ENE 411 - ENGINEERING LAB II

PHOTOVOLTAIC ENERGY GENERATION

EXPERIMENT MANUAL

OBJECTIVE

The purpose of this experiment is to analyze the system behavior when the light rays strike the PV panel and a portable rheostat is connected. A second PV panel, connected to the first one in parallel or series, is also available. The photovoltaic panel efficiency is calculated from the behavior of the system.

THEORY

Characteristic Curves of Photovoltaic Generators

The electrical behavior of a cell (or a module, a panel, or a field), is represented with the characteristic curves called characteristic I-V of the generator. The extreme voltage and current values are respectively the open circuit voltage V_{oc} (in correspondence of a null current) and the short circuit current I_{sc} (in correspondence of a null voltage).

The characteristic curve of a module, for a given temperature of the cells and a given value of solar radiation, is shown in Fig. 1. The same figure shows the output power curve equal to the product between the voltage and the current as follows:

$$P = I \cdot V \tag{1}$$

It is equal to the area of the rectangle which sides are the x-axis and the y-axis of the operation point. You can note that there is an operation point corresponding to the maximum power. This point, which is also optimum operation point, is called maximum power point (mpp) of the PV cell.

Usually, the PV generators are provided with a device, called maximum power tracker, which can make the generator operate constantly nearby this point. P_{mpp} can be calculated same as output power.

$$P_{mpp} = I_{mpp} \cdot V_{mpp} \tag{2}$$

Table 1 reports, for a mono-crystalline silicon cell with diameter of 4”, which corresponds an area of 78.5 cm^2, the short-circuit current I_{sc0} and the open circuit voltage V_{oc0} and current and voltage I_{mpp} and V_{mpp} values at a reference condition, which are 1000 W/m^2 of irradiance and 25 °C cell temperature. The maximum efficiency of the cell at the reference conditions is

$$\eta_R = \frac{I_{mpp} \cdot V_{mpp}}{G_R \cdot A_{cel}} \tag{3}$$

where: G_R: is the irradiance on the PV surface at the reference conditions (W/m^2)
A_{cel} is the cell surface (m^2)
V_{mpp} is the voltage at the maximum power point (V)
I_{mpp} is the current at the maximum power point (A)

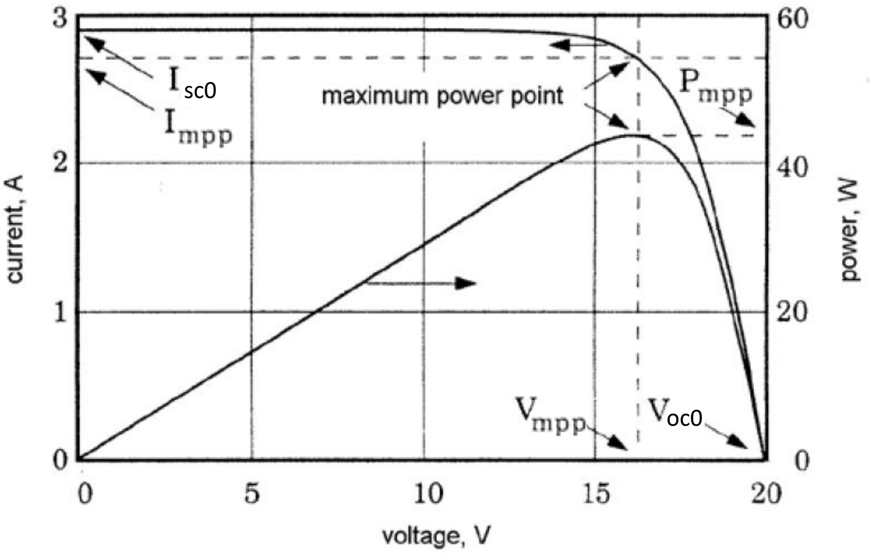


Fig. 1 Characteristics I - V and P – V of a photovoltaic module

Table 1 Characteristic data of a PV silicon cell at the reference conditions

Silicon mono-crystalline cell, 4”-diameter, (A=78.5 cm2)	
V_{oc0}	0.585 V
I_{sc0}	2.3 A
V_{mpp}	0.465 V
I_{mpp}	2.047 A
Efficiency	12.1 (%)

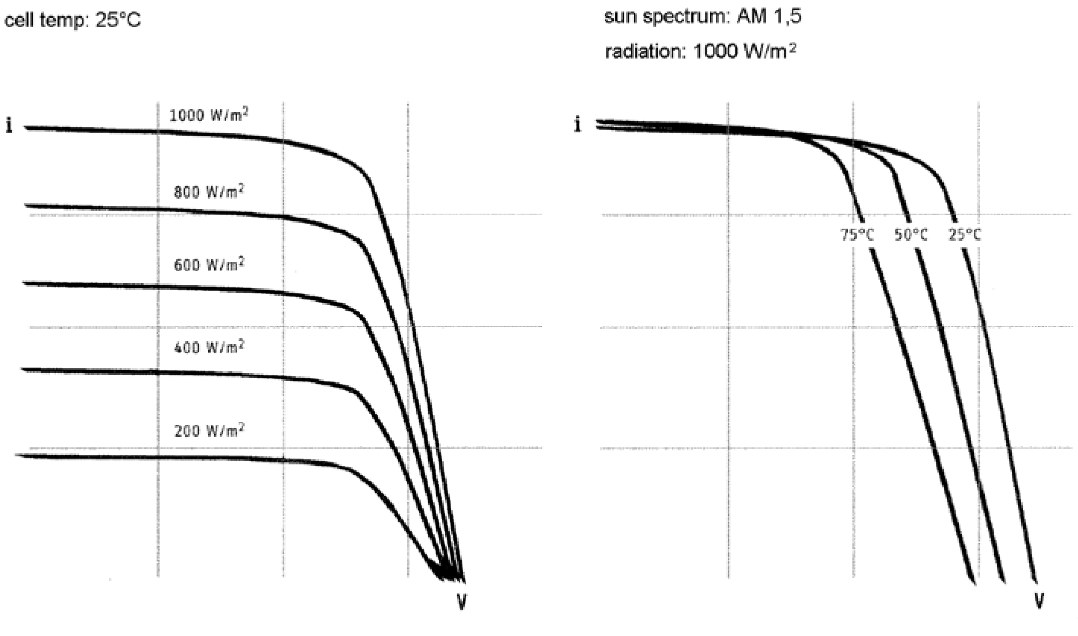


Fig. 2 Current - voltage characteristic of a photovoltaic silicon cell at variation of the solar radiation and the temperature

The performances of a photovoltaic device depend on several variables, among which the most important are:

- → solar radiation;
- → cell temperature;
- → spectrum of incident solar radiation.

Fig. 3.15 shows how the characteristic I-V of the cell varies changing the solar radiation and the cell temperature. As you can see in the graph on the left, the current drops when the radiation drops, while the voltage keeps almost constant. An increase in the cell temperature instead, graph on the right, has only a light effect on the short circuit current (the increase is equal to about the 0.2%/°C), while it negatively influences the open circuit voltage, with a drop of about 2.2 mV/°C (these variations can be taken as reference in the temperature range of 0-60 °C).

Note how the two phenomena, although of opposed sign, practically results in a drop of the given power at the maximum power point, that can be measured around the 6-7% for each increase of 10 °C of the cell temperature.

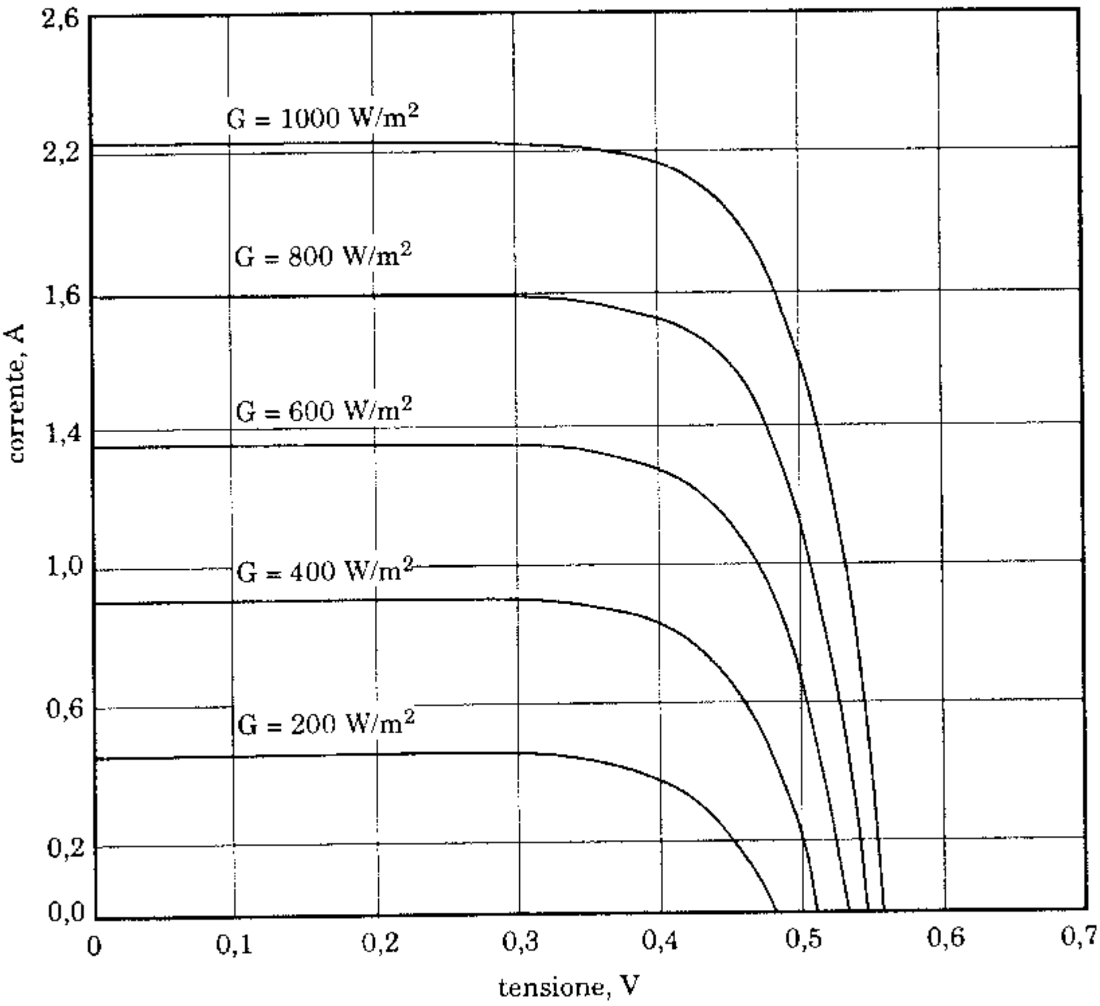


Fig. 3 Characteristic I - V of a photovoltaic silicon cell at variation of the sun radiation

Fig. 3 shows, as an example, the behavior of the characteristic curves of the mono-crystal silicon cell of diameter 4” of Table 1, with respect to variation in the solar radiation.

The next three figures report some of the existent correlations between short circuit current (I_{sc}), open circuit voltage (V_{oc}), maximum power (P_{max}), cell temperature (T_c) and incident solar power (G). In particular, Fig. 4 shows the short circuit current behavior at variation of the incident power once the cell temperature is fixed. Fig. 5 shows the open circuit voltage behavior as function of the incident power once the cell temperature is fixed. Then Fig. 6 shows the short circuit current, open circuit voltage and maximum power behaviors at variation of the cell temperature once the incident power is fixed.

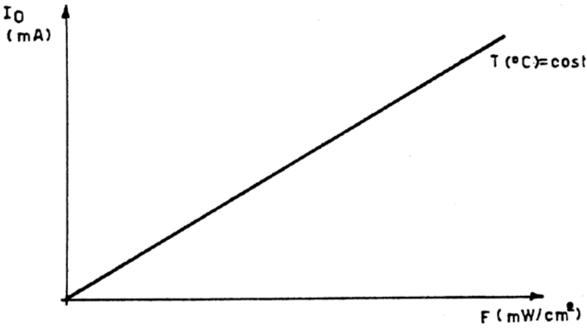


Fig. 4: The short-circuit current behavior at variation of the incident power, once the cell temperature is fixed

Fig. 5: The open circuit voltage behavior as function of the incident power, once the cell temperature is fixed

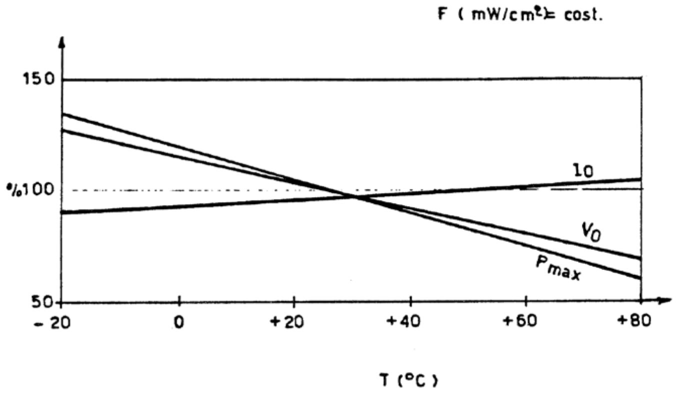


Fig. 6: The short-circuit current, open circuit voltage and maximum power behaviors, at variation of the cell temperature, once the incident power is fixed

So, as the performance of a photovoltaic device depend, in particular, by sun radiation, cell temperature and solar spectrum of the incident radiation, in order to define them it is necessary to fix the reference values for such parameters. The used values, at international level, as test conditions for the cells and photovoltaic modules, are called standard testing conditions (STC). Their values are as follows:

1. radiation = 1000 W/m^2;
2. cell temperature = 25 °C;
3. solar spectrum = AM 1.5.

Note how the maximum power of a cell, a module, or a photovoltaic system, indicated by the manufacturers as peak power, refer to the standard conditions; such value so, considering the real operating conditions, can be reached only for short periods during the system operation.

As the cells are assembled into module, they can be connected in series or parallel to obtain the required voltage. For identical modules (or cells) connected in series the voltages are additional, when the modules are connected in parallel, the currents are additional, see Fig 7.

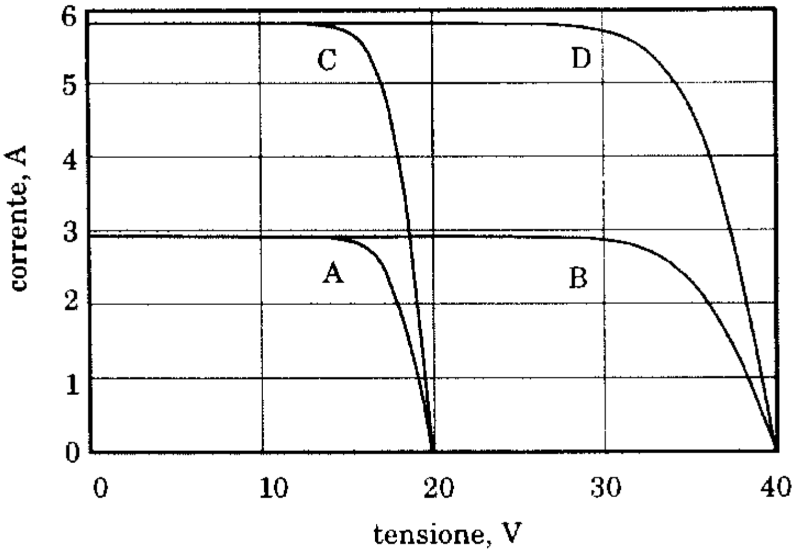


Fig. 7: Characteristic curves of a module (A), of two modules connected in series (B), of two modules connected in parallel (C) and two pairs of modules connected in series (D)

Remember then a parameter that is often used to evaluate the quality of a photovoltaic cell: the “fill factor (FF)”, given by the ratio between the maximum power and the product V_{oc} x I_{sc}:

$$\mathrm{FF} = \frac{I_{mpp} \cdot V_{mpp}}{I_{sc} \cdot V_{oc}} \tag{4}$$

The fill factor would be 1 if the I-V curve were a rectangle of sides I_{sc} and V_{oc}. For the usual silicon crystal cells produced today it ranges between 0.75 and 0.80. High values of this parameter usually indicate better performance.

Efficiency of the Flat Photovoltaic Panel

The following instant energy balance equation can be written for a single photovoltaic cell

$$P_{cel} = \tau\alpha \cdot G \cdot A_{cel} - A_{cel} \cdot U_c \cdot (T_c - T_a) \qquad (5)$$

where P_{cel} = the electrical power provided by the cell,
T_c = the cell average temperature,
T_a = the external air temperature,
U_c = the coefficient of thermal exchange between the cell and the external ambient,
$\tau\alpha$ = product of the absorbance and the transmittance of the panel
G = radiated power

The cell efficiency is defined as

$$\eta_{cel} = \frac{P_{cel}}{G \cdot A_{cel}} \qquad (6)$$

from which

$$\eta_{cel} = \tau\alpha - \frac{U_c \cdot (T_c - T_a)}{G} \qquad (7)$$

The module (or panel) efficiency can be expressed as follows

$$\eta = \frac{P}{G \cdot A} \qquad (8)$$

where P is the power found by multiplication of I and V measurements from the system.

Experimentally they found that the efficiency of a cell (or a module, or a panel) at temperature T_c can be expressed by means of the reference efficiency η_R (evaluated at the reference temperature of the cell T_R=298 K, for a radiation of 1000 W/m^2, and a mass of relative air m = 1), with the equation.

$$\eta = \eta_R \cdot [1 - \beta \cdot (T_c - T_R) + \gamma \cdot \log_{10} \cdot G] \qquad (9)$$

in which the radiation G is expressed in kW and for the silicon cells $\beta = 0.0045°C^{-1}$ and $\gamma = 1.3$

To simplify the calculation, the logarithmic term is often neglected and the equation is simplified in the form

$$\eta = \eta_R \cdot [1 - \beta \cdot (T_c - T_R)] \qquad (10)$$

Supposing the panel has a uniform temperature, equal to the average temperature of the cells T_c, an energy balance equation can be written at panel level expressed as

$$P_e = A \cdot G \cdot \tau\alpha - A \cdot U_c(T_c - T_a) = A \cdot G \cdot \eta \qquad (11)$$

This same equation is often applied to the whole photovoltaic field.

Taking the cell T_c temperature from the eq. (10) and introducing it into the eq. (11) you obtain the following equation

$$\eta = \eta_R \frac{\left[1 - \beta \cdot (T_a - T_R) - \beta \frac{G \cdot \tau\alpha}{U_c}\right]}{1 - \frac{\eta_R \cdot \beta \cdot G}{U_c}} \tag{12}$$

with which it is possible to calculate the instant efficiency of the panel according to the instant values of the ambient temperature T_a of the solar radiation G.

Once the instant efficiency of the panel is calculated, the cells' instant temperature can be calculated, by means of the eq. (11); we have:

$$T_c = T_a + \frac{G \cdot \tau\alpha}{U_c} - \frac{G \cdot \eta}{U_c} \tag{13}$$

More simply the cell temperature can be determined with a good approximation using the equation

$$T_c = T_a + k \cdot G \tag{14}$$

where k is usually between 0.02 and 0.03 cm^2W^{-1}

It is often useful, for the calculation of the average monthly performances of a photovoltaic plant, to calculate the average monthly daily efficiency of the panels.

The parameter U_c represents the thermal loss of the panel toward the external ambient. Note how the photovoltaic modules are not insulated on the rear side, as the convective and radiative cooling keeps the cells' temperature low and improves their efficiency. A simple estimation method of U_c is based on the knowledge of the operative nominal temperature of the cell (NOCT). This variable is the cell temperature, detected experimentally, with the module set in working position, for an incident radiation of 800 W/m^2, a wind speed of 1 m/s, an ambient temperature of 20 °C, and with the module operating with open circuit (i.e. with null efficiency). If you use the eq. (7) under these conditions, you obtain

$$\frac{\tau\alpha}{U_c} = \frac{NOCT - 20}{800} \tag{15}$$

In the specified conditions, you can determine the ratio $\tau\alpha/U_c$ and then the parameter U_c, if the product $\tau\alpha$ is known.

EXPERIMENTAL SETUP

The kit for studying the photovoltaic panels, simulating the behavior of a photovoltaic power system, represents the configuration of a typical stand-alone plant, with storage battery and inverter, for using the power provided by panel and battery with external electric loads.

The components of the experimental setup are:

- a photovoltaic panel, composed by crystal silicon cells, with wheeled framework with adjustable inclination
- a charge controller, optimizing the power flows involving PV panel, battery and load
- a storage battery, allowing the plant to operate even without radiation
- a DC / AC inverter to power an external AC load
- a clamp meter, for electric parameters measurement in the different branches of the circuit.
- a spotlight, to be used as AC load
- a lamp, to be used a DC load
- a portable rheostat, to construct the photovoltaic panel characteristic curve
- an indoor lighting device, to operate the photovoltaic panel indoor
- a second photovoltaic panel, composed by crystal silicon cells, with wheeled framework with adjustable inclination to be connected to the first one in parallel or in series
- a data logger including specific software and sensor, to do data acquisition via PC.
- a solar radiation meter, to measure the solar radiation incident on the plane of the photovoltaic panel

Fig. 8 shows an overall view of the experimental set-up.

Fig. 8: (1) photovoltaic panel with variable, (2) solar charge controller, (3) storage battery inclination supporting structure, (4) DC/AC inverter, (5) AC/DC clamp meter, (6) Rheostat, (7) Solar simulator

In Table 2, you find the photovoltaic panel electric specifications while in Fig 9 you find its characteristic curve.

Table 2: Photovoltaic panel specifications

Specification	*Units*	*Value*
at STC		
Peak Power (P_{mpp})	W	121.01
Short circuit current (I_{SC})	A	7.23
Open circuit voltage (V_{OC})	V	22.72
Voltage at the maximum power point (V_{MPP})	V	18.79
Current at the maximum power point (I_{MPP})	A	6.44
NOCT	°C	50
$\tau\alpha$	-	0.9
Module area	m^2	0.838

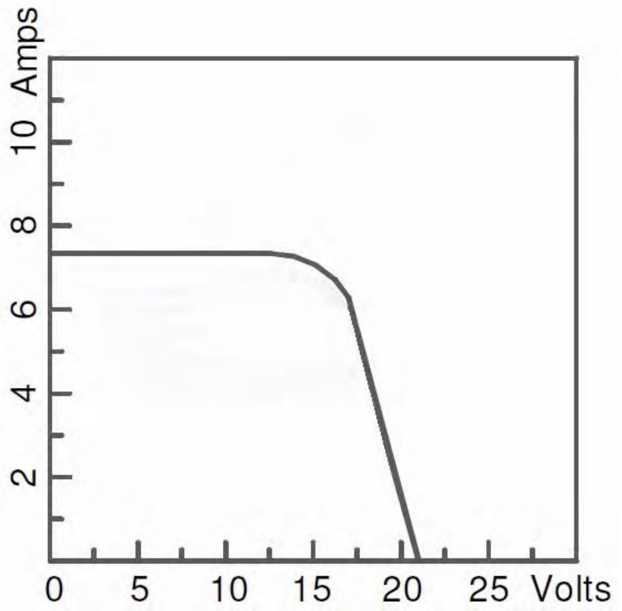


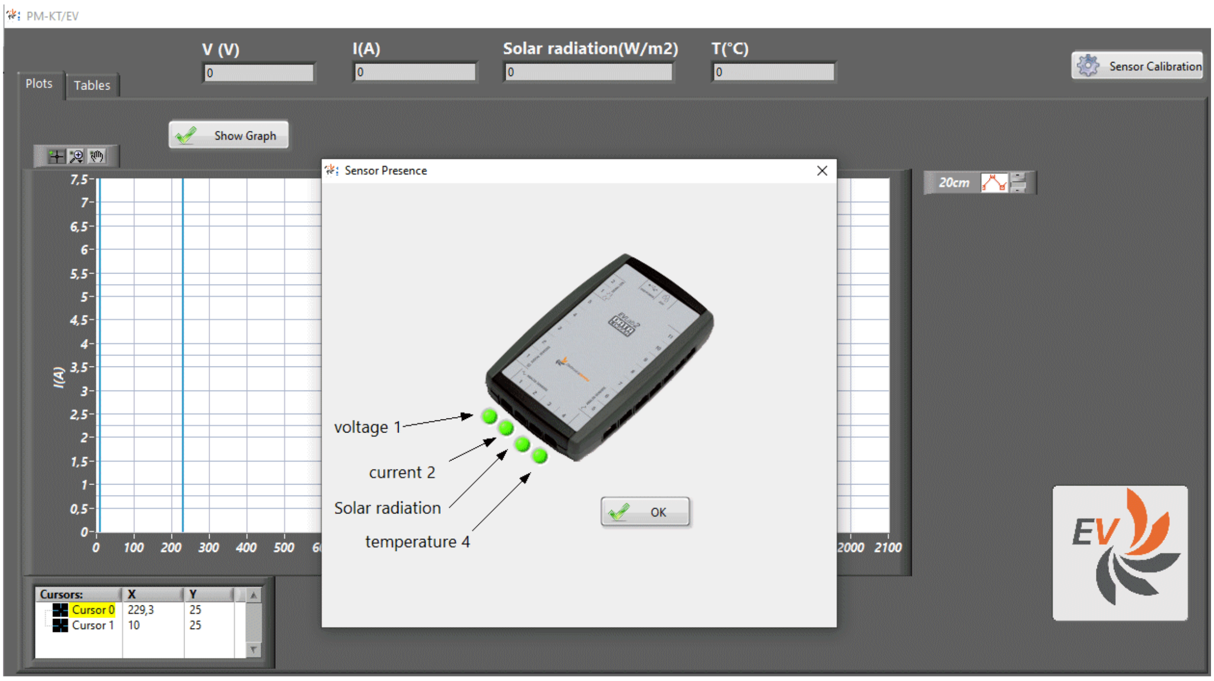
Fig 9: Photovoltaic panel characteristic curve at STC

Data Acquisition via PC

The PC data acquisition system includes:

- Datalogger
- Voltage sensor
- Current sensor
- Solar radiation sensor
- Temperature sensor
- Software

The interface of the software is shown in Fig. 10 and Fig. 11.



V (V): 0

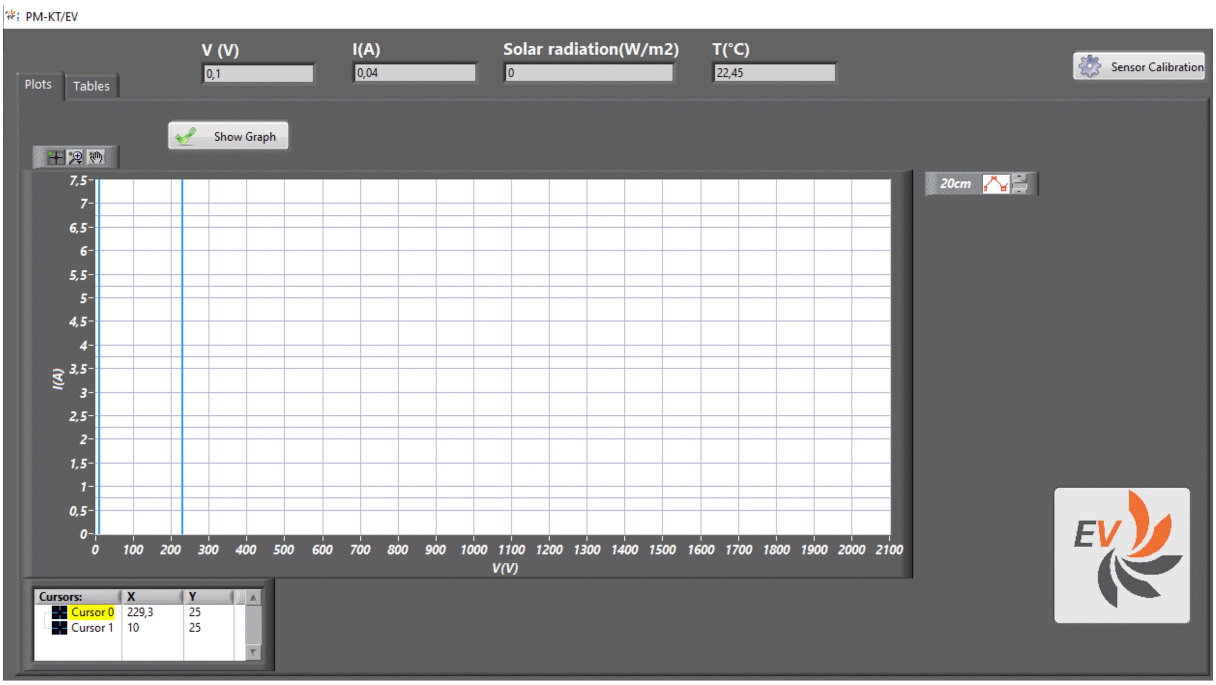
I(A): 0

Solar radiation(W/m2): 0

T(°C): 0

Cursors:	X	Y
Cursor 0	229,3	25
Cursor 1	10	25

Fig. 10



V (V): 0,1

I(A): 0,04

Solar radiation(W/m2): 0

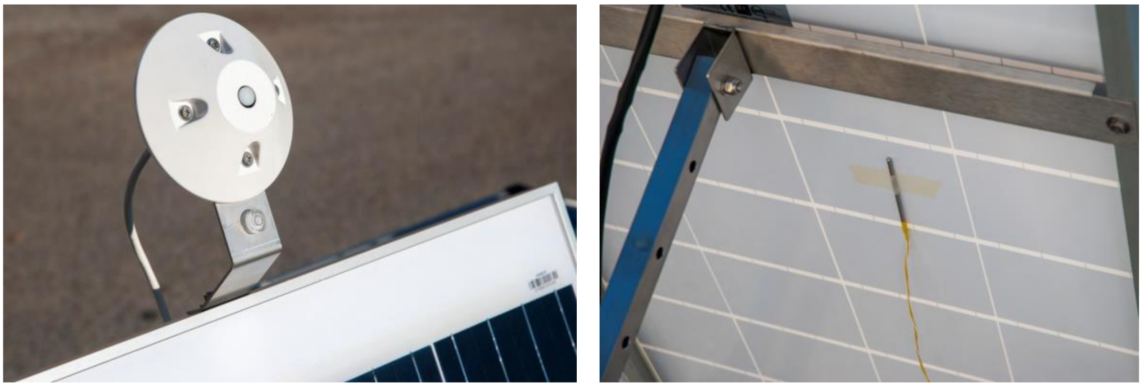
T(°C): 22,45

Cursors:	X	Y
Cursor 0	229,3	25
Cursor 1	10	25

Fig. 11

How to connect sensors and terminals

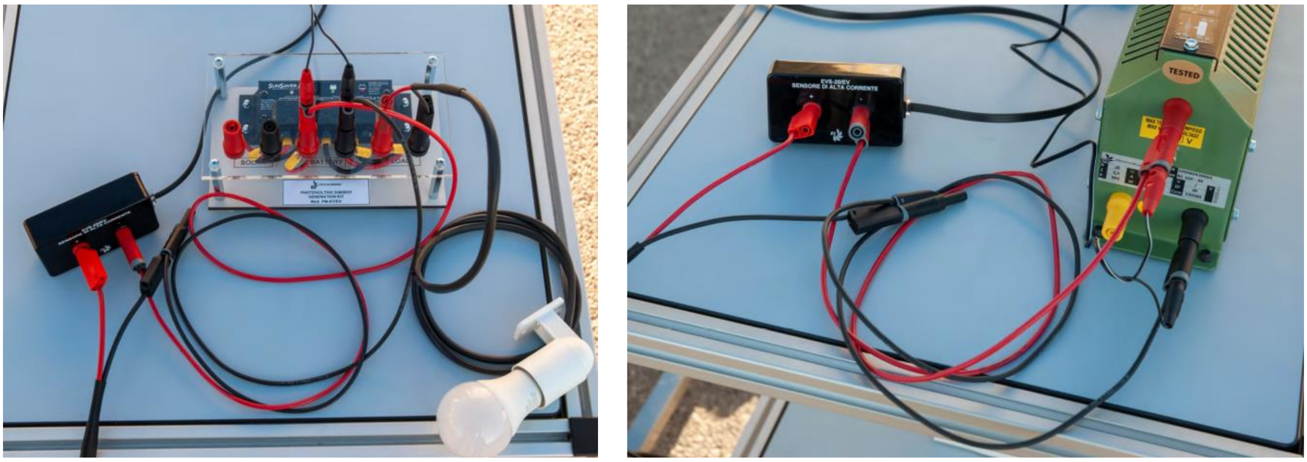
Fig. 12 shows how to install the solar radiation sensor at photovoltaic panel top and how to fix the temperature sensor at photovoltaic panel back.



(a) (b)

Fig. 12: (a) solar radiation sensor; (b) temperature sensor

Fig. 13 shows examples of how to connect to the kit current sensor terminals and voltage sensor terminals:



(a) (b)

Fig.13: (a) refers to the battery output and a DC load; (b) refers to the photovoltaic panel output and connection to rheostat.

EXPERIMENTAL PROCEDURE

The objective of this exercise consists in plotting the characteristics curves of the photovoltaic panel concerning:

- the supplied current versus the output voltage;
- the electric power supplied versus the output voltage.

System layout is shown in the Fig 10 schematically.

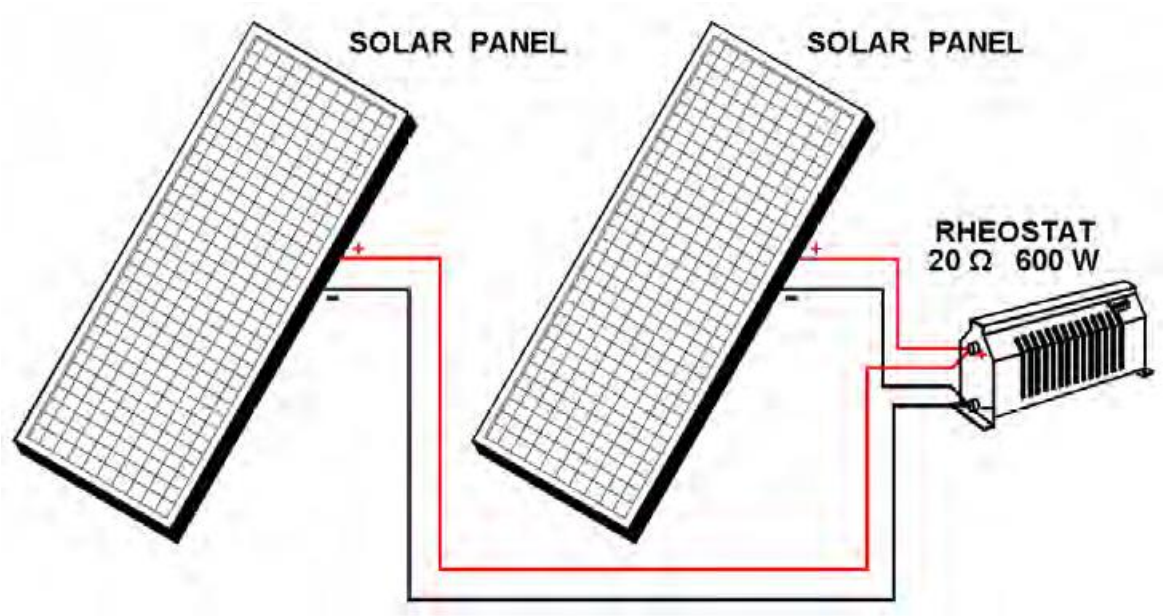


Fig. 10

1. Set the rheostat cursor to 0 cm, i.e. on the opposite side on the respect to the terminals.
2. Connect the photovoltaic panel in parallel to the rheostat respecting the polarities.
3. Turn on the indoor lighting device
4. Changing the position of the rheostat cursor record the resulting voltage, current, irradiation and temperature for both photovoltaic panels in the table provided in the PC data acquisition system.
5. Set the rheostat cursor to 0 cm and connect two photovoltaic panels (in series or in parallel) and repeat the steps 3 and 4.

MEASUREMENTS

Single PV panel

Data point	G W/m^2	Cursor position cm	Voltage V	Current A	T_c °C	T_a °C
1		OC				
2		0				
3		2				
4		4				
5		6				
6		8				
7		10				
8		15				
9		20				
10		25				
11		30				
12		35				
13		40				
14		42				
15		44				
16		46				
17		48				
18		50				

Two PV panels

Data point	G W/m^2	Cursor position cm	Voltage V	Current A	T_c °C	T_a °C
1		OC				
2		0				
3		2				
4		4				
5		6				
6		8				
7		10				
8		15				
9		20				
10		25				
11		30				
12		35				
13		40				
14		42				
15		44				
16		46				
17		48				
18		50				

CALCULATIONS

Configuration	G W/m^2	V_{mpp} V	I_{mpp} A	P_{mpp} W	FF -
Single panel					
Two panels					

Single PV Panel

Data point	G W/m^2	P eq.(1) W	η eq.(8) -	η eq.(10) -	P_e eq.(11) W	U_c W/m^2	T_c °C
1							
2							
3							
4							
5							
6							
7							
8							
9							
10							
11							
12							
13							
14							
15							
16							
17							
18							

IN YOUR REPORT

Following graphs, calculations and discussions should be presented in your report. Show your steps with each calculation for one example data point only.

1. Plot I-V and P-V graphs of both configurations in the same plot. From the plot, determine connection type of the two-panel configuration (in series or in parallel).
2. Determine V_{mpp} and I_{mpp} from the I-V curves you plotted approximately and calculate P_{mpp} and FF for both configurations.

For single panel configuration only;

3. Calculate the power production of the panel using equation (1), measured I and V values for data points 1 to 18.
4. Calculate the panel efficiency using equation (8), measured G, I and V values for data points 1 to 18.
5. Calculate the panel efficiency using equation (10), STC data and measured T_c for data points 1 to 18.
6. Calculate the power production of the panel using equation (11) for data points 1 to 18.
7. Using NOCT, calculate U_c and T_c for data points 1 to 18.

Discuss differences and similarities between I-V and P-V curves of the configurations and I-V and P-V curve at STC given in the manual. Compare fill factors you calculated with each other and with the fill factor of the panel at STC. Discuss the reasons for differences if there is any.

Compare efficiency and power production of the panel resulting from different formulas with efficiency and power at mmp point at STC. Discuss the difference between them if there is any.

Compare calculated T_c with the measured one and discuss the difference between them if there is any.

List possible reasons for discrepancies in your results.