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RENEWABLE ENERGY SOURCES LABORATORY
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# LABORATORY INSTRUCTION NO. 10-PV

# PHOTOVOLTAIC MODULE


### 1. Purpose & range of the exercise

The exercise aims to familiarize students with the following topics:
• Measurement the current-voltage characteristic of a photovoltaic module.
• Calculating the electric parameters of a photovoltaic module in constant lighting conditions.
• Connecting photovoltaic modules in series and parallel.
• Calculating the influence of module angle on its work parameters.

## 2. Scope of exercise

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

Solar cells can be coupled and connected with each other to create photovoltaic modules. Connected modules form photovoltaic panels, the elements of a photovoltaic system, also known as a PV generator or module array (Figure 1).

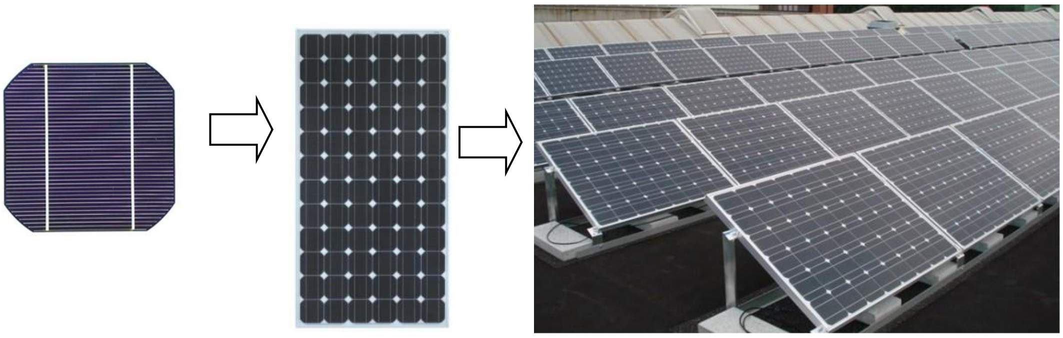


**Figure 1 1.** Photovoltaic cell - photovoltaic module - photovoltaic system

The most important element of a photovoltaic system is a solar module and its parameters (current-voltage characteristic, spectral characteristic, energy conversion efficiency), which decide on the final energetic gain.

PV cells need to be connected, and then laminated, to protect them from damage, because - in form of monocrystalline plates - they're thin and brittle, while, in form of supported thin film - they're utilized as rigid thin plates (in case of glass base) or elastic foil.

The lamination process depends on the cell's production technology and the module's purpose. Connections must maintain good conductivity and reliability for long time periods, regardless of temperature fluctuations and other atmospheric factors, which can have an influence on their operation. Different module electric parameters are obtained, based on the number of connected cells, as well as the type of connection (series, parallel, mixed). In actual implementations, the module's dimensions and weight are also important.

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 characteristic 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. MPP – maximum power point (ang.: *Maximum Power Point*) and its corresponding coordinates: $U_{MPP}$ and $I_{MPP}$.

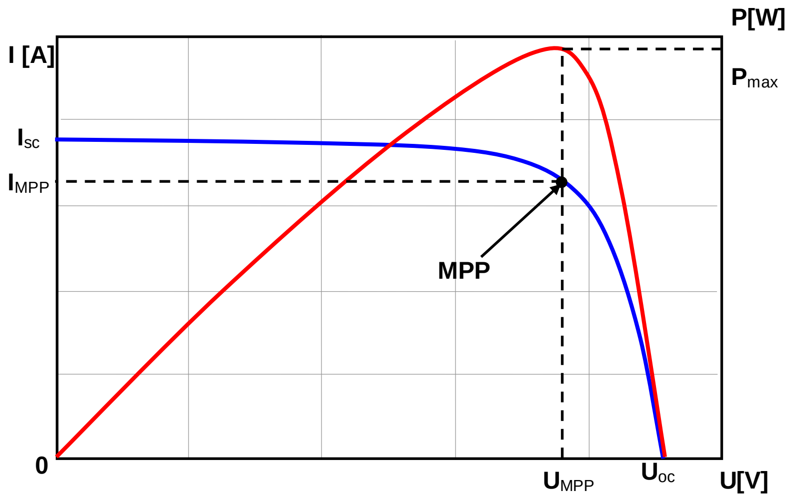



**Figure 2.2** Current-voltage characteristic of a module and generated electric power as a function of voltage

Maximum power point. A decisive parameter in PV module implementation in photovoltaic energetics is maximum power output, which can be achieved at a load resistance, $\boldsymbol{R_{opt}}$, at which the rectangle below the *I(U)* characteristic has the largest surface area, equal to maximum power:

$$P_{MPP} = I_{MPP} \cdot U_{MPP},$$

and the rectangle's intersection with the *I(U)* characteristic is, in this case, the maximum power point (*MPP*). The panel's/module's circuit load resistance *R* should be matched in such a way, so that the power output has a maximum value of $P = P_{MPP}$.
The MPP (Maximum Power Point) is a point, the coordinates of which: $I_{MPP}$ and $U_{MPP}$, form a rectangle with the highest possible surface area under the *I(U)* curve.

***FF*- fill factor of the current-voltage characteristic** – a parameter describing the quality of a photovoltaic cell/module:

$$FF = \frac{U_{MPP} \cdot I_{MPP}}{U_{oc} \cdot I_{sc}} \quad ,$$

$I_{MPP}$ – current value in the maximum power point,
$U_{MPP}$ – voltage value in the maximum power point.

**Photovoltaic conversion efficiency** determines what percentage of solar radiation is converted into useful electric energy. Photovoltaic conversion efficiency of a photovoltaic cell/module $h_{PV}$ can be calculated from the maximum power output:

$$\eta_{PV} = \frac{I_{MPP} U_{MPP}}{E \cdot S_C} \cdot 100\% \, ,$$

where: $S_C$ – panel/module surface area, *E*- solar radiation intensity [W/m$^2$].

Photovoltaic modules can be connected in series, in parallel or in a mixed manner.

In a series connection, current flowing through every cell in the chain remains the same ($I_1 = I_2 = ... = I_{36}$), whereas voltage is added: $U = n \cdot U_i$ (Figure 3 and 4).

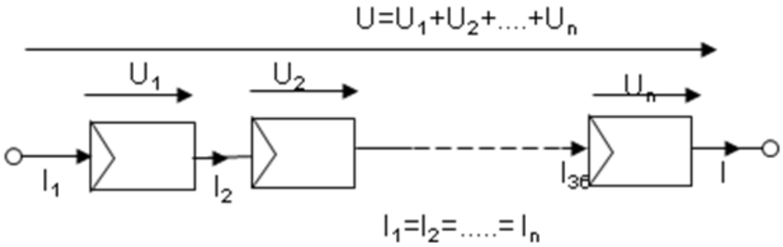



**Figure 3.** Connecting PV cells in a series to obtain a module with desired electrical properties

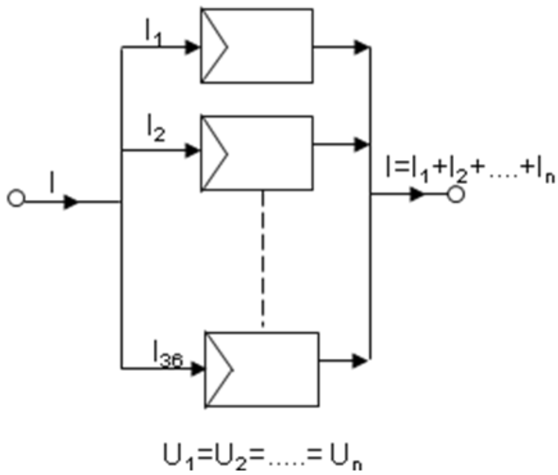



**Figure 4.3** Connecting PV cells in parallel to obtain a module with desired electrical properties

In a parallel connection of generators with the same voltages, the node's input current values are added $I = n \cdot I_i$ (Figure 5 and 6).

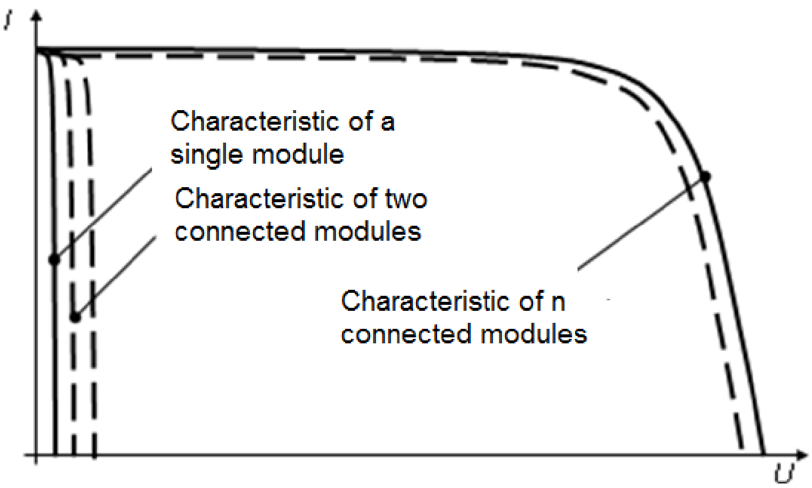



**Figure 5.** Current-voltage characteristic of an installation containing n series-connected modules

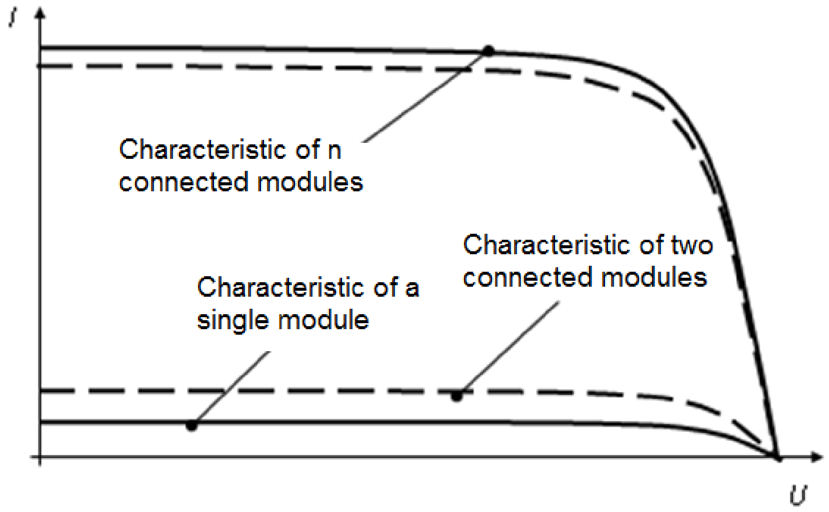



**Figure 4.** Current-voltage characteristic of an installation containing n parallel-connected modules

**Set of experiments for the study:**

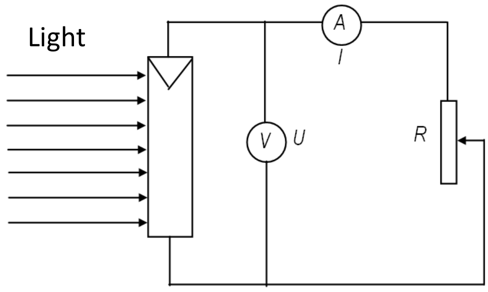
A. Measuring the current-voltage characteristic I-U, series-connected module's optimal work point, determining maximum power, conversion efficiency and fill factor for the characteristic.

B. Measuring the current-voltage characteristic I-U, parallel-connected module's optimal work point, determining maximum power, conversion efficiency and fill factor for the characteristic.

C. Measuring the current--voltage curve I-U and determining maximum power, based on the module's angle**.**

## 3. Description of the experimental station

### 3A. Photovoltaic modules

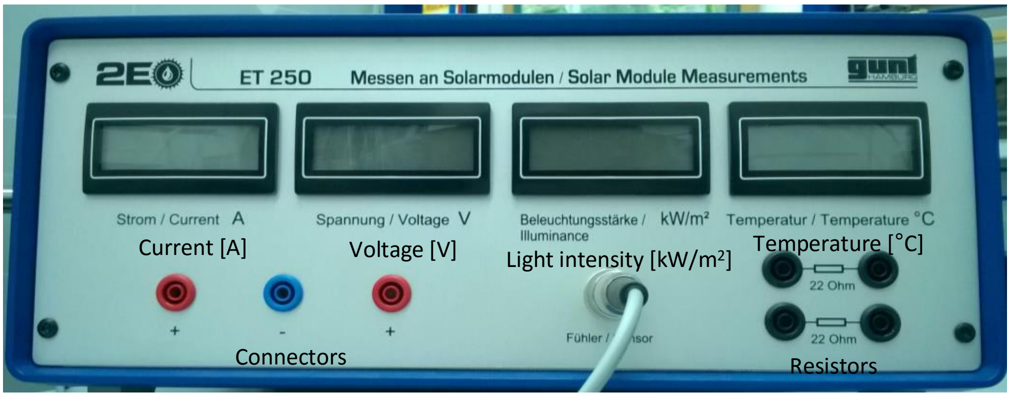



Photovoltaic modules are mounted on a rotating frame. The support allows changing the slope from 0° to 90°. The angle can be precisely set with the attached inclinometer.

Every utilized module contains 36 monocrystalline cells, with a total surface area of 0.557 $m^2$. Without a load, every cell produces approx. 0.6V of voltage. To minimize losses caused by partial shading, the cells have been arranged in two rows, each containing 18 series-connected cells. In case of interference, the circuit is closed with a so-called bypass diode.

### 3B. Measuring unit

The measuring unit allows recording current (*I*), voltage (*U*) and reading the measurement results of radiation intensity, as well as module temperature. All measurement required for described experiments can be read on the measuring unit display.




### 3C. Rheostat

The rheostat provides variable load to the circuit (*R*) within the range of 1 Ω to 10 Ω. Two additional 22 Ω resistors are built into the measuring unit.

### 3D. Illumination and temperature sensors

The illumination sensor is a small, reference solar cell with a specific sensitivity. This sensor enables constant, real-time measurements of light intensity. The measured radiation intensity, displayed on the unit screen, is expressed in kW/$m^2$. The sensor's photosensitive surface is mounted in the same plane as the modules.

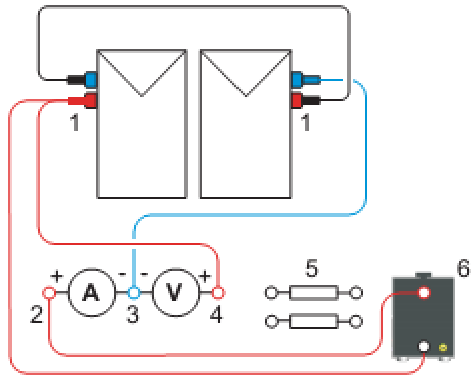
Thermal sensors are attached on the opposite side of the modules with a thermal contact. They analyze changes in resistance (which depends on temperature), based on changes in voltage. Values displayed on the measuring unit are expressed in °C.

## 4. The course of exercise

### A. Measuring the *I-U* curve, optimal work point of a series-connected module, determining maximum power, conversion efficiency and the characteristic's fill factor

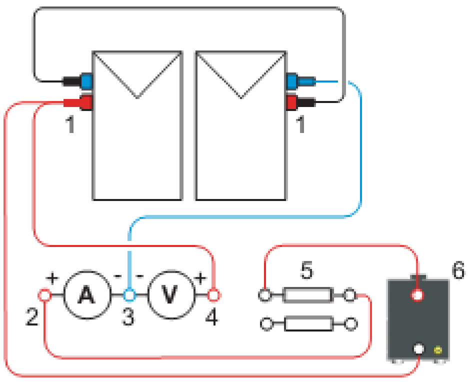
A1. Connect the cables according to the scheme.
A2. Enable the lighting with a switch on the relay box. Read the radiation intensity value (desirable value is approx. 1 kW/m$^2$).
A3. Wait approx. 10 min until the module temperature stabilizes at approx. 50°C (read temperature on the measuring unit's panel).
A4. After the temperature stabilizes, conduct measurements of voltage and current, shifting the rheostat setting. Note the module's temperature during measurement.

1 – PV module connectors;
2-4 – measuring unit connectors;
5 – fixed resistors;
6 – rheostat.



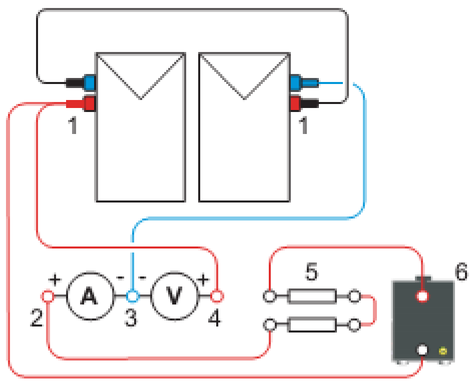

A5. Connect the cables according to the new schematic A and conduct the measurement, similarly to point A4. Next, connect the cables according to the schematic B and conduct a similar measurement.

**A**



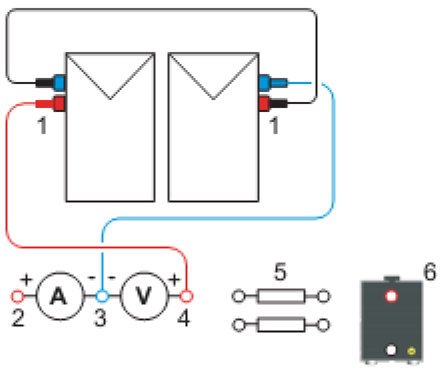

1 – PV module connectors;
2-4 – measuring unit connectors;
5 – fixed resistors;
6 – rheostat.

**B**

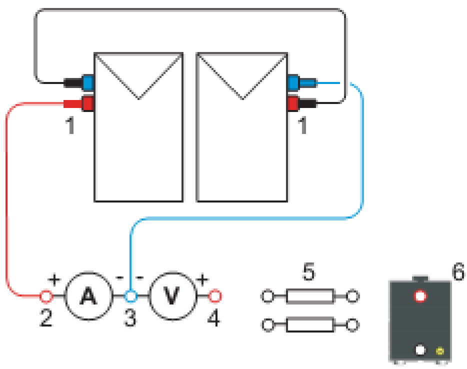



A6. After finishing, measure the open-circuit voltage and closed-circuit current, connecting the system according to the schematics.

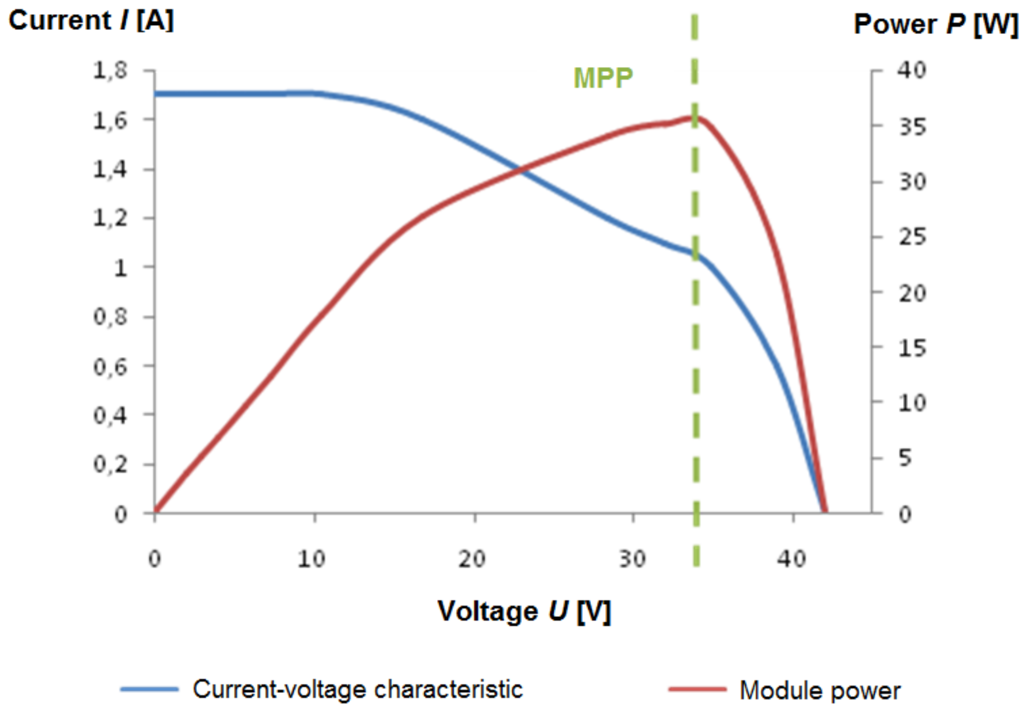
**Open-circuit voltage ($U_{oc}$)**




**Short-circuit current ($I_{sc}$)**




A7. Based on the obtained results, plot a current-voltage characteristic curve, as well as a graph illustrating the dependence of module's power on voltage.




A8. Calculate the values:

- maximum power $P_{MPP}$,
- module efficiency $\eta = \frac{P_{MPP}}{(E \cdot S)}$,
- optimal resistance $R_{opt} = \frac{U_{MPP}}{I_{MPP}}$,
- characteristic's fill factor $FF = \frac{P_{MPP}}{(U_{OC} \cdot I_{SC})}$.

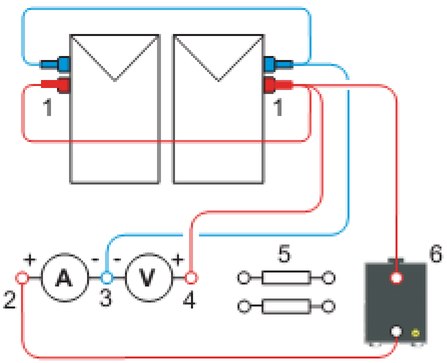
## B. Measuring the *I-U* curve, optimal work point of a parallel-connected module, determining maximum power, conversion efficiency and the characteristic's fill factor

B1. Connect the cables according to the scheme.

B2. Enable the lighting with a switch on the relay box. Read the radiation intensity value (desirable value is approx. 1 kW/m$^2$).

B3. Wait approx. 15 minutes until module temperature stabilizes (temperature can be read on the measuring unit's panel).

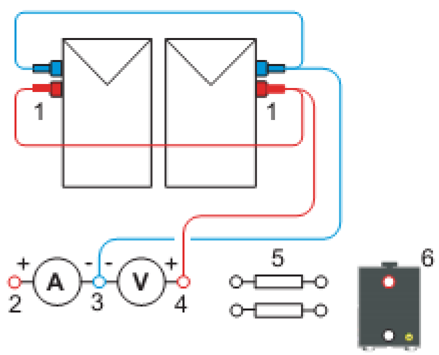
1 – PV module connectors;
2-4 – measuring unit connectors;
5 – fixed resistors;
6 – rheostat.



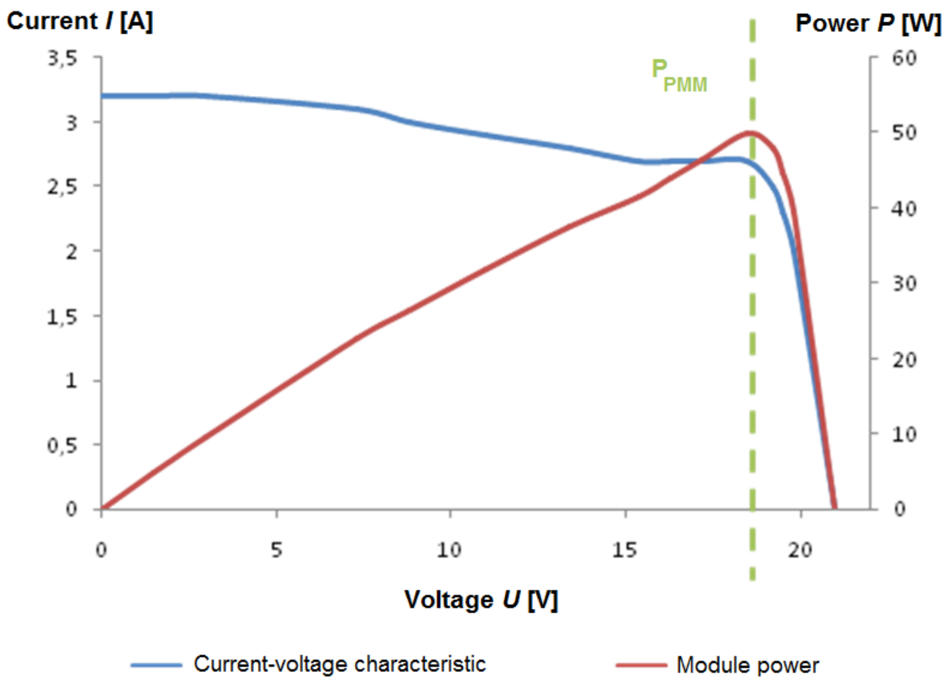

B4. After the temperature stabilizes, conduct measurements of voltage and current, shifting the rheostat setting. Note the module's temperature during measurement.

B5. After finishing, measure the open-circuit voltage and closed-circuit current, connecting the system according to the schematics.

**Open-circuit current measurement ($U_{oc}$)** **Short-circuit current measurement ($I_{sc}$)**




B6. Based on the obtained results, plot a current-voltage characteristic curve, as well as a graph illustrating the dependence of module's power on voltage.



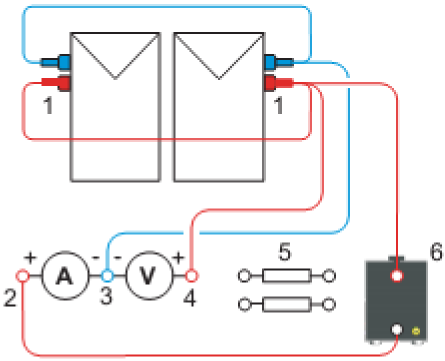

B7. Calculate the values:

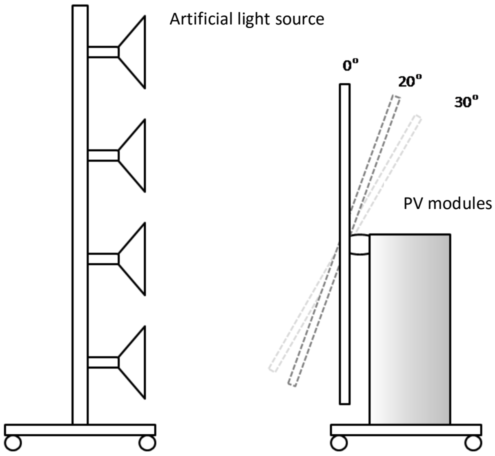
- maximum power $P_{MPP}$,
- module efficiency $\eta = \frac{P_{MPP}}{(E \cdot S)}$,
- optimal resistance $R_{opt} = \frac{U_{MPP}}{I_{MPP}}$,
- characteristic's fill factor $FF = \frac{P_{MPP}}{(U_{OC} \cdot I_{SC})}$.

## C. Measuring the *I-U* curve and determining maximum power, based on the module's angle.

C1. Connect the cables according to the scheme.
C2. Enable the lighting with a switch on the relay box. Read the radiation intensity value (desirable value is approx. 1 kW/m2).
C3. Set the module slope angle to 0° with the inclinometer. Place the inclinometer in the back of the module, and then - using the handle and a wrench, adjust the slope angle, observing the inclinometer's readings.

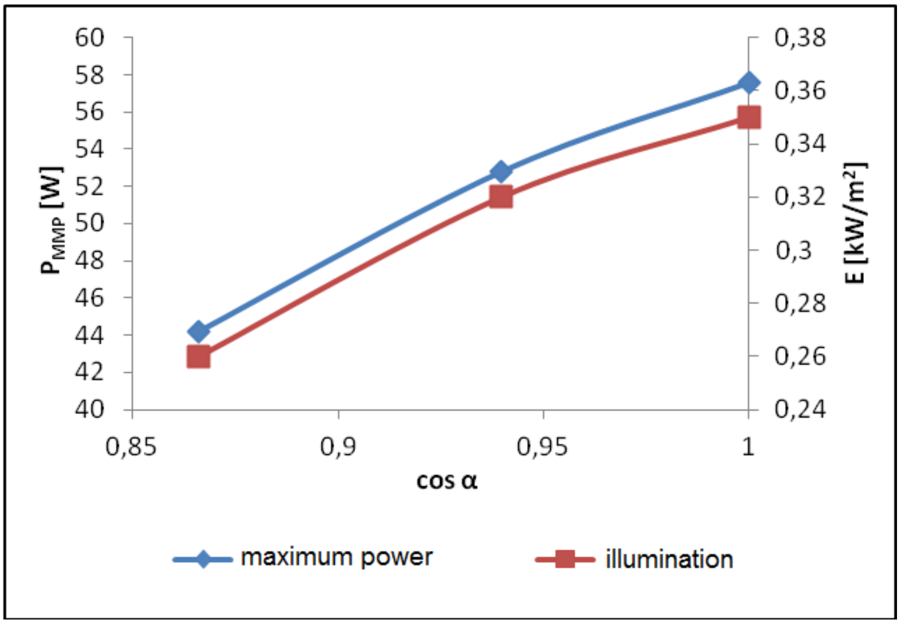
1 – PV module connectors;
2-4 – measuring unit connectors;
5 – fixed resistors;
6 – rheostat.




C4. Wait approx. 15 minutes until module temperature stabilizes (temperature can be read on the measuring unit's panel).
C5. After the temperature stabilizes, conduct measurements of voltage and current, shifting the rheostat setting. Note the module temperature during measurement.
C6. After finishing, measure the open-circuit voltage and closed-circuit current, connecting the system according to the schematics from B5.
C7. After finishing, change the angle to 20° and 30°. Repeat the measurements for both angles, as in B5-B6.

C8. Based on the obtained results, plot current-voltage characteristic curves for every angle.




C9. Calculate the maximum power value $P_{MMP}$.
C10. Draw a graph illustrating the dependence of module's maximum power from its angle and compare it with loss of power graph, calculated based upon the angle's cosine.

## 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 250 Pomiary modułów słonecznych, G.U.N.T. Gerätebau, Barsbüttel, Germany 2015