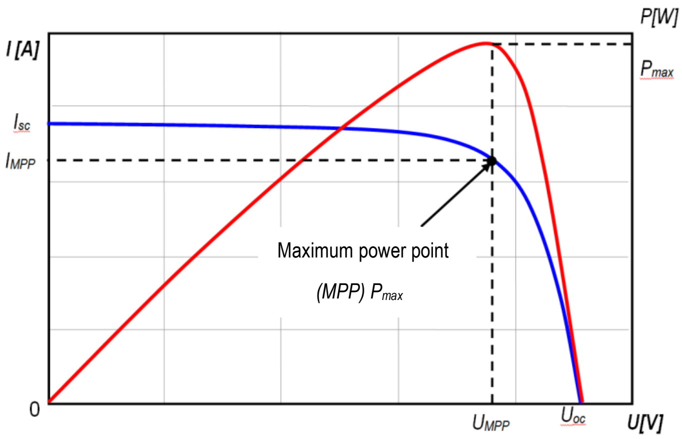
If the p-n junction is exposed to photons, which have an energy equal or higher than the width of the energetic gap E_g, then electron-hole pairs are formed on both sides of the junction, as with thermal generation. Carriers forming in a distance from the potential barrier, which is smaller than the route of diffusion[1] of minority carriers, will reach the potential barrier through diffusion and will be separated by the electric field, related to the existence of a junction. This field shifts both types of carriers in opposite directions - electrons towards the n-area, and holes towards p-area. This charge distribution forms a potential difference U across the junction. Because of that, in a closed circuit, a photoelectric current I is created, which has the same direction as I_{s0} current and, similarly to I_{s0}, does not depend on height of the potential barrier.

A current-voltage characteristic of a PV cell/module is a graph illustrating the photovoltaic generator's output current in a function of voltage, at specific temperature and radiation intensity.

Distinctive points of the curve *I(U)* have been presented in Figure 2:

1. open-circuit voltage (U_{oc}) – voltage at the endings of an unloaded (open) photovoltaic generator, at specific temperature and radiation intensity.
2. short-circuit current (I_{sc}) – photovoltaic generator output current in short-circuit, at specific temperature and radiation intensity.
3. maximum power point current I_{MPP}
4. maximum power point voltage U_{MPP}
5. fill factor of a current-voltage characteristic *FF*

Actual current-voltage characteristic curve can be measured by changing voltage in a connected circuit with a regulated ohm resistor.



For every pair of U, $I(U)$ values on the characteristic curve, electric power can be determined as a product: $P = U \cdot I$. MPP (maximum power point) is reached, when power P (red curve) reaches maximum value:

$\boldsymbol{P_{MPP} = U_{MPP} \cdot I_{MPP}}$.

FF - a parameter describing the quality of a photovoltaic cell/module: $\boldsymbol{FF = P_{MPP}/(U_{oc} \cdot I_{sc})}$.

Fig. 2. Current-voltage characteristic and power as a function of voltage

A pair of *I and U* values, related to the photovoltaic cell's work point, may be determined graphically. To do so, the load graph of the resistor has been plotted onto the *I(U)* graph. The work point is determined by the intersection of load line and the cell's characteristic curve.

[1]Route of diffusion – average distance, which the minority carriers need to cross before they are recombined with majority carriers.

Optimal resistance load (R_c in Fig.3) determines the maximum power point: $\boldsymbol{R_{opt} = U_{MPP}/I_{MPP}}$.

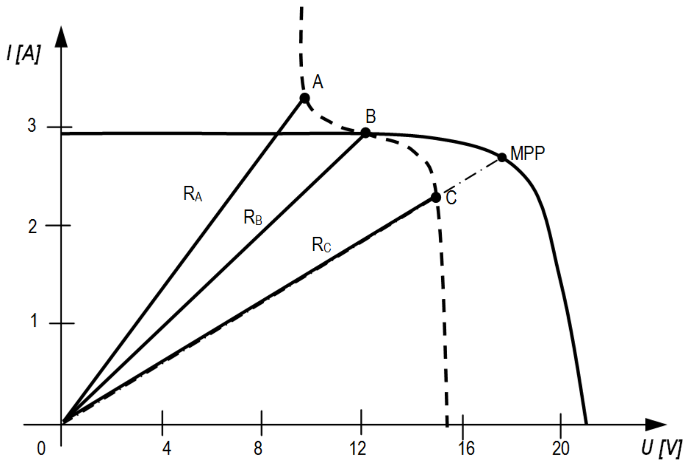


Fig. 3. Current-voltage characteristic of a PV module, and the load characteristic for 3 different load values A, B and C

Set of experiments for the study:

A. The *I-U* curve measurement, cell's optimal work point, determining maximum power, conversion efficiency and the characteristic's fill factor

B. Connecting cells, maximum current, voltage and power of a system of series-/parallel-connected photovoltaic cells.

3. Description of the experimental station

Light intensity, temperature and electrical load have direct influence on photovoltaic cell's electrical parameters.

A lighting system, allowing intensity regulation, lights four solar cells. The cell's temperature is kept at a constant level with a Peltier module.

The provided set of cables and a switchboard are used to connect the cells in a series or in parallel. Variable load electrical resistor, built into the switchboard, enables manual calculation, based on the measured current--voltage characteristic curve. A diode can be attached parallel to every cell in order to study the effects of shading.

Measurements of the characteristic curve may be automated with a built-in current release system, controlled with software and allowing constant modifications of the electric load. A system of software-operated sensors is used to measure light intensity, current, voltage and temperature.

3A. Lighting

The lighting unit contains 16 singular halogen lamps, used for illuminating solar cells. Lighting intensity can be regulated through software, by setting a specific value, expressed in [W/m^2]. After setting the value, regulate the lamp's intensity with the lighting unit's power supply, until it reaches desirable lighting level. Light intensity can be regulated within the range of 200 W/m^2-800 W/m^2. If achieving desired value is impossible, an error message will be displayed.

3B. Solar cells

The system contains four monocrystalline cells. Front and back of the cells have been connected with a tin-coated copper tape. Cables leading to the switchboard have been attached to the cells' electrical contacts.

A reference solar cell has been mounted between the cells. Its purpose is to measure light intensity. The measured value controls the lamp's intensity.

Heat-conducting assembly base provides heat conductivity between solar cells and the heating/cooling Peltier module, which is used to heat or cool down the solar cells, depending on the temperature set.

3C. Switchboard

The switchboard allows for various connections, using the provided set of cables. Red and blue cables in different lengths, as well as short-circuit plugs are available.

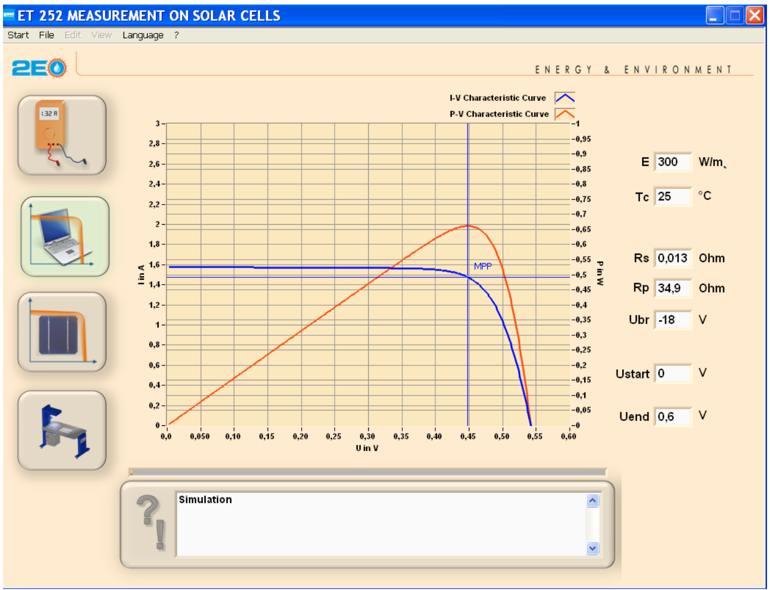
Cables leading to the switchboard have been attached to every cell's front and back contacts.

3D. Measuring & control unit with automatic current release

The relay box contains all main components used for measuring and data recording. There's no need to open the box during work.

The measurement is possible only after connecting via USB to the computer, on which suitable software has been installed. Unit's main switch, as well as the switches for lighting unit and Peltier module are placed in front of the relay box. These can be turned on only once, after launching the software used to control all device functions.

3E. Software



The software allows for reading and observing the graphs, as well as conducting the simulation. Icons for switching software functions:

Multimeter - measured values

Simulation

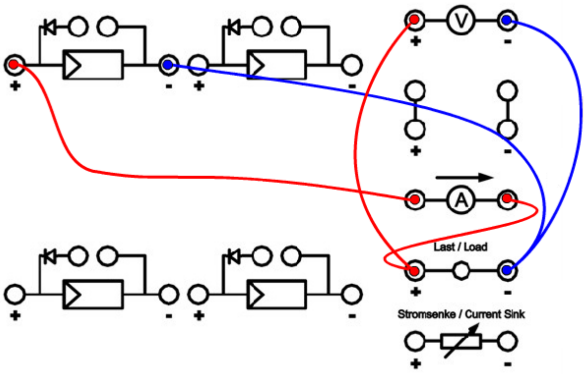
***I-U* and *P-U* characteristic graph**

Exercise module activation switch

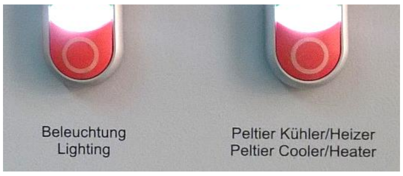
4. The course of exercise

A. **Measuring the *I-U* curve, cell's optimal work point, determining maximum power, conversion efficiency and the characteristic's fill factor**

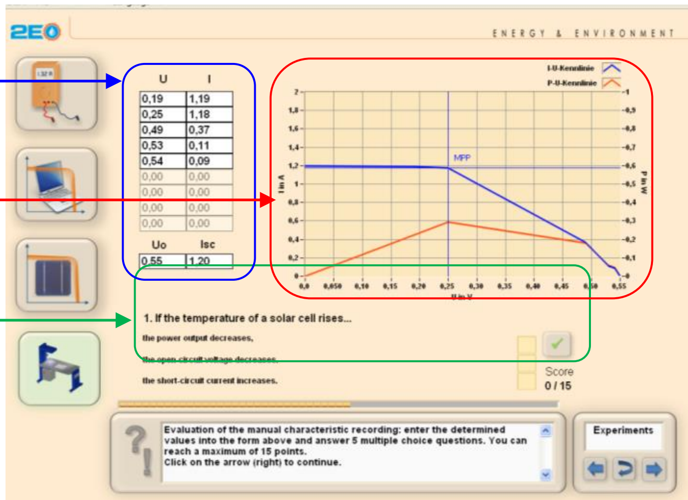
Press the exercise module activation switch.
Press the arrow on the exercise module, until an animation is shown.



A1. Connect the cables according to the figure/animation (current is measured in a series connection, while voltage - in parallel).
After pressing the arrow (lower right corner), a picture of *multimeter is shown*. This space is used to display: current and voltage.
A2. Enable the lighting and the Peltier module, using the switch on the relay box. Set the lighting intensity to 300 W/m² in the ET252 software.



To activate, click anywhere within the program area or press ENTER on the computer's keyboard.
A3. Slowly turn the potentiometer on the switchboard counterclockwise, as far as possible and observe the changes in current and voltage in the ET252 software window.
Write down the current and voltage of the illuminated cell (conduct 5 measurements: for voltage between 0.1 and 0.52 V).
A4. Measure the short-circuit current by directly connecting the cell to an ammeter, and open-circuit voltage by directly connecting the cell to a voltmeter.
Press the arrow on the exercise module, until a table is shown.
A5. Enter the measurement results into the table shown in ET252 software.
Results will be displayed directly on the graph, allowing real-time monitoring of I-U characteristic curve formation*. Red curve represents the solar cell's electrical power (y-axis on right-hand side). Maximum power point (MPP) is achieved in the highest point of red curve.
A6. Answer 5 multiple-choice question, which will be displayed after a moment. Maximum number of points is 15.

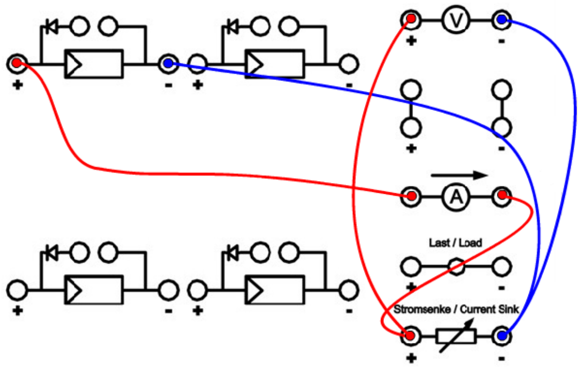


*Attention: adjust maxium values on the graph to the values measured.
A7. Calculate the values: P_{MMP}, $\eta = P_{MMP}/(E\cdot S)$, $R_{opt} = U_{MPP}/I_{MPP}$, $FF = P_{MPP}/(U_{OC}\cdot I_{SC})$.

A'. Automatic *I-U curve measurement*

Press the arrow on the training module to proceed to the next exercise. Press the arrow on the exercise module, until an animation is shown.

A'1. Connect the cables according to the figure/animation.



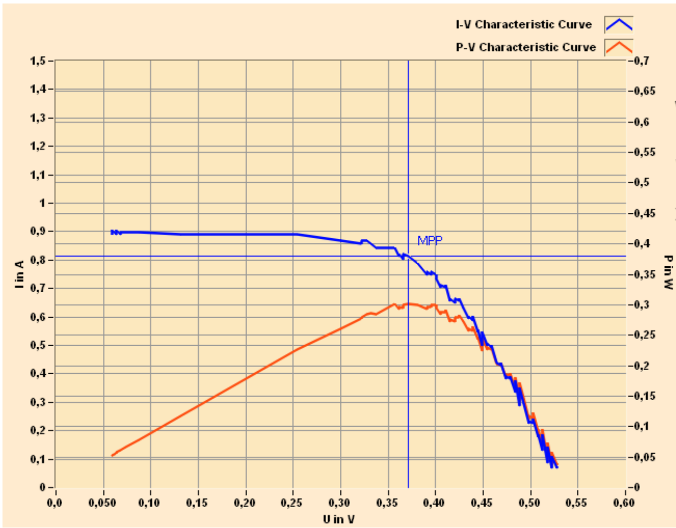
Current is measured in a series connection, in the direction of cell & receiver, while voltage - in a parallel connection.

Instead of the potentiometer, use the current release system socket.

A'2. Utilizing the software

After pressing the arrow in the multimeter's preview, set the temperature to 25°C and cell illumination to 300 W/m².

A'3. After pressing the arrow, a preview of the *I-U* characteristic curve will be displayed. Next step is plotting the characteristic curve, by regulating the intensity in short time gaps.



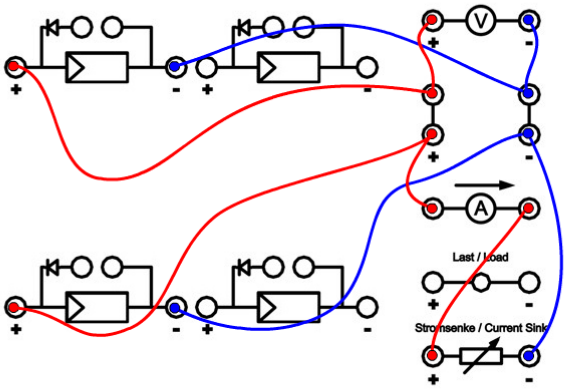
Temperature and lighting control elements are placed on the right-hand side.

Modify the light intensity to observe changes in the characteristic plot.

B. Connecting cells, maximum current, voltage and power of a system of series-/parallel-connected photovoltaic cells

Press the arrow on the exercise module, until an animation is shown.

B1**.** Determining the current--voltage characteristic curve for two parallel-connected solar cells. Perform all the connections according to the figure.



The characteristic curve plot can be observed after pressing the icon Characteristic plot (3rd from the top).

Set the lighting to 300 W/m^2 and temperature to 25°C.

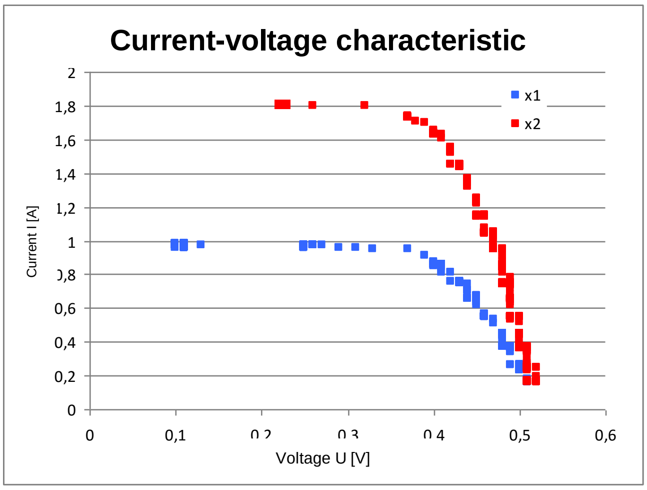
Observe the current-voltage characteristic curve and save the data in a properly named file (file → save graph), e.g. IU_para_2.dat.

Disconnect one of two solar cells and record the following characteristic curve in a different file, e.g.IU_para_1.dat.

After finishing the automatic measurement in manual mode, measure U_{oc} and I_{sc} (according to A4).

When the exercise is finished, copy the obtained results from .dat file into EXCEL software and create a point graph illustrating the current--voltage characteristic curves.

Current--voltage characteristic curves for one cell and two parallel-connected solar cells are presented in the figure.



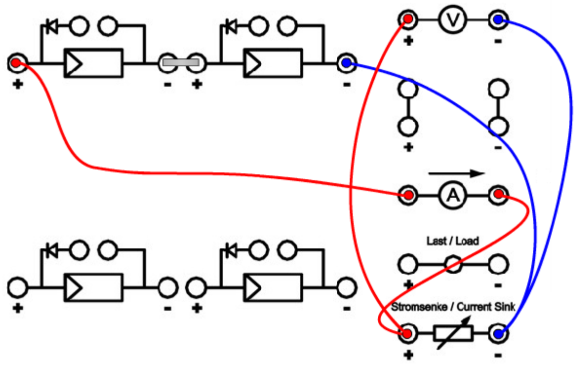
Analyze the results and calculate maximum power and the characteristic fill factor for a single cell and two, parallel-connected solar cells.

	1 cell	2 cells
Open-circuit voltage [V]	0.53	0.53
Short-circuit current [A]	0.91	1.8
Maximum power [W]	0.36	0.65
Fill factor [%]	75	68

Conclusions: in a parallel connection, currents and electric powers of cells add up, while voltage and fill factor remain unchanged.

B2. Determining the current--voltage characteristic curve for two series-connected solar cells.

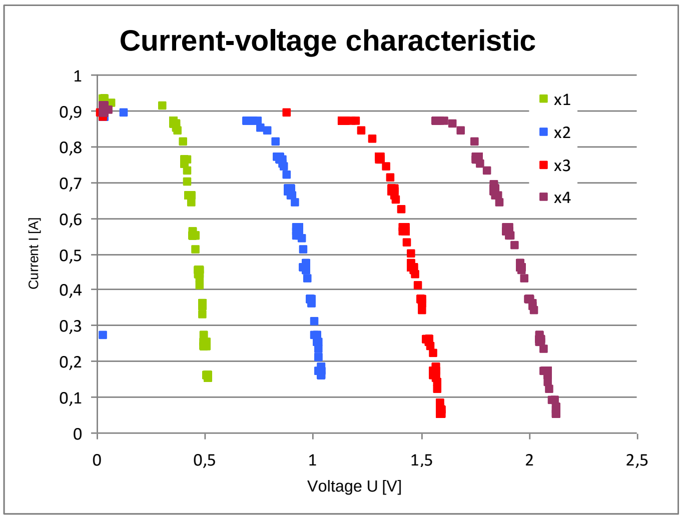
Press the arrow on the training module to proceed to the next exercise.



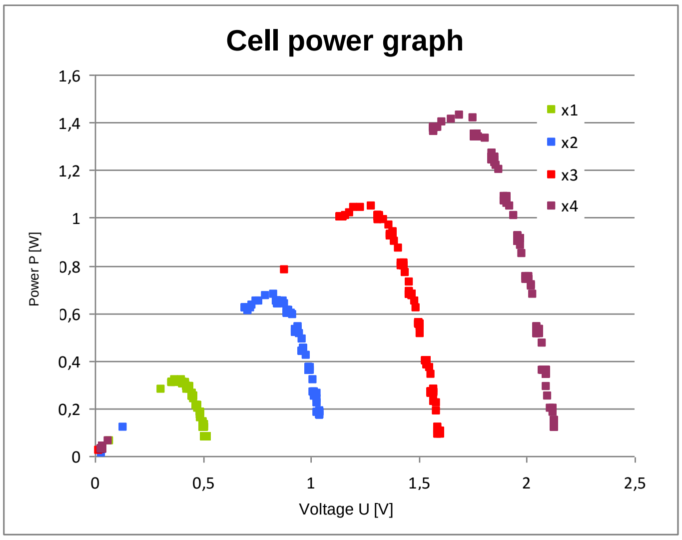
Perform all the connections according to the figure.
Observe the current-voltage characteristic curve after pressing the icon Characteristic graph (3rd from the top), and save the data in a properly named file (file → save graph), e.g. IU_seri_2.dat.

Repeat the measurements for a single cell, as well as for 3 and 4 series-connected cells.
Save all data in a .dat file.
After finishing the automatic measurement in manual mode, measure U_{OC} and I_{SC} (according to A4).

When the exercise is finished, copy the obtained results from .dat file into EXCEL software and create a point graph illustrating the current--voltage characteristic curves.



Current--voltage characteristic curves for one cell and two series-connected solar cells are presented in the figure.
Notice that open-circuit voltages of series-connected cells add up, while currents remains constant.



The figure illustrates results of measurements of electrical power P in a function of voltage for 4 tests. Notice that the power increases with the number of connected cells. Corresponding voltage also shifts towards higher values.

Analyze the results and calculate maximum power
and characteristic fill factor for a single cell and 2-4 series-connected cells. Formulate conclusions.

	1 cell	2 cells	3 cells	4 cells
Open-circuit voltage [V]	0.53	1.04	1.55	2.04
Short-circuit current [A]	0.91	0.91	0.91	0.91
Maximum power [W]	0.36	0.67	1.05	1.41
Fill factor [%]	64	71	74	76

5. Literature:

[1] Ewa Klugmann-Radziemska, Fotowoltaika w teorii i Praktyce, Wydawnictwo BTC, Warszawa-Legionowo 2009

[2] Ewa Klugmann-Radziemska, Odnawialne źródła energii - przykłady obliczeniowe, Wydanie V, Wydawnictwo Politechniki Gdańskiej 2015

[3] ET 252 Pomiary na ogniwach słonecznych, G.U.N.T. Gerätebau, Barsbüttel, Germany 2015