Electricity and New Energy

Solar Power

Course Sample

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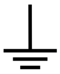
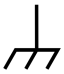
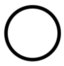
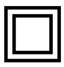
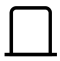
Safety and Common Symbols

The following safety and common symbols may be used in this course and on the equipment:

Symbol	Description
⚠ DANGER	**DANGER** indicates a hazard with a high level of risk which, if not avoided, will result in death or serious injury.
⚠ WARNING	**WARNING** indicates a hazard with a medium level of risk which, if not avoided, could result in death or serious injury.
⚠ CAUTION	**CAUTION** indicates a hazard with a low level of risk which, if not avoided, could result in minor or moderate injury.
CAUTION	**CAUTION** used without the *Caution, risk of danger* sign ⚠, indicates a hazard with a potentially hazardous situation which, if not avoided, may result in property damage.
	Caution, risk of electric shock
	Caution, hot surface
	Caution, risk of danger. Consult the relevant user documentation.
	Caution, lifting hazard
	Caution, belt drive entanglement hazard
	Caution, chain drive entanglement hazard
	Caution, gear entanglement hazard
	Caution, hand crushing hazard
	Notice, non-ionizing radiation
	Consult the relevant user documentation.
⎓	Direct current
∿	Alternating current

Safety and Common Symbols

Symbol	Description
	Both direct and alternating current
	Three-phase alternating current
	Earth (ground) terminal
	Protective conductor terminal
	Frame or chassis terminal
	Equipotentiality
	On (supply)
	Off (supply)
	Equipment protected throughout by double insulation or reinforced insulation
	In position of a bi-stable push control
	Out position of a bi-stable push control

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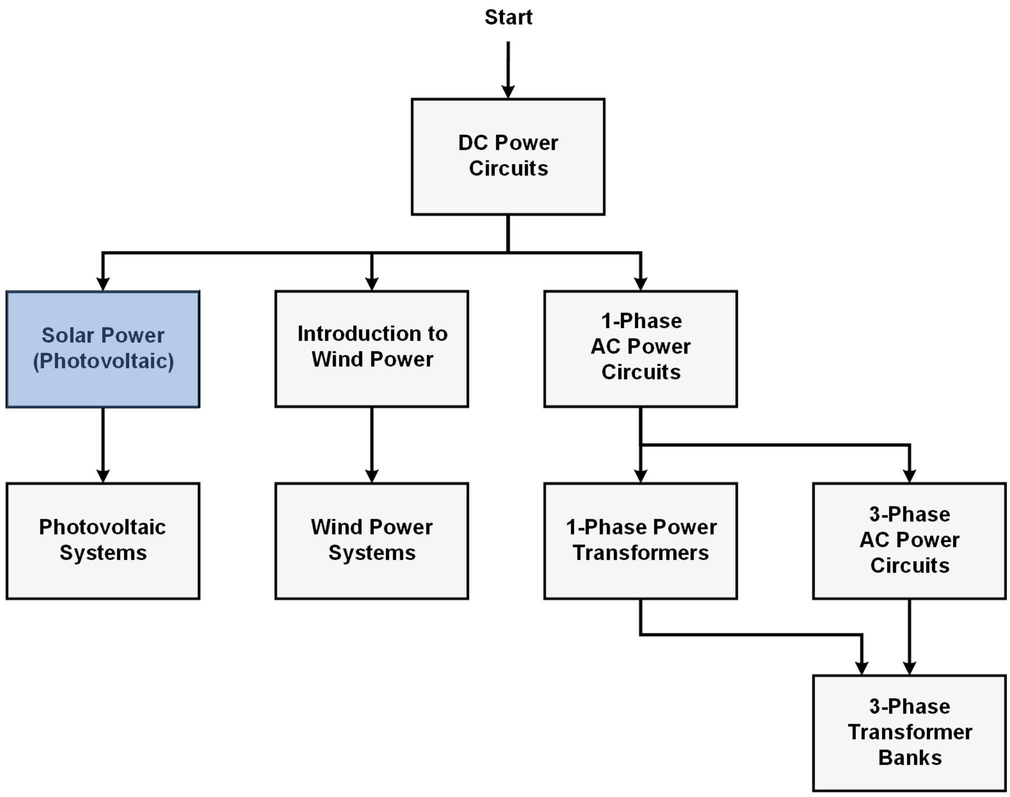
Preface

Electrical energy is part of our life since more than a century and the number of applications using electric power keeps increasing. This phenomenon is illustrated by the steady growth in electric power demand observed worldwide. In reaction to this phenomenon, the production of electrical energy using renewable natural resources (e.g., wind, sunlight, rain, tides, geothermal heat, etc.) has gained much importance in recent years since it helps to meet the increasing demand for electric power and is an effective means of reducing greenhouse gas (GHG) emissions.

To help answer the increasing needs for training in the wide field of electrical energy, Festo Didactic developed a series of modular courses. These courses are shown below as a flow chart, with each box in the flow chart representing a course.



Festo Didactic courses in electrical energy.

Teaching includes a series of courses providing in-depth coverage of basic topics related to the field of electrical energy such as dc power circuits, ac power circuits, and power transformers. Other courses also provide in-depth coverage of solar power and wind power. Finally, two courses deal with photovoltaic systems and wind power systems, with focus on practical aspects related to these systems.

We invite readers to send us their tips, feedback, and suggestions for improving the course.

Please send these to services.didactic@festo.com.

The authors and Festo Didactic look forward to your comments.

About This Course

Climate changes observed throughout the world in recent years have led to an ever-growing demand for renewable sources of energy to counteract these changes and to help minimize their negative effects on our lives. Solar power is by far Earth's most available source of renewable energy, easily capable of providing many times the total current energy demand.

The Solar Power Technology Training System is designed to introduce students to the production of electrical energy from solar power, with emphasis on the use and operation of photovoltaic panels.

The Solar Power Technology Training System mainly consists of a solar panel test bench and a monocrystalline silicon solar panel. By installing the solar panel in the solar panel test bench, you will conduct several indoor experiments on solar panel operation and performance using the artificial light source of the test bench. You can also install the solar panel on a tripod to perform outdoor experiments using sunlight.

Part of the energy used by the International Space Station is supplied by solar panels.

Safety considerations

Safety symbols that may be used in this course and on the equipment are listed in the Safety and Common Symbols table at the beginning of this document.

Safety procedures related to the tasks that you will be asked to perform are indicated in each exercise.

Make sure that you are wearing appropriate protective equipment when performing the tasks. You should never perform a task if you have any reason to think that a manipulation could be dangerous for you or your teammates.

Before performing manipulations with the equipment, you should read all sections regarding safety in the Safety Instructions and Commissioning manual accompanying the equipment.

About This Course

Prerequisite

As a prerequisite to this course, you should have completed the course *DC Power Circuits*.

Systems of units

Units are expressed using the International System of Units (SI).

To the Instructor

You will find in this Instructor version of the course all the elements included in the Student version of the course together with the answers to all questions, results of measurements, graphs, explanations, suggestions, and, in some cases, instructions to help you guide the students through their learning process. All the information that applies to you is placed between markers and appears in red.

Accuracy of measurements

The numerical results of the hands-on exercises may differ from one student to another. For this reason, the results and answers given in this course should be considered as a guide. Students who correctly perform the exercises should expect to demonstrate the principles involved and make observations and measurements similar to those given as answers.

Equipment installation and use

In order for students to be able to safely perform the hands-on exercises in this course, the equipment must have been properly installed, i.e., according to the instructions given in the accompanying Safety Instructions and Commissioning manual. Also, the students must familiarize themselves with the safety directives provided in the Safety Instructions and Commissioning manual and observe these directives when using the equipment.

Sample

Extracted from

Instructor Guide

The Solar Panel (Photovoltaic Panel)

EXERCISE OBJECTIVE

When you have completed this exercise, you will be familiar with the operation of the silicon photovoltaic (PV) cell. You will be introduced to the characteristic U-I curve of a PV cell. You will observe the effect of irradiance on the power produced by solar panels. You will also be introduced to the Solar Panel Test Bench and Monocrystalline Silicon Solar Panel.

DISCUSSION OUTLINE

The Discussion of this exercise covers the following points:

- Photovoltaic cell, module, and panel
- Characteristic $\boldsymbol{U}$-$\boldsymbol{I}$ curve of a PV cell
- Electric power output
- Irradiance
- Standard test conditions (STC)
- Efficiency
- Solar Panel Test Bench
- Monocrystalline Silicon Solar Panel

DISCUSSION

Photovoltaic cell, module, and panel

A photovoltaic (PV) panel is a device that produces electrical energy when it is illuminated by a source of light. By placing PV panels outdoors, it is possible to use the sunlight (a source of renewable energy) to directly produce electrical energy. PV panels installed outdoors that produce electrical power from sunlight are commonly referred to as solar panels.

Figure 21. Photovoltaic (PV) panels in sunlight.

The basic component of a PV panel is the photovoltaic (PV) cell. Each PV panel consists of many PV cells which are interconnected in such a way as to obtain specific voltage and current values. A PV cell is basically a P-N junction that is usually made of silicon, just like the P-N junction in a silicon diode. However, the P-N junction in a PV cell is made of a thin slice of silicon to maximize its surface area, thereby allowing the PV cell to intercept as much light as possible. See Figure 22.

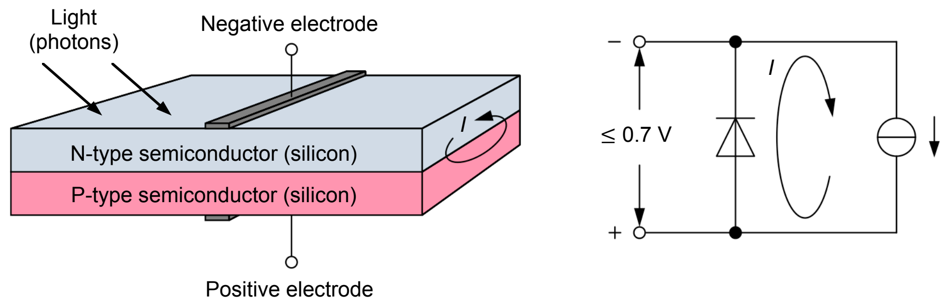


Figure 22. Photovoltaic cell construction and simplified equivalent diagram.

When light illuminates the N-type semiconductor surface of the P-N junction, the PV cell starts generating energy and becomes a source of current. When no electrical load is connected to the electrodes of the PV cell, the current produced is simply recirculated within the PV cell, i.e., through the P-N junction which is in fact a silicon diode. Therefore, the open-circuit voltage U_{OC} of a PV cell (and more generally the output voltage of a PV cell) cannot exceed the value of the forward-bias voltage of a silicon diode, i.e., 0.7 V. The actual open-circuit voltage U_{OC} of most PV cells is between 0.5 V and 0.6 V. The larger the dimensions of the P-N junction, the larger the amount of light intercepted by the PV cell and the higher the current produced.

The electrical symbol of a PV cell is shown in Figure 23. The symbol on the left-hand side of this figure is the standard symbol while the symbol on the right-hand side is an alternative symbol that is often used.

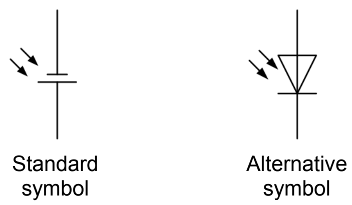


Figure 23. Electrical symbols of a photovoltaic cell.

Because the output voltage of a single PV cell is low (less than 0.7 V), it is common practice to connect several PV cells of the same size in series to obtain higher voltages. Figure 24 shows a typical arrangement used to connect PV cells in series. An arrangement of several PV cells interconnected together with its positive and negative electrodes is commonly referred to as a photovoltaic (PV) module.

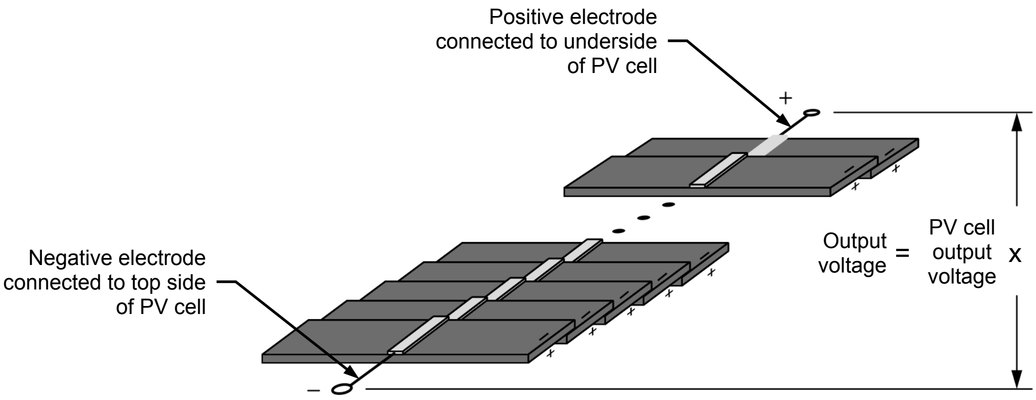


Figure 24. Typical arrangement used to connect photovoltaic cells in series.

The electrical symbol commonly used to represent a PV module is shown Figure 25.

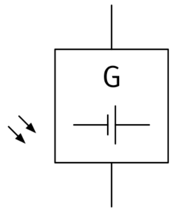


Figure 25. Symbol of a photovoltaic module.

Photovoltaic (PV) panels often consist of several PV modules fastened to a common frame, electrically interconnected, and covered with transparent material (glass, transparent epoxy, etc.) to let the light in and protect the PV modules from weather (rain and hail in particular). Figure 26 shows an example of a PV panel.

Figure 26. Photovoltaic panel.

Characteristic U-I curve of a PV cell

Figure 27 shows the characteristic U-I curve of a PV cell when it is illuminated by light, i.e., when it produces electric power. When illuminated, a PV cell is equivalent to a source of current in parallel with a diode. When the PV cell is short-circuited, all the current produced by the source of current flows through the PV cell output terminals and the PV cell output voltage is 0 V. The short-circuit current I_{SC} value depends on (in principle, is proportional to) the surface area of the PV cell. Because a PV cell acts like a current source, the voltage that develops across the PV cell increases as the electrical load decreases (resistance increases). However, as the voltage increases, there comes a point when the diode in the PV cell becomes forward biased and lets current flow through it. This causes the PV cell output current to decrease rapidly while the output voltage remains almost constant and equal to the diode forward-bias voltage (typically between 0.5 V and 0.6 V). In conclusion, the PV cell has two distinct operating regions: the constant-current region and the constant-voltage region. The PV cell operates as a current source (constant-current region) as long as the output voltage is below the forward-bias voltage of the diode. The PV cell operates as a source of voltage (constant-voltage region) when the output voltage reaches or exceeds the forward-bias voltage of the diode. The output voltage measured when the PV cell is left open is referred to as the open-circuit voltage U_{OC}.

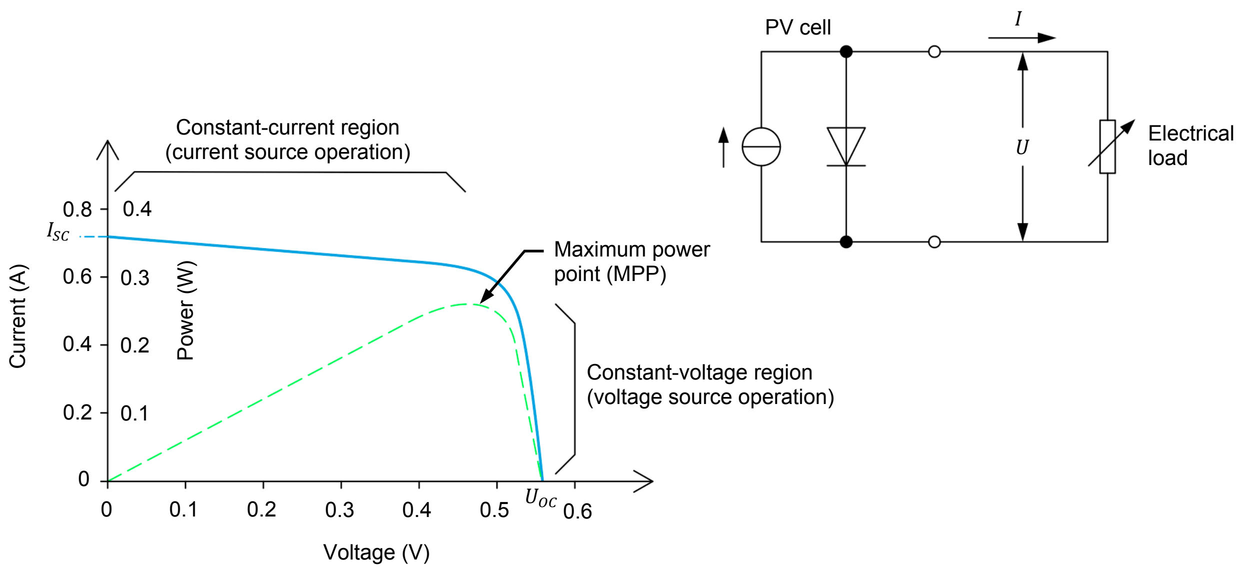


Figure 27. Characteristic U-I curve and equivalent circuit of a PV cell.

The characteristic U-I curve shown in Figure 27 applies to a single PV cell. When several PV cells of the same fabrication and size are connected in series to form a PV module, the short-circuit current I_{SC} remains virtually the same but the open-circuit voltage U_{OC} is proportional to the number of PV cells connected in series, as shown in Figure 28. For instance, when four PV cells are connected in series, U_{OC} is between 2 V and 2.4 V.

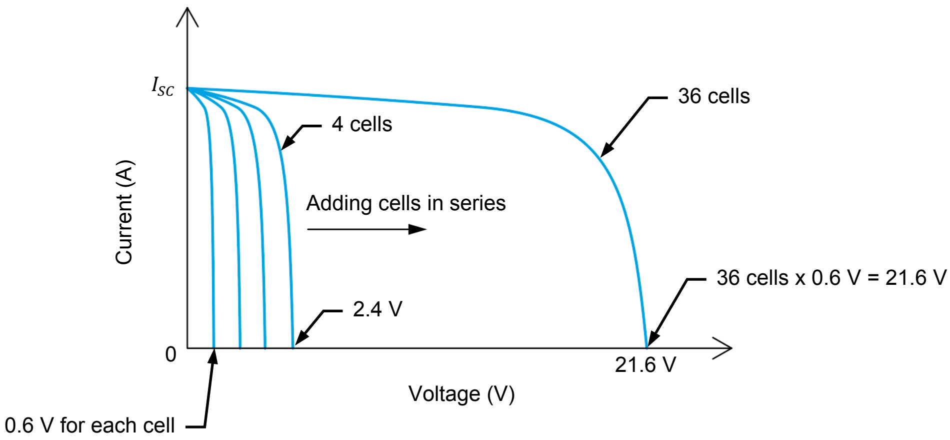


Figure 28. The open-circuit voltage U_{OC} is proportional to the number of PV cells connected in series.

When several PV cells of the same fabrication and size are connected in parallel to form a PV module, the open-circuit voltage U_{OC} remains virtually the same but the short-circuit current I_{SC} is proportional to the number of PV cells connected in parallel, as shown in Figure 29. For instance, when 10 PV cells are connected in parallel, I_{SC} is multiplied by 10.

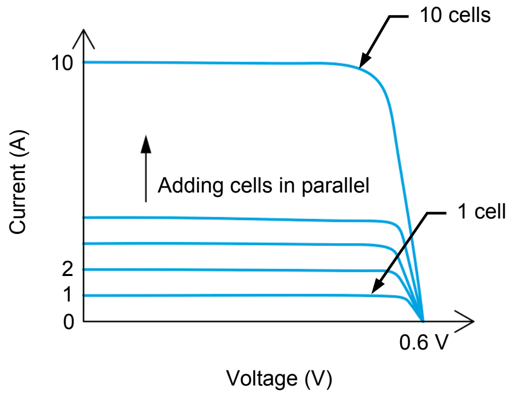


Figure 29. The short-circuit current I_{SC} is proportional to the number of parallel-connected PV cells.

Electric power output

The amount of electric power that a PV cell provides depends on the point on the U-I curve at which the PV cell operates. In other words, this depends on the electrical load applied to the PV cell (in practice, this depends on the electrical load applied to the PV module or PV panel). The point on the U-I curve where the PV cell output power is maximum is commonly referred to as the maximum power point (MPP). As Figure 27 shows, this point is located just between the constant-current and constant-voltage regions of the characteristic U-I curve. It is very important that PV panels operate as close as possible to the maximum power point to maximize the amount of energy produced.

The amount of light incident to a PV cell (cell illumination) has a great incidence on the short-circuit current I_{SC} but a mitigated effect on the open-circuit voltage U_{OC}, as shown in Figure 30. The short-circuit current I_{SC} is in fact directly proportional to cell illumination while the open-circuit voltage U_{OC} increases only a little (logarithmic relationship) with cell illumination. The output power of a PV cell is thus virtually proportional to cell illumination.

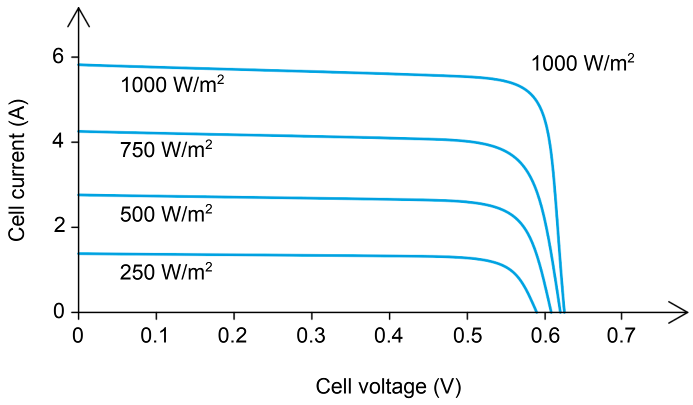


Figure 30. Characteristic U-I curve under various cell illumination levels.

Irradiance

Cell illumination is referred to as the solar irradiance when PV cells are illuminated by sunlight. Irradiance due to solar radiation is also called **insolation**. The global irradiance on a PV cell positioned horizontally on Earth's surface consists of direct irradiance and diffuse irradiance. On a tilted surface, there is also a component reflected from the ground. The average ground reflection is generally about 20% of the global irradiance. Irradiance is expressed in W/m^2.

Standard test conditions (STC)

Solar noon is the moment during a day when the Sun is at the highest point in the sky.

Since the U-I curve of a PV module, and thus the output power, depends on cell illumination, standard test conditions (STC) have been devised to determine the specifications of PV panels (e.g. values of I_{SC} and U_{OC}) and to enable fair comparison of one PV module with another. The standard test conditions specify a cell temperature of 25˚C (not the ambient temperature) and an irradiance of 1000 W/m^2 with an air mass coefficient equal to 1.5 (AM1.5). The air mass (AM) coefficient characterizes the solar spectrum after the solar radiation has traveled through the atmosphere. The standard test conditions approximately represent solar noon near the spring and fall equinoxes in the continental United States with PV module surface aimed directly at the Sun.

Efficiency

When light illuminates a PV module or PV panel, only a portion of the energy contained in the incident light is converted into electric power. The more efficient the PV cells in the PV module or panel are, the higher the amount of electric power produced. The efficiency of PV modules or panels is usually calculated using the characteristic U-I curve obtained under STC and Equation (1).

$$\eta = \frac{\text{MPP}}{\text{Irradiance} \times A} \times 100 \tag{1}$$

where η is the efficiency of the PV module or panel in %.
MPP is the maximum power point of the PV module or panel in W at STC.
Irradiance is the irradiance in W/m^2 at STC.
A is the surface area of the PV module or panel in m^2.

For example, under standard test conditions [25˚C, 1000 W/m^2, AM1.5], a solar panel having a 15% efficiency and 0.01 m^2 of surface area will produce approximately 15.0 watts of power.

Multi-crystalline silicon (mc-SI) is also referred to as polycrystalline silicon (poly-SI).

Various semiconductor materials are used to produce PV cells. This results in PV cells having different conversion efficiencies. Table 2 shows the conversion efficiency of common PV cells made of different types of semiconductor material. The table includes thick SI-based semiconductor material such as the monocrystalline silicon (mono-SI) and multi-crystalline silicon (mc-SI), as well as thin-film semiconductor material such as the copper indium gallium selenide (CIGS), cadmium telluride (CdTe), and amorphous silicon (a-SI).

Table 2. Conversion efficiency of common PV cells made of different types of semiconductor material.

PV cell material		Conversion efficiency (%)
Thick SI-based	Monocrystalline silicon (mono-SI)	14 to 17
	Multi-crystalline silicon (mc-SI)	11.5 to 14
Thin-film	Copper indium gallium selenide (CIGS)	9 to 11.5
	Cadmium telluride (CdTe)	8 to 10
	Amorphous silicon (a-Si)	5 to 9.5

Thin-film PV cells generally have lower conversion efficiencies (5% to 11.5%) than thick SI-based PV cells (11.5% to 17%). Consequently, PV panels made of thin-film PV cells require more surface area than PV panels made of thick SI-based PV cells to produce a same amount of power. For this reason, PV panels made of thick SI-based PV cells are generally preferred in applications where space is limited, such as solar-powered battery chargers, solar-powered road-side information panels, home energy production, etc. On the other hand, PV panels made of thin-film PV cells are well suited in commercial and industrial applications. This is because large walls and roofs are often available to provide the space required for the installation of PV panels made of thin-film PV cells.

Different techniques are used to produce the various types of semiconductor material just discussed. This has a significant effect on the cost of each of these types of semiconductor material, and consequently, on the cost of PV panels. For instance, manufacturing monocrystalline silicon is costlier than manufacturing multi-crystalline silicon. Consequently, PV panels made of monocrystalline silicon PV cells are generally more expensive than PV panels made of multi-crystalline silicon PV cells.

Solar Panel Test Bench

The Solar Panel Test Bench is a module in which the Monocrystalline Silicon Solar Panel can be installed. The test bench contains a powerful halogen lamp used to illuminate the solar panel under test. Panel illumination (irradiance) can be adjusted using the dimmer knob provided on the front panel of the test bench. A ventilation system in the test bench keeps the solar panel at near room temperature. The halogen lamp and ventilation system can be turned on and off using switches mounted on the front panel of the test bench.

Monocrystalline Silicon Solar Panel

The Monocrystalline Silicon Solar Panel consists of two independent photovoltaic (PV) modules mounted on a common metal chassis, as shown in Figure 31. Each module consists of 18 PV cells connected in series (the PV cells are in fact separated into two groups of nine PV cells connected in series). Each PV cell is made of a thin rectangular slice of silicon which measures about 1 cm x 5 cm. Adjacent PV cells overlap slightly (like dominoes) to allow the bottom side of one cell to be in contact with the top side of the next cell, thereby achieving series connection of the PV cells. The uniform color of each PV cell in the Monocrystalline Silicon Solar Panel indicates that the cells are made of single crystal silicon. Such PV cells are commonly referred to as monocrystalline silicon PV cells.

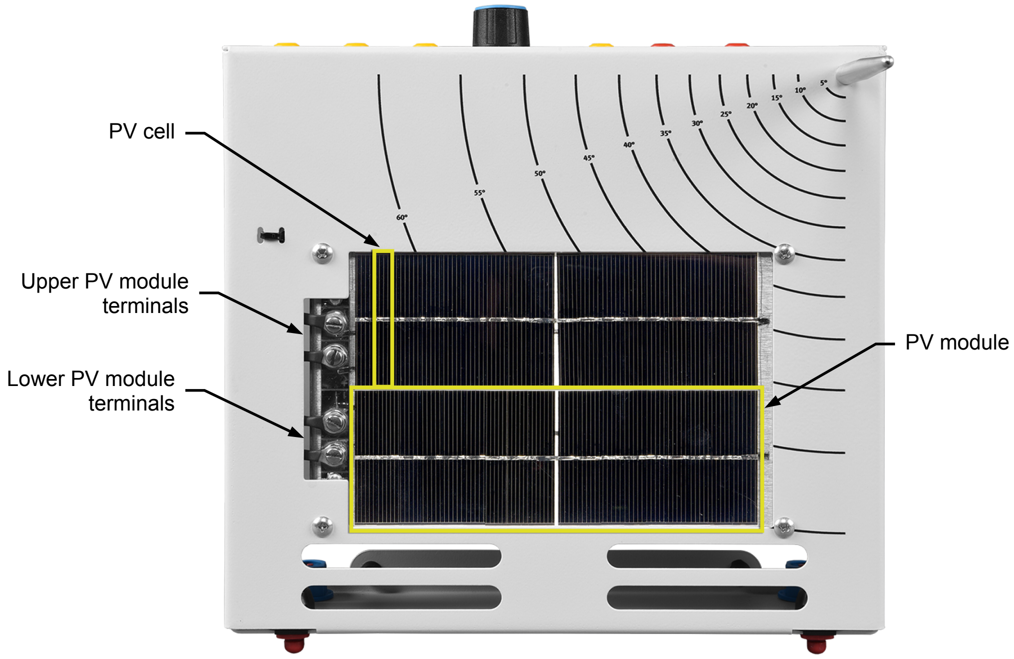


Figure 31. The Monocrystalline Silicon Solar Panel.

A digital thermometer attached to the solar panel chassis allows the temperature of the PV modules to be monitored. The surface of the metal chassis on which the PV modules lie is provided with a perpendicularly-mounted metal pin and silk-screened angular markers. When performing exercises outdoors, the metal pin allows the orientation to be adjusted so that the solar panel is perfectly aimed at the Sun.

The Monocrystalline Silicon Solar Panel includes a potentiometer and a set of diodes. The potentiometer is used to apply a variable electrical load to the output of the solar panel. The diodes can be connected to the solar panel to serve either as bypass diodes or blocking diodes.

The Monocrystalline Silicon Solar Panel is intended to be installed in the Solar Panel Test Bench. Four fasteners at the bottom of the solar panel chassis allow the panel to be secured to the test bench: two fixed (black) fasteners and two twist-lock fasteners (fasteners with a blue knob and a red tab).

The next procedure shows how to install the Monocrystalline Silicon Solar Panel in the Solar Panel Test Bench.

– First, turn the blue rotating knob of each twist-lock fastener on the Solar Panel Test Bench so that the red tab of each fastener is fully visible and perpendicular with the bottom of the solar panel chassis (see Figure 32a).

– Making sure the PV modules face the halogen lamp, align the red pins of the four fasteners of the Monocrystalline Silicon Solar Panel with the holes perforated in the base of the Solar Panel Test Bench, and insert the solar panel into the base of the test bench (see Figure 32b).

– Lock the Monocrystalline Silicon Solar Panel into place by turning the blue knob of the left-hand twist-lock fastener ½ turn clockwise, and the blue knob of the right-hand twist-lock fastener ½ turn counterclockwise (see Figure 32c), i.e., until the red tab of each fastener is no longer visible (Figure 32d), which indicates that the solar panel is properly secured to the bench.

To remove the Monocrystalline Silicon Solar Panel from the Solar Panel Test Bench, proceed as follows: first, unlock the solar panel by turning the blue knob of the left-hand twist-lock fastener ½ turn counterclockwise, and the blue knob of the right-hand twist-lock fastener ½ turn clockwise (the red tabs of each twist-lock fastener becomes fully visible). Then, withdraw the solar panel by pulling it up.

(a)

(b)

(c)

(d)

Figure 32. Installing the Monocrystalline Silicon Solar Panel in the Solar Panel Test Bench.

PROCEDURE OUTLINE

The Procedure is divided into the following sections:

- PV panel construction
- Positioning the Monocrystalline Silicon Solar Panel in the Solar Panel Test Bench and measuring the short-circuit current
- Open-circuit voltage
- Characteristic U-I curve of a PV module operating at near room temperature
- Maximum power point produced by a single PV module operating at near room temperature
- Open-circuit voltage and short-circuit current of two PV modules connected in parallel operating at near room temperature
- Characteristic U-I curve of two PV modules connected in parallel operating at near room temperature

PROCEDURE

PV panel construction

In this part of the exercise, you will observe the construction of the Monocrystalline Silicon Solar Panel.

1. Refer to the Equipment Utilization Chart in Appendix A to obtain the list of equipment required to perform this exercise.

   Place the equipment on your work surface.

2. Make sure that the *Lamp* switch and *Fan* switch of the Solar Panel Test Bench are set to the *O* (off) position then connect the unit to an ac power outlet that is properly protected.

   If necessary, refer to the instructor to ensure that the ac power outlet to which you connect the Solar Panel Test Bench is properly protected.

3. Ask your instructor to turn on (i.e., to unlock) electric power at your workstation, if applicable.

4. On the Monocrystalline Silicon Solar Panel, locate the two independent PV modules. The PV module near the top side of the solar panel is identified as the “upper” PV module and the other one as the “lower” PV module. Notice that each module has its own electrical output terminals. This allows parallel or series connection of the two PV modules, as well as independent operation.

5. Observe that each PV module consists of 18 PV cells connected in series (the PV cells are separated into 2 groups of 9 PV cells connected in series). Notice that each PV cell is made of a thin rectangular slice of silicon which measures about 1 cm x 5 cm. Also notice that adjacent PV cells overlap slightly (like dominoes) to allow the bottom side of one cell to be in contact with the top side of the next cell, thereby achieving series connection of the PV cells.

Positioning the Monocrystalline Silicon Solar Panel in the Solar Panel Test Bench and measuring the short-circuit current

In this part of the exercise, you will position the Monocrystalline Silicon Solar Panel in the Solar Panel Test Bench to obtain the nominal short-circuit current I_{SC} of the solar panel. This procedure must be performed whenever measurements have to be taken using the Solar Panel Test Bench.

WARNING

Risk of burns. The halogen lamp and the surrounding components can become very hot during this exercise.

6. To ensure consistency between the results obtained during the various exercises of this course, you should always use the same Monocrystalline Silicon Solar Panel and Solar Panel Test Bench. To do so, record the serial number shown on each module.

   Serial number of the Monocrystalline Silicon Solar Panel: ____________

   Serial number of the Solar Panel Test Bench: ____________

   Serial number of the Monocrystalline Silicon Solar Panel: see the label on the module.

   Serial number of the Solar Panel Test Bench: see the label on the module.

7. Install the Monocrystalline Silicon Solar Panel into the Solar Panel Test Bench, making sure the PV modules face the halogen lamp. (Refer to the Discussion of this exercise if necessary).

   Lock the Monocrystalline Silicon Solar Panel into place using the twist-lock fasteners.

8. Connect the "lower" PV module as shown in Figure 33.

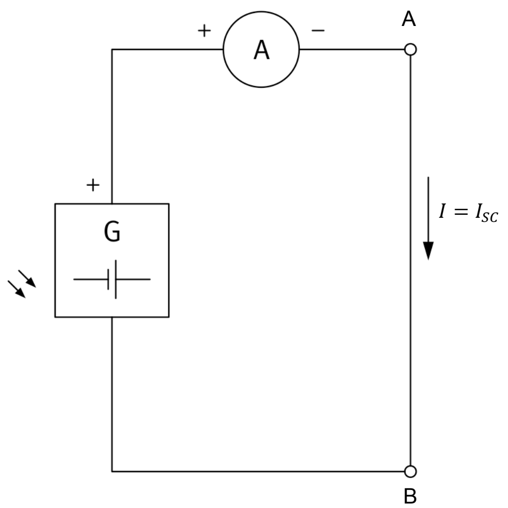


Figure 33. Circuit used to measure the short-circuit current I_{SC} of a PV module.

9. On the Solar Panel Test Bench, turn the lamp and fan on. Adjust the dimmer on the Solar Panel Test Bench to obtain a short-circuit current I_{SC} of 100 mA. Let the temperature stabilize (approximately 20 min), then measure the short-circuit current I_{SC}. If the value differs from 100 mA, readjust the dimmer to obtain a short-circuit current I_{SC} of approximately 100 mA (± 10 mA). This value corresponds to the nominal short-circuit current I_{SC} of the solar panel. Record below the value of the measured short-circuit current I_{SC}.

Measured short-circuit current I_{SC} = _______ A

Measured short-circuit current I_{SC} = 100.3 mA (value should be between 90 mA and 110 mA).

Open-circuit voltage

In this part of the exercise, you will estimate and measure the open-circuit voltage U_{OC} of a PV module.

10. Considering an output voltage of 0.55 V/PV cell, estimate the open-circuit voltage U_{OC} of the PV modules in the Monocrystalline Silicon Solar Panel when they are illuminated at standard test conditions.

Open-circuit voltage U_{OC} = _______ V

Open-circuit voltage U_{OC} = 9.9 V

11. Once the dimmer on the Solar Panel Test Bench is correctly adjusted for a short-circuit current I_{SC} of approximately 100 mA and the temperature has stabilized, modify your circuit as shown in Figure 34.

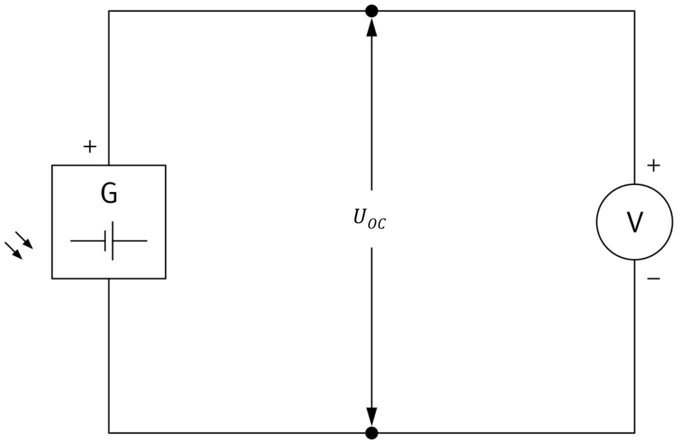


Figure 34. Circuit used to measure the open-circuit voltage U_{OC} of a PV module.

12. Measure the open-circuit voltage U_{OC}, and the corresponding PV panel temperature.

Open-circuit voltage U_{OC} = _______ V

PV panel temperature: _______˚C

As you will learn in the next exercise, the temperature affects the efficiency of solar panels. For this reason, it is important to always record the PV panel temperature at which measurements are performed.

Open-circuit voltage U_{OC} = 10.28 V

PV panel temperature = 31.0˚C

13. Does the measured open-circuit voltage U_{OC} confirm your estimation made in step 10?

❑ Yes ❑ No

Yes

Characteristic U-I curve of a PV module operating at near room temperature

In this part of the exercise, you will plot the characteristic U-I curve of a PV module operating at near room temperature. You will also observe the regions in the U-I curve where the PV module operates as a voltage source and as a current source.

14. Modify your circuit as shown in Figure 35 using the "lower" PV module and the potentiometer of the Monocrystalline Silicon Solar Panel.

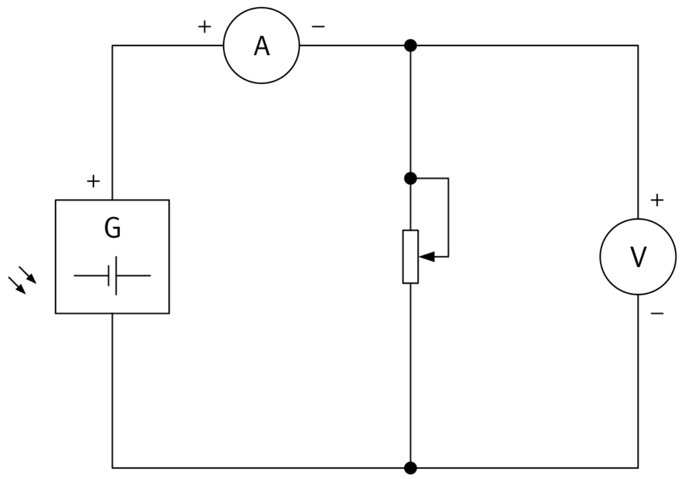


Figure 35. Circuit used to determine the characteristic *U-I* curve of a PV module.

15. Using the potentiometer as a variable load, vary the output voltage from minimum to maximum by increments of 0.5 V. For each voltage setting, record the output voltage and the corresponding current in Table 3.

Record the PV panel temperature in the blank at the bottom of Table 3.

Table 3. Characteristic *U*-*I* curve of a PV module.

Voltage (V)	Current (mA)	Power (W)	Voltage (V)	Current (mA)	Power (W)
Temperature of the PV panel during the measurements = _______°C					

The results are presented in the next table.

Characteristic *U*-*I* curve of a PV module.

Voltage (V)	Current (mA)	Power (W)	Voltage (V)	Current (mA)	Power (W)
0.52	100.3	0.052	5.52	96.5	0.533
1.02	100.1	0.102	6.02	96.1	0.579
1.52	99.9	0.152	6.52	95.7	0.624
2.02	99.8	0.202	7.02	95.2	0.668
2.52	99.7	0.251	7.52	94.5	0.711
3.02	99.4	0.300	8.02	91.2	0.731
3.52	99	0.348	8.52	83.8	0.714
4.02	98.5	0.396	9.02	70.9	0.640
4.52	97.9	0.443	9.52	49.6	0.472
5.02	97.2	0.488	10.0	19.8	0.198
Temperature of the PV panel during the measurements = 31.0˚C					

16. Using the values in Table 3, plot the characteristic U-I curve of the PV module in Figure 36.

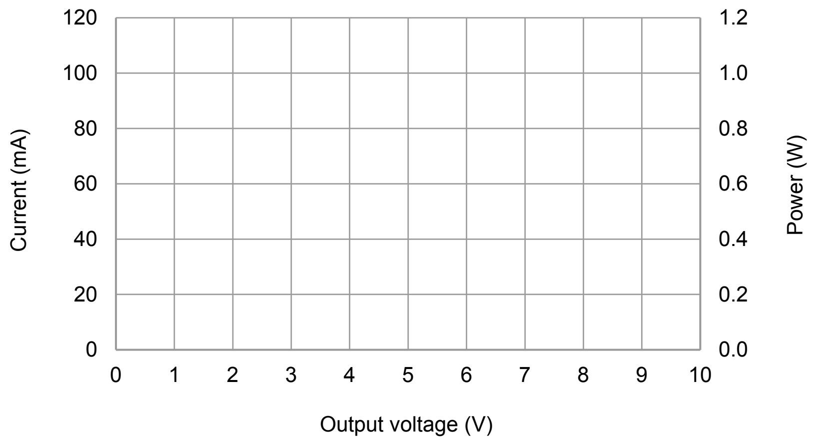
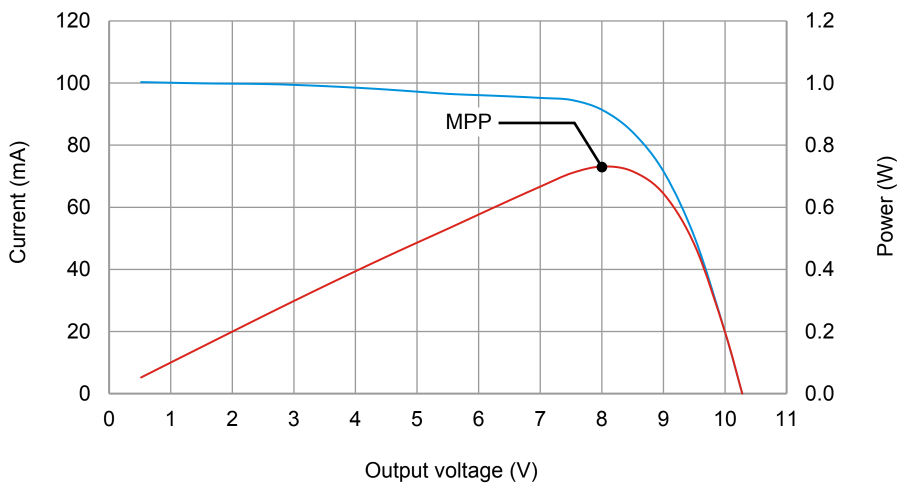


Figure 36. Characteristic U-I curve of a PV module.

The results are presented in the next graph.



Characteristic U-I curve of a PV module.

17. Notice that the current is virtually constant when the output voltage is maintained between 0 V and about 7.5 V. Does the PV module act as a source of current or as a source of voltage in this region?

The PV module acts as a source of current.

18. Notice the large variation in current that occurs when the output voltage exceeds about 8.5 V, as the voltage varies little while the current varies from about 80% to about 20% of maximum (a variation of about 60 mA). Does the PV module act as a source of current or as a source of voltage in this region? Explain what causes the PV module to operate this way in this region.

In the region where the voltage exceeds about 8.5 V, the PV module operates as a voltage source. This is because, when illuminated, each PV cell in the PV module is equivalent to a current source in parallel with a diode. However, as the voltage increases, there comes a point when the diode in each PV cell begins to be forward biased and lets current flow through it. This causes the PV cell output current to decrease while the output voltage remains almost constant and equal to the diode forward-bias voltage (typically between 0.5 V and 0.6 V per cell).

Maximum power point produced by a single PV module operating at near room temperature

In this part of the exercise, you will calculate the output power produced by the PV module and locate the maximum power point (MPP) on the U-I curve.

19. Calculate the output power of the PV module for each measured U-I point. Record your results in Table 3.

Plot the curve of the PV module output power versus PV module output voltage on the graph used to plot the characteristic U-I curve.

Determine the voltage and current at the maximum power point (MPP) using the output power curve and the U-I curve.

Voltage = _______ V

Current = _______ A

Voltage = 8.02 V

Current = 91.2 mA

20. Is the maximum power point just between the constant-current and constant-voltage regions of the PV module U-I curve?

❑ Yes ❑ No

Yes

Open-circuit voltage and short-circuit current of two PV modules connected in parallel operating at near room temperature

In this part of the exercise, you will compare the open-circuit voltage U_{OC} and short-circuit current I_{SC} of two PV modules connected in parallel operating at near room temperature with those measured with a single PV module.

21. Make sure that the dimmer on the Solar Panel Test Bench is still adjusted so that each PV module produces a short-circuit current I_{SC} of approximately 100 mA when the temperature has stabilized.

Connect the “upper” PV module in parallel with the “lower” PV module and measure the open-circuit voltage U_{OC}, short-circuit current I_{SC}, and PV panel temperature. Refer to Figure 33 and Figure 34 if necessary.

Open-circuit voltage U_{OC} = _______ V

Short-circuit current I_{SC} = _______ A

PV panel temperature = _______ C

Open-circuit voltage U_{OC} = 10.24 V

Short-circuit current I_{SC} = 199.2 mA

PV panel temperature = 32.3˚C

22. Compare the open-circuit voltage U_{OC} measured in the previous step with the one measured with a single PV panel in step 12. What can you conclude about the difference between the values?

The open-circuit voltage U_{OC} produced by the two PV modules connected in parallel is virtually equal to the voltage produced by a single PV module. The open-circuit voltage U_{OC} is not affected by the surface area of PV panels.

23. Compare the short-circuit current I_{SC} measured with two PV modules connected in parallel, with the one measured with a single PV panel in step 9. What can you conclude about the difference between the values?

The short-circuit current I_{SC} measured with two PV modules connected in parallel is about twice the value obtained with a single module. This confirms that the current is proportional to the surface area of PV panels.

Characteristic U-I curve of two PV modules connected in parallel operating at near room temperature

In this part of the exercise, you will plot the characteristic U-I curve of two PV modules connected in parallel operating at near room temperature.

24. Connect the circuit shown in Figure 37.

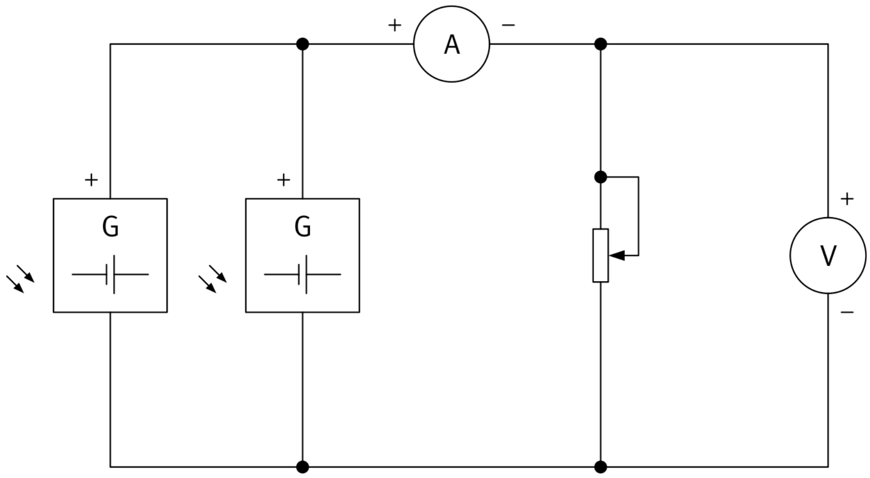


Figure 37. Circuit used to determine the characteristic U-I curve of two PV modules connected in parallel.

25. Using the potentiometer as a variable load, vary the output voltage from minimum to maximum by increments of 0.5 V. For each voltage setting, record the output voltage and the corresponding current in Table 4.

Table 4. Characteristic U-I curve of two PV modules connected in parallel.

Voltage (V)	Current (mA)	Voltage (V)	Current (mA)
Temperature of the PV panel during the measurements = _______°C			

The results are presented in the next table.

Characteristic *U*-*I* curve of two PV modules connected in parallel.

Voltage (V)	Current (mA)	Voltage (V)	Current (mA)
0.58	199.2	6.08	190.0
1.08	199.0	6.58	188.6
1.58	198.9	7.08	187.5
2.08	198.0	7.58	183.6
2.58	197.6	8.08	174.2(1)
3.08	197.2	8.58	156.4
3.58	196.0	9.08	126.6
4.08	194.5	9.58	82.4
4.58	193.5	10.08	22.7
5.08	192.4	10.10	20.0
5.58	191.6		

(1) Maximum power point (MPP)
Temperature of the PV panel during the measurements = 32.3˚C

26. Using the values in Table 4, plot the characteristic *U*-*I* curve of the PV module in Figure 38.

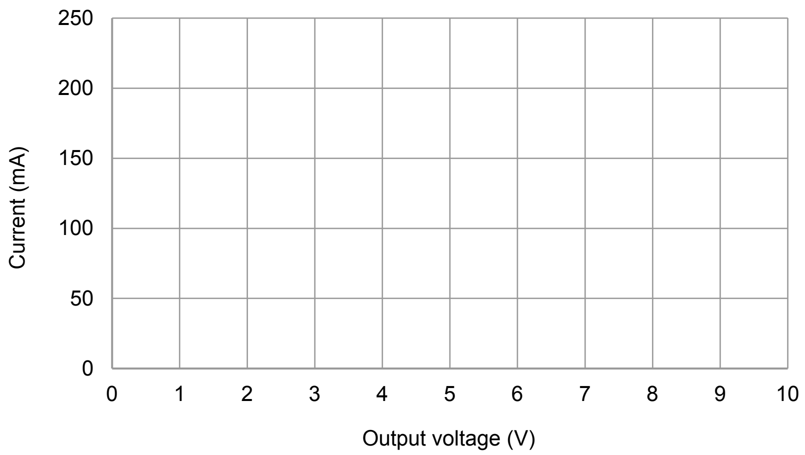
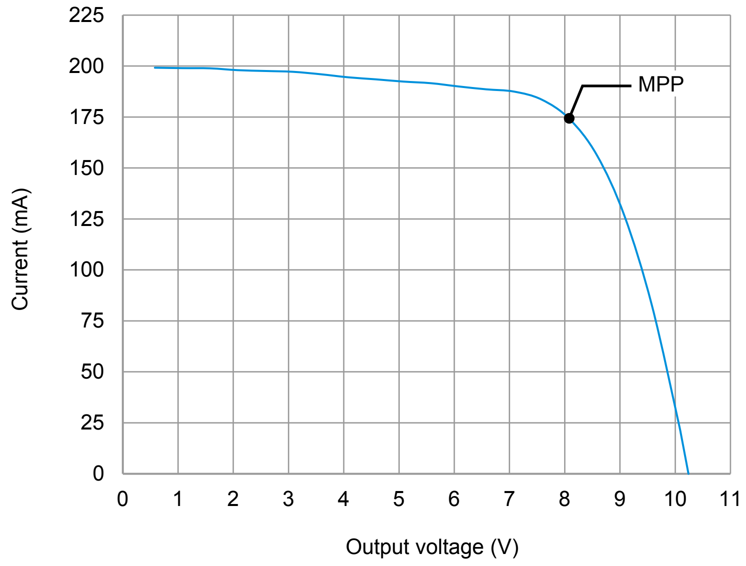


Figure 38. Characteristic *U*-*I* curve of two PV modules connected in parallel.

The results are presented in the next graph.



Characteristic *U*-*I* curve of two PV modules connected in parallel.

27. Using the values in Table 4, determine the voltage and current values corresponding to the maximum power point (MPP), and indicate the point in Figure 38.

28. How does the shape of the *U*-*I* curve of two PV modules connected in parallel compare with that obtained with a single PV module?

The shape of the *U*-*I* curve of the two PV modules connected in parallel is similar to the shape of the *U*-*I* curve obtained with a single PV module.

Conclusion

In this exercise you were introduced to photovoltaic panels. You learned that a PV cell is basically a P-N junction just like a diode. You saw that, depending on the electrical load, a PV cell operates as a current source or as a voltage source. You learned that the output power increases when the surface area of PV panels is increased. You also learned that the output power increases when the irradiance level is increased.

Review Questions

1. What are standard test conditions (STC) used for?

Standard test conditions (STC) have been devised to determine the PV panel specifications and to enable fair comparisons of one PV panel with another.

2. The point on the *U*-*I* curve where the output power is maximum is referred to as

the maximum power point (MPP).

3. What units are used to express the irradiance?

Watt per square meter (W/m^2)

4. Why is it common to connect many PV cells of the same size in series?

Because the output voltage of a single PV cell is low (less than 0.7 V) for most applications.

5. Determine the maximum power produced by a solar panel having 15% efficiency and 5.0 m^2 of surface area at standard test conditions.

750 W

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