Renewable Energy

Solar Power

Courseware Sample

86352-F0

RENEWABLE ENERGY

SOLAR POWER

Courseware Sample

by
the staff
of
Lab-Volt Ltd.

FIRST EDITION, NOVEMBER 2009

Printed in Canada
November 2009

Foreword

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 Lab-Volt Solar Power Technology Training System is designed to introduce you 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.

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Sample Exercise

Extracted from

Student Manual

Solar Panel Orientation

EXERCISE OBJECTIVE When you have completed this exercise, you will understand how the solar illumination at any location on Earth varies over the course of a year. You will know how to correctly set the orientation of fixed PV panels installed outdoors to maximize annual energy production.

DISCUSSION OUTLINE The Discussion of this exercise covers the following points:

- Introduction to the importance of solar panel orientation
- Earth's orbit
- Sunlight at Earth's surface
- Solar declination and Sun's path in the sky
- Solar altitude angle at solar noon
- Optimal orientation of fixed PV panels
- Sun tracking systems

DISCUSSION

Introduction to the importance of solar panel orientation

PV panels installed outdoors generally produce 80% to 90% of their electrical energy (which is proportional to output power) from direct sunlight striking their surface, the remaining electrical energy they produce is due to diffuse sunlight (e.g., sunlight scattered by atmospheric particles and moisture) and reflected sunlight from surrounding objects. Furthermore, the amount of energy produced by a PV panel is highly dependent on the angle of arrival of light. The closer the angle of arrival of incident light to the normal to the surface of the PV panel, the higher the equivalent irradiance (insolation) at the panel surface, and the higher the relative output power of the PV panel as is shown in the following figure.

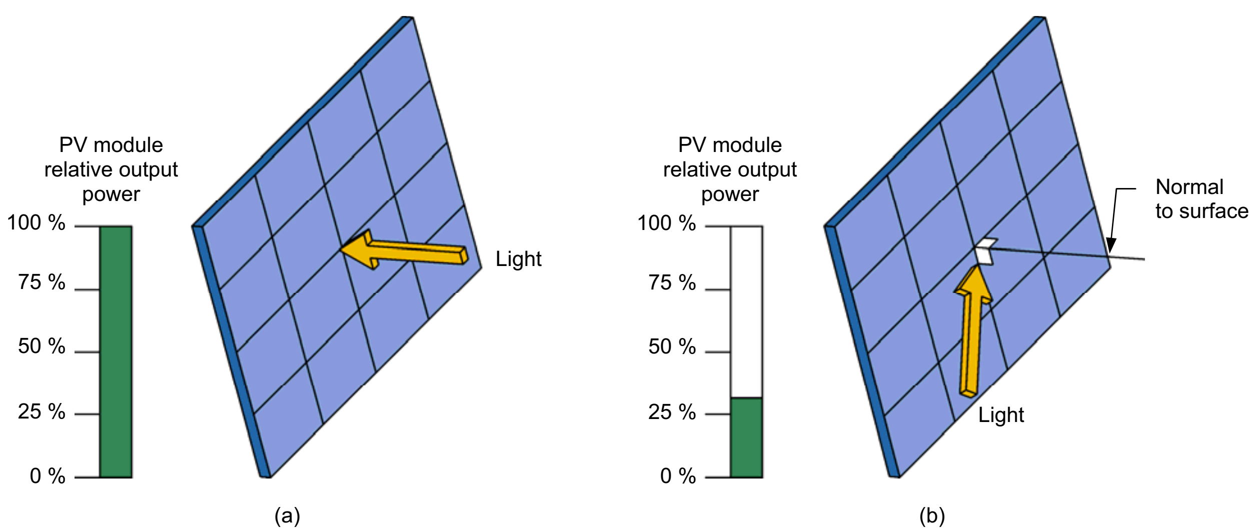


Figure 66. Effect of the angle of arrival of light on the relative output power of a PV panel.

The equivalent solar irradiance (**insolation**) at the surface of a PV panel is a simple function of the angle between the incoming sunlight (direct radiation) and the normal to the surface of a PV panel, i.e., the angle of incidence θ (see Figure 67). It can be calculated using the following equation:

$$I_{PANEL} = I_{SUN} \times \cos\theta \quad (2)$$

where I_{PANEL} is the insolation at the panel surface
I_{SUN} is the insolation from direct sunlight
θ is the angle of incidence of direct sunlight

For instance, the solar insolation I_{PANEL} at the surface of a PV panel is about 13% less than the direct sunlight insolation I_{SUN} when the angle of incidence θ is 30° (cos 30° = 0.866).

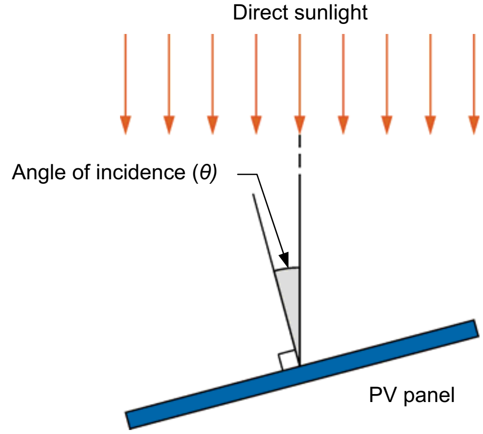


Figure 67. Angle of incidence *θ*.

The above characteristics clearly demonstrate that it is essential to correctly set the orientation of PV panels with respect to the source of light in order to maximize the amount of energy they produce. When installed outdoors, this means that PV panels must be correctly aligned with respect to the Sun's path in the sky. This path depends on the time of the year as well as on the location of the PV panel on Earth, as is explained later in this discussion.

Earth's orbit

Earth revolves around the Sun at a rate of 1 revolution every year (365.25 days) following a slightly elliptical orbit as shown in Figure 68. Earth also rotates around its own axis at a rate of one revolution per day. Note that Earth's spin axis is tilted 23.45° with respect to the plane of its elliptic orbit (ecliptic plane) around the Sun. The tilt of Earth's spin axis is responsible for the seasons observed each year. It is also at the origin of the variations of the Sun's path in the sky observed over the year. On March 21 and September 21, a line from the center of the Sun to the center of Earth passes right through the **equator**, and everywhere on Earth daytime and nighttime last 12 hours each, hence the term equinox (equal day and night). This corresponds to the spring and autumn times of the year. On June 21, the tilt (23.45°) of Earth's spin axis makes the North Pole closer to the Sun than the South Pole. This results in longer day times in the Northern

Hemisphere and shorter day times in the Southern Hemisphere. This corresponds to the summer solstice in the Northern Hemisphere and the winter solstice in the Southern Hemisphere. Conversely, on December 21, the tilt of Earth's spin axis makes the South Pole closer to the Sun than the North Pole. This results in shorter day times in the Northern Hemisphere and longer day times in the Southern Hemisphere. This corresponds to the winter solstice in the Northern Hemisphere and the summer solstice in the Southern Hemisphere.

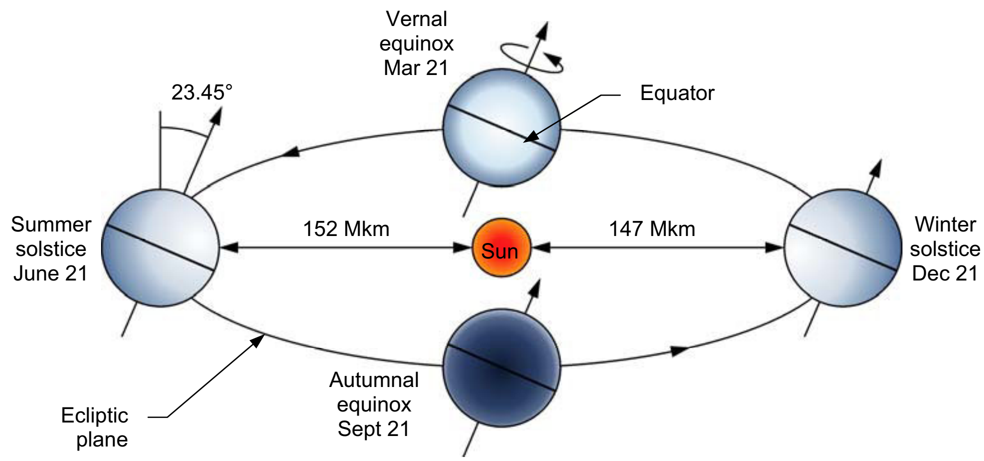


Figure 68. Simple representation of Earth revolving around the Sun.

Sunlight at Earth's surface

Figure 69 illustrates the physical relationship between Earth and the Sun.

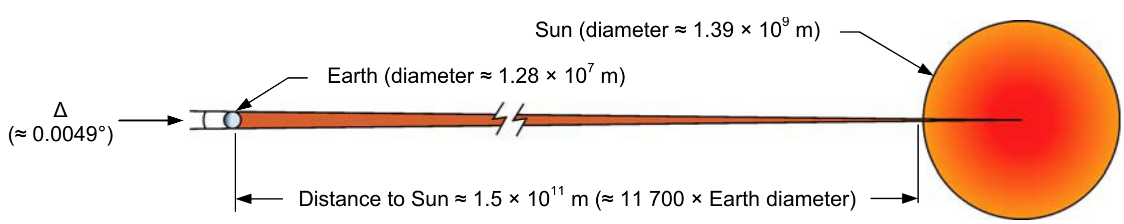


Figure 69. Physical relationship between Earth and the Sun.

The Sun is much larger than Earth, their diameters being equal to about 1.39×10^9 m and 1.28×10^7 m, respectively. The Sun's diameter is thus about 109 times Earth's diameter. The distance that separates Earth from the Sun is approximately 1.5×10^{11} m, i.e., about 108 times the Sun's diameter and more than 11 700 times Earth's diameter. Consequently, the portion of sunlight that illuminates the complete surface of Earth is contained in a very small angular segment Δ of about 0.0049° (see calculation below).

$$\Delta = 2 \times \tan^{-1} (\text{Earth's diameter} \div 2 \text{ Distance to Sun}) = 2 \times \tan^{-1} (1.28 \times 10^7 \div 3 \times 10^{11}) = 0.0049^\circ$$

Because of this, it is common practice to consider that all of the Sun's rays striking Earth's surface are parallel to each other as is shown in the following figure.

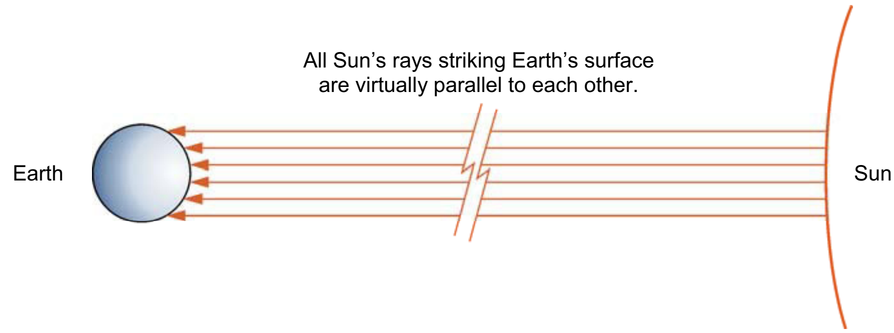


Figure 70. Sun rays striking Earth's surface.

Solar declination and Sun's path in the sky

Earlier in this discussion, we saw that the tilt (23.45°) of Earth's spin axis is responsible for the seasons as well as the variations of the Sun's path in the sky observed over the year. Figure 71 shows a summary of Earth's position with respect to the Sun at four key periods of the year. At the equinoxes (March 21 and September 21), the Sun's rays are perpendicular to Earth's surface at the equator (**latitude** 0°), i.e., they are aligned with the normal to Earth's surface at the equator. At the summer solstice in the Northern Hemisphere (June 21), the Sun's rays are perpendicular to Earth's surface at the **Tropic of Cancer** (i.e., at latitude +23.45°) but offset +23.45° from the normal to Earth's surface at the equator. The angular offset of +23.45° observed at the equator is due to the tilt (23.45°) of Earth's spin axis. Conversely, at the winter solstice in the Northern Hemisphere (December 21), the Sun's rays are perpendicular to Earth's surface at the **Tropic of Capricorn** (i.e., at latitude −23.45°) but offset −23.45° from the normal to Earth's surface at the equator. The angular offset of −23.45° observed at the equator is also due to the tilt (23.45°) of Earth's spin axis.

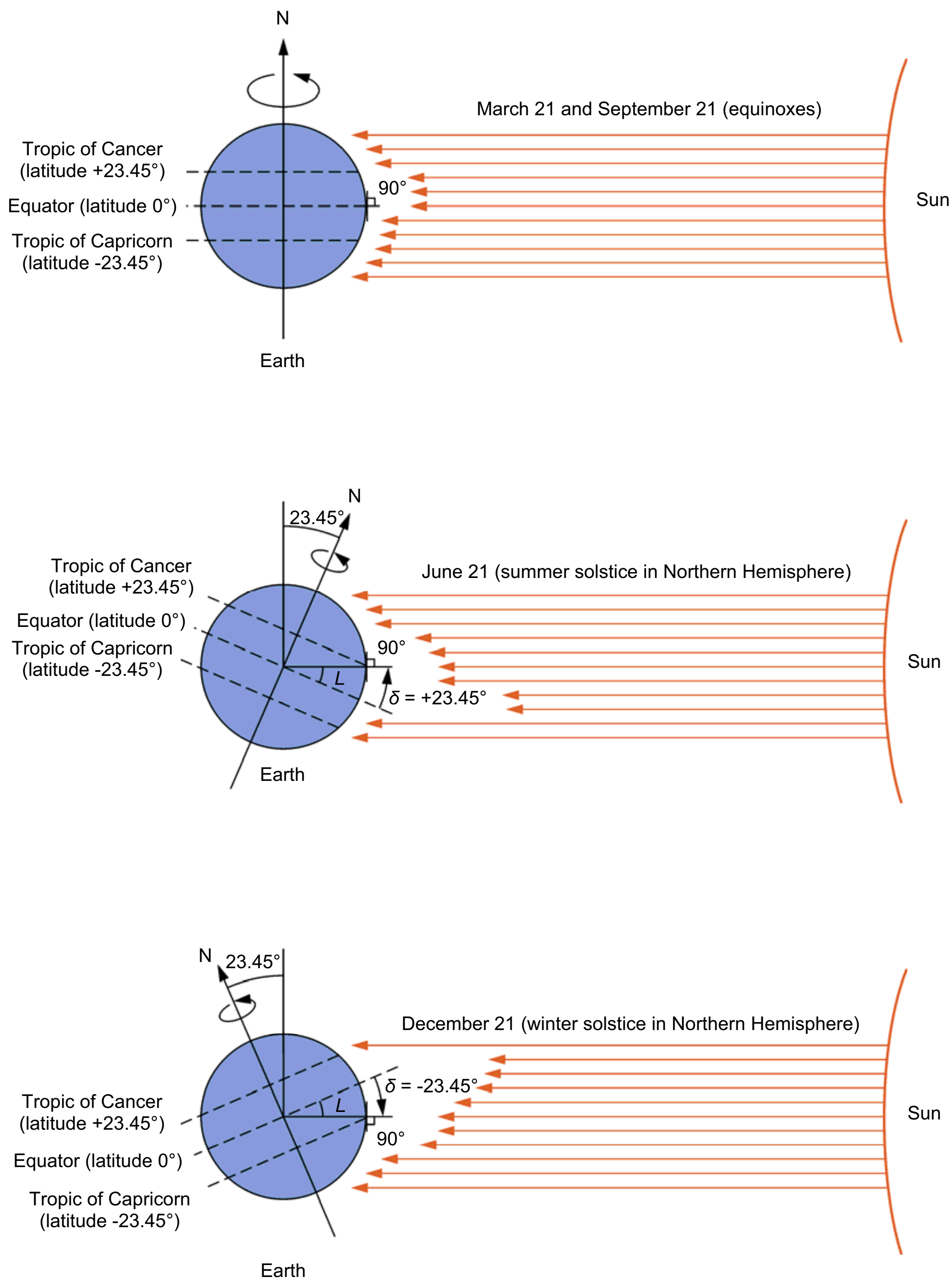


Figure 71. The solar declination δ varies from +23.45° to −23.45° each year.

The angle between the normal to Earth's surface at the equator and the direction of the Sun's rays is referred to as the **solar declination** δ. The solar declination is 0° at the equinoxes (March 21 and September 21), +23.45° at the summer solstice in the Northern Hemisphere (June 21) and −23.45° at the winter solstice in the Northern Hemisphere (December 21). The solar declination δ thus varies from +23.45° to −23.45° each year. This causes the angle of arrival of the Sun's rays at any latitude on Earth to vary according to the time of the year. This explains why the Sun's path observed in the sky varies depending on the time of the year.

The following equation allows the solar declination δ to be determined for each day of the year.

$$\delta = 23.45 \sin\left[\frac{360}{365} \times (n - 81)\right] \tag{3}$$

where δ is the solar declination
n is the n^{th} day of the year

The following table gives the value of the solar declination δ (in degrees) for the 21^{st} day of each month. Note that solar declination values vary slightly from year to year.

Table 7. Solar declination δ for the 21^{st} day of each month.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
δ	−20.1	−11.2	0.0	11.6	20.1	23.4	20.4	11.8	0.0	−11.8	−20.4	−23.4

Solar altitude angle at solar noon

Every day, the Sun rises in the east and sets in the west, reaching its highest point in the sky at some time in the middle of the day. The moment at which the Sun is at its highest point in the sky is referred to as **solar noon**. The position of the Sun at its highest point is commonly quantified using an angular measurement called **solar altitude angle** at solar noon (β_N). The solar altitude angle β_N is simply the angle between the Sun and the ground surface at solar noon, as is shown in Figure 72. This figure also shows that the solar altitude angle β_N depends on the latitude L at which you are and the solar declination δ. Because the solar declination varies over the year, the solar altitude angle β_N also varies depending on the time of the year. The following equation is used to calculate the solar altitude angle β_N.

$$\beta_N = 90 - L + \delta \tag{4}$$

where β_N is the solar altitude angle at solar noon;
L is the latitude at which you are;
δ is the solar declination.

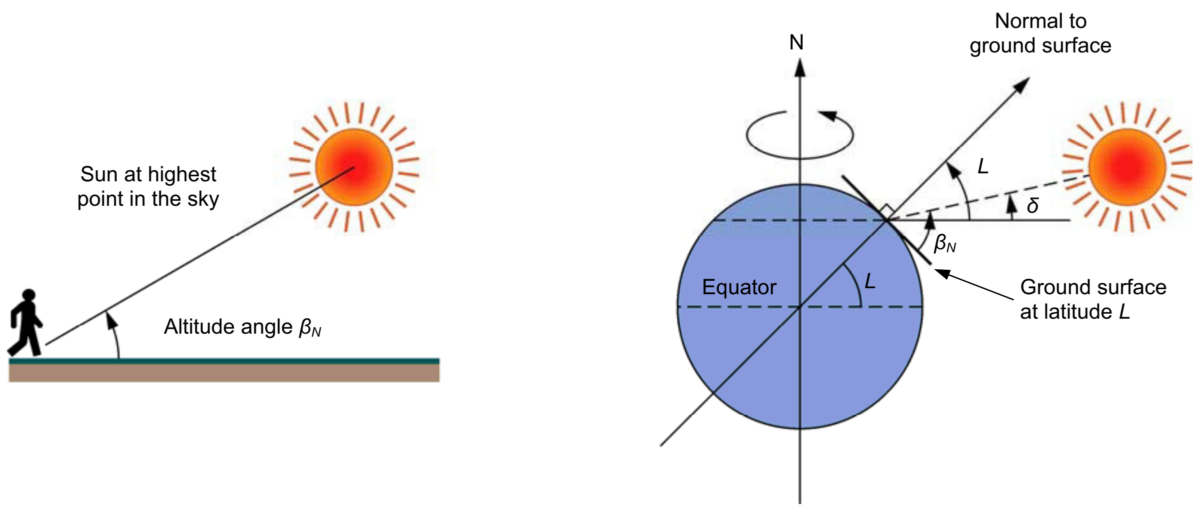


Figure 72. Solar altitude angle at solar noon (β_N).

Optimal orientation of fixed PV panels

Figure 73 summarizes the overall effect which the variation in solar declination δ observed each year (+23.45° to −23.45°) has on the angle of arrival of the Sun's rays at the equator. The figure clearly shows that the best orientation for a fixed PV panel installed at the equator is parallel to the ground surface (i.e., set in horizontal position) as this ensures the best possible alignment of the panel surface with the Sun's rays over a year. Consequently, this ensures that the PV panel produces the maximum amount of energy over a year.

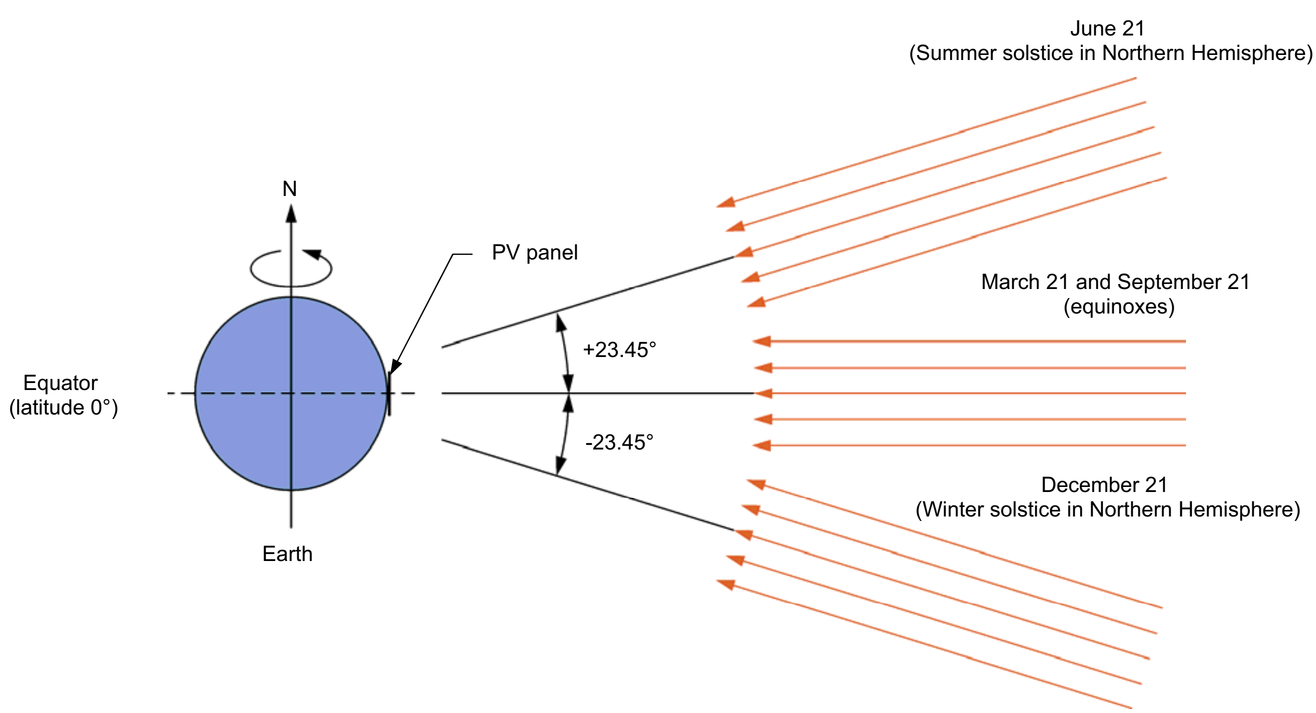


Figure 73. Effect of the variation in solar declination δ on the angle of arrival of the Sun rays at the Equator.

Figure 74 shows a fixed PV panel set in horizontal (optimum) position at the equator, a fixed PV panel installed in the Northern Hemisphere at latitude L_1, and a fixed PV panel installed in the Southern Hemisphere at latitude L_2. The PV panel at latitude L_1 in the Northern Hemisphere is tilted toward the equator (i.e., toward South) at an angle with respect to the ground surface that is equal to latitude L_1. Similarly, the PV panel at latitude L_2 in the Southern Hemisphere is tilted toward the equator (i.e., toward North) at an angle with respect to the ground surface that is equal to latitude L_2. As a result, the PV panels in the Northern Hemisphere and Southern Hemisphere have the same orientation (with respect to the Sun) as the PV panel installed in horizontal position at the equator. Over a year, this ensures that the surface of the PV panels in the Northern Hemisphere and Southern Hemisphere have the best possible alignment with the Sun's rays, and thereby, produce the maximum amount of energy.

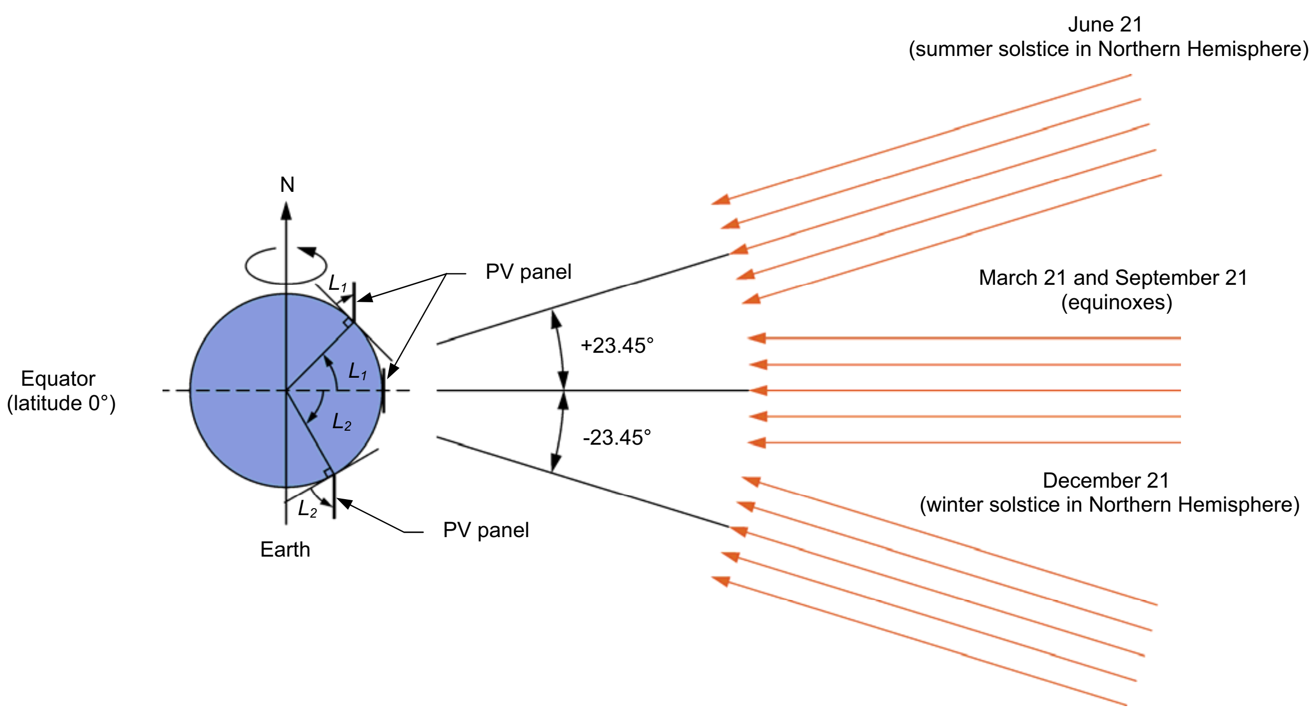


Figure 74. Optimal orientation of fixed PV panels installed at different latitudes.

From the example of Figure 74, it becomes obvious that any fixed PV panel installed outdoors must be tilted toward the equator at an angle with respect to the ground that is equal to the latitude L at which the PV panel is located, to maximize the annual energy production. This is the general rule of thumb to be followed when installing fixed PV panels outdoors.

To improve energy production of fixed PV panels a little further, the tilt angle can be decreased slightly during summer and increased slightly during winter (refer to the monthly solar declinations in Table 7). For fixed PV panels located in the Northern Hemisphere, this means that the tilt angle could be decreased slightly from May to July and increased slightly from November to January. Conversely, for PV panels located in the Southern hemisphere, this means that the tilt angle could be increased slightly from May to July and decreased slightly from November to January.

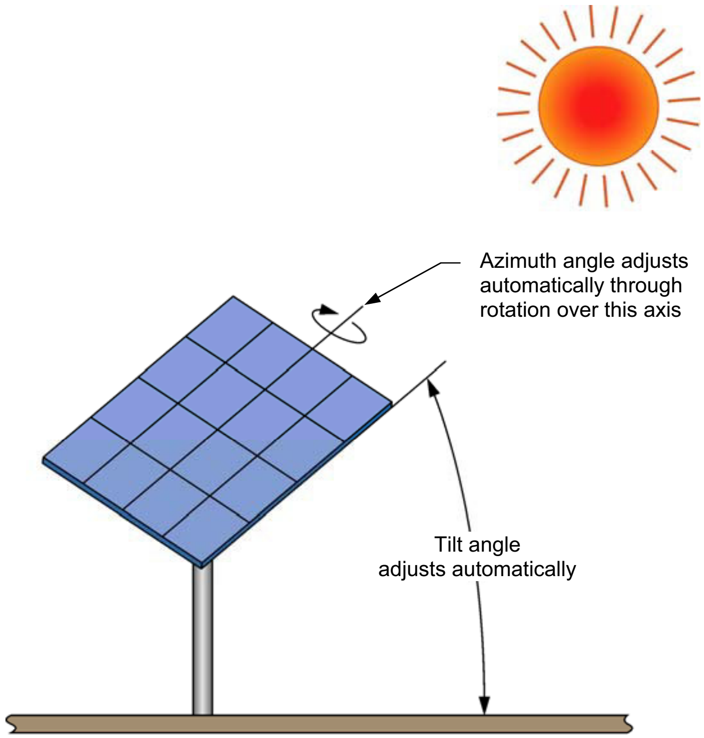
Finally, since the Sun rises in the east and sets in the west every day, the azimuthal orientation of a fixed PV panel installed in the Northern Hemisphere must be South. Conversely, the azimuthal orientation of a fixed PV panel installed in the Southern Hemisphere must be North.

Sun tracking systems

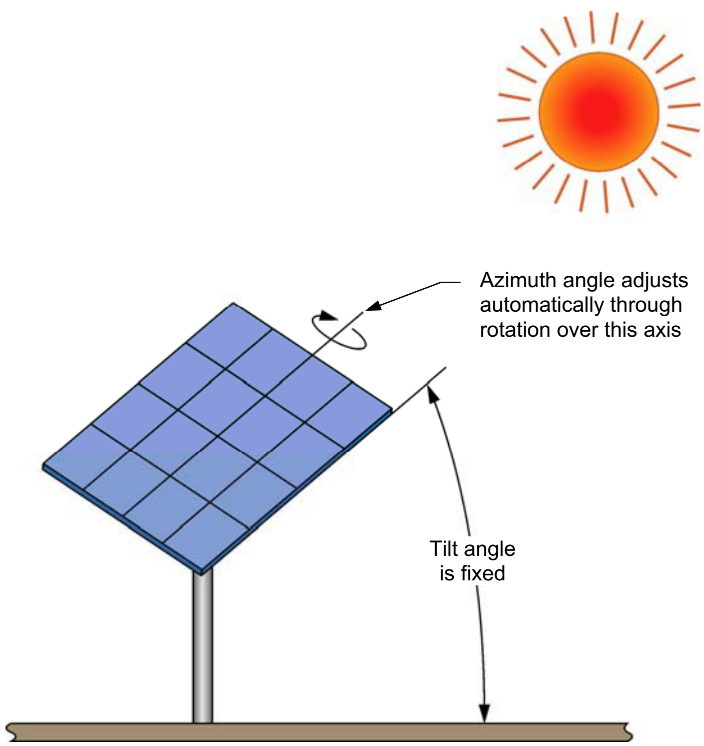
So far, we discussed the installation of fixed PV panels outdoors and the optimization of their orientation to maximize the annual energy production. To further increase the energy production of PV panels, these can be mounted onto movable supports that automatically track the Sun's position instead of being simply installed in a fixed position. These movable supports are generally referred to as Sun tracking systems or Sun trackers.

Sun tracking systems are divided into two types based on whether they operate on two axes or a single axis. Two-axis Sun tracking systems can vary their tilt and azimuth angles so as to keep the PV panel surface perfectly aimed at the Sun at all times. A two-axis Sun tracking system is shown in Figure 75a. On the other hand, single-axis Sun tracking systems can only vary their azimuth angle so as to follow the east-to-west motion which the Sun performs every day, their tilt angle being fixed (usually set to the value of the latitude at which the PV panel is installed). A single-axis Sun tracking system is shown in Figure 75b. Note that in both tracking systems, the azimuth changes at a rate matching Earth's rotation, i.e., 15°/hour.

Figure 75 shows clockwise rotation for azimuth tracking of the Sun's position. This direction of rotation is valid for PV panels installed in the Northern Hemisphere. Counterclockwise rotation is used for PV panels installed in the Southern Hemisphere.



(a) Two-axis sun tracking system



(b) Single-axis Sun tracking system

Figure 75. Two-axis and single-axis Sun tracking systems.

Figure 76 shows curves of average daily insolation over a year for a PV panel located at latitude 40° in the Northern Hemisphere. Curve 1 in the figure shows the average daily insolation obtained when the PV panel is installed in a fixed position (panel tilted 40° toward the equator and oriented toward South). Curve 2 shows the average daily insolation obtained when the PV panel is mounted on a single-axis sun tracking system, the tilt angle being set to 40° (toward the equator, of course). Curve 3 shows the average daily insolation obtained when the PV panel is mounted on a two-axis sun tracking system.

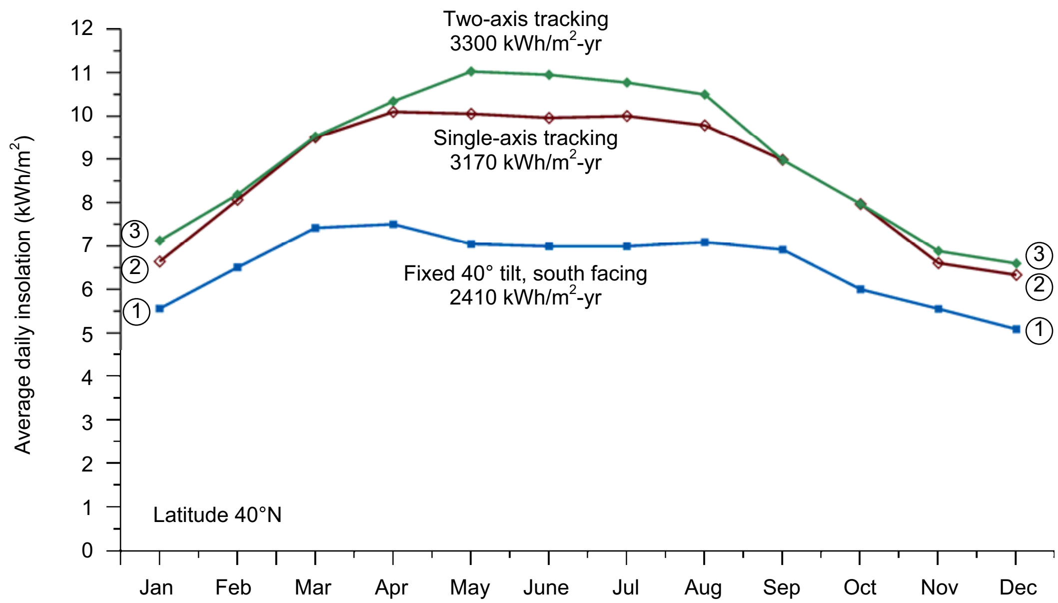


Figure 76. Average daily insolation over a year for a PV panel located at latitude 40° in the Northern Hemisphere.

Comparing the curve of average daily insolation obtained with the fixed PV panel to that obtained when the PV panel is mounted on a single-axis sun tracking system (i.e., comparing curves 1 and 2) shows that using a single-axis sun tracking system improves the average daily insolation significantly (by nearly 30% over a year). This interesting improvement is mainly because the azimuth of the Sun varies over 180° (Sun rises in the east and sets in the west) every day. On the other hand, comparing the curve of average daily insolation obtained when the PV panel is mounted on a single-axis sun tracking system with that obtained when the PV panel is mounted on a two-axis sun tracking system (i.e., comparing curves 2 and 3) reveals that using a two-axis sun tracking system improves the average daily insolation only very slightly (by a little less than 5% over a year). This is mainly because the solar altitude angle β varies over less than 90° every day (at latitude 40°, the solar altitude angle β varies over less than 75°).

Under any circumstances, for the use of sun tracking systems to be worthwhile, the gain in annual energy production resulting from the use of such systems must largely exceed the amount of energy required for daily motion of the PV panels. In general, it is worthwhile using sun tracking systems in PV solar plants producing a large amount of energy. In this case, even a slight increase in the average insolation measured over a year often results in a valuable increase in annual energy production.

PROCEDURE OUTLINE

The Procedure is divided into the following sections:

- Determination of the altitude angle of the Sun at solar noon
- PV panel optimal orientation
- Altitude angle of the Sun at optimal orientation of PV panel
- Effect of the tilt angle error on the short-circuit current I_{SC}
- Effect of the azimuth error on the short-circuit current I_{SC}

PROCEDURE

Determination of the altitude angle of the Sun at solar noon

In this part of the exercise, you will determine the altitude angle of the Sun at solar noon (β_N) at your latitude.

1. Determine the latitude at which you are:

Latitude: _____

2. Knowing the latitude at which you are, calculate the altitude angle of the sun at solar noon β_N.

Altitude angle of the sun β_N: _____

PV panel optimal orientation

In this part of the exercise, you will use the Monocrystalline Silicon Solar Panel outdoors. You will adjust the orientation (azimuth and tilt angle) of the PV Panel so as to maximize the short-circuit current I_{SC}.

This part of the exercise (step 3 to step 7) must be performed on a clear day and at a time close to solar noon, time at which the Sun is at its highest point in the sky.

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

Go outdoors and install the Monocrystalline Silicon Solar Panel onto a tripod at a location where the measurements will not be affected by sunlight reflected off buildings or other large objects. It is also important that the tripod head is level.

Connect an ammeter directly across the output of one of the two 18-cell PV modules of the PV panel.

Note: Wait for the PV panel temperature to stabilize before taking voltage and current measurements.

4. Adjust the orientation (azimuth and tilt angle) of the Monocrystalline Silicon Solar Panel so that that the metallic stem mounted on the panel chassis no longer produces shading. This ensures that the PV panel surface is perfectly aimed at the Sun and the short-circuit current I_{SC} is maximized.

Altitude angle of the Sun at optimal orientation of PV panel

In this part of the exercise, you will measure the tilt angle of the PV panel at the optimal orientation and calculate the altitude angle of the Sun β_N. You will then compare the altitude angle of the Sun calculated in step 2 with that determined from the position of the solar panel.

A protractor and a level are required to measure the tilt angle of the solar panel. If you do not have these items, go directly to step 8.

5. Once the orientation of the PV panel is optimized, measure the tilt angle of the PV panel with respect to ground.

Tilt angle of the PV panel: _____

6. Using the tilt angle measured in the previous step, calculate the altitude angle of the Sun at solar noon (β_N = 90° − tilt angle).

Altitude angle of the Sun β_N: _____

7. Compare the altitude angle of the Sun β_N determined in the previous step with the altitude angle β_N of the Sun calculated in step 2. Are they similar?

❑ Yes ❑ No

Effect of the tilt angle error on the short-circuit current I_{SC}

In this part of the exercise, you will vary the tilt angle of the PV panel and observe the effect on the short-circuit current I_{SC} produced by the PV panel.

Take care to not modify the azimuth of the PV panel during this part of the exercise.

8. Using the angular markers screened on the surface of the Monocrystalline Silicon Solar Panel, vary the tilt angle of the PV panel over a range of 60° by steps of 5° to offset the tilt angle from the optimum value. For each tilt angle, measure the short-circuit current I_{SC} indicated by the ammeter. Enter the results in Table 8.

Table 8. Short-circuit current I_{SC} versus tilt angle error.

Tilt angle error (°)	I_{SC} (mA)	Tilt angle error (°)	I_{SC} (mA)
0		35	
5		40	
10		45	
15		50	
20		55	
25		60	
30			
Temperature of the PV panel during the measurements: ______			

9. Plot the curve of the short-circuit current I_{SC} as a function of the tilt angle error in Figure 77.

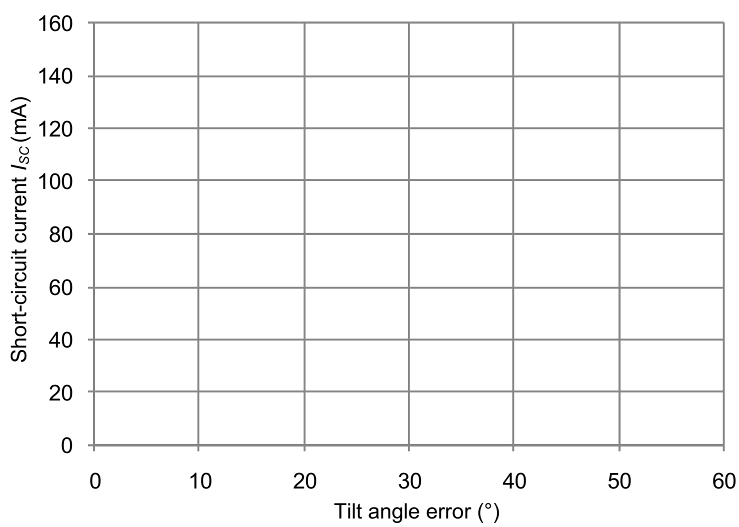


Figure 77. Short-circuit current versus tilt angle error.

10. Does the short-circuit current I_{SC} versus tilt angle error curve you plot in Figure 77 confirm that the short-circuit current decreases significantly (and thus the output power) when the tilt angle error increases?

❑ Yes ❑ No

11. Readjust the orientation (azimuth and tilt angle) of the Monocrystalline Silicon Solar Panel so that the metallic stem mounted on the panel chassis produces no shading. This ensures that the PV panel surface is perfectly aimed at the Sun and the short-circuit current I_{SC} is maximized.

Effect of the azimuth error on the short-circuit current I_{SC}

In this part of the exercise, you will vary the azimuth of the PV panel and observe the effect on the short-circuit current I_{SC} produced by the PV panel.

Make sure that the tripod head is level, and do not modify the tilt angle during this part of the exercise.

12. Using the angular markers screened on the surface of the Monocrystalline Silicon Solar Panel, vary the azimuth of the PV panel over a range of 60° by steps of 5° to offset the azimuth from the optimum value. For each azimuth value, measure the short-circuit current I_{SC} indicated by the ammeter. Enter the result in Table 9.

Table 9. Short-circuit current versus azimuth error.

Azimuth angle error (°)	I_{SC} (mA)	Azimuth angle error (°)	I_{SC} (mA)
0		35	
5		40	
10		45	
15		50	
20		55	
25		60	
30			
Temperature of the PV panel during the measurements: _____			

13. Plot the curve of the short-circuit current I_{SC} as a function of the azimuth error in Figure 78.

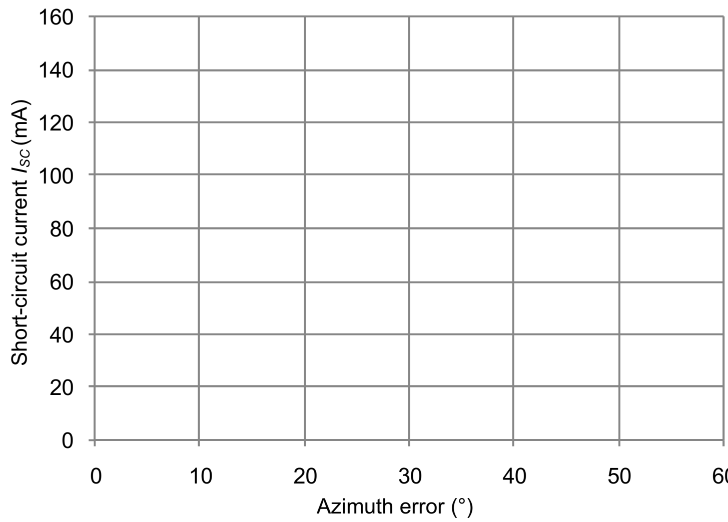


Figure 78. Short-circuit current I_{SC} versus azimuth error.

14. Does the short-circuit current I_{SC} versus azimuth error curve you plot in Figure 78 confirm that the short-circuit current decreases significantly (and thus the output power) when the azimuth error increases?

❑ Yes ❑ No

CONCLUSION

In this exercise you learned that it is essential to correctly set the orientation of fixed PV panels installed outdoors because most of the electrical energy they produce comes from direct sunlight striking their surface.

You learned that Earth revolves around the Sun, and that it also rotates around its own axis. You saw that Earth's spin axis is tilted 23.45° with respect to the plane of its elliptic orbit around the Sun.

You learned that the angle between the normal to Earth's surface at the equator and the direction of the Sun's rays is referred to as the solar declination δ. The solar declination varies from +23.45° (value reached at the summer solstice in the Northern Hemisphere) to −23.45° (value reached in the winter solstice in the Northern Hemisphere) every year.

You saw that the position of the Sun at its highest point is commonly quantified using an angular measurement called solar altitude angle at solar noon β_N. The solar altitude angle is the angle between the Sun and the ground surface at solar noon. You also saw that the solar altitude angle β_N depends on the latitude at which you are and the solar declination. Because the solar declination varies over the year, the solar altitude angle β_N also varies depending on the time of the year.

You learned that the general rule of thumb to be followed when installing fixed PV panels outdoors, is to tilt the PV panels toward the equator at an angle with respect to the ground that is equal to the latitude at which the PV panels are located. Since the Sun rises in the east and sets in the west every day, the optimal azimuthal orientation of fixed PV panels installed in the Northern Hemisphere is South, and North when the PV panels are installed in the Southern Hemisphere.

You learned that using a single-axis sun tracking system to control the azimuth of solar panels instead of having fixed solar panels can increase the average daily insolation by about 30% over a year. You also learned that using a two-axis sun tracking system, to control the azimuth and tilt angle of solar panels, instead of having a single-axis sun tracking system provides a slight increase (generally 5%) in the average daily insolation observed over a year.

REVIEW QUESTIONS

1. The moment at which the Sun is at its highest point in the sky is referred to as

   ____

2. Explain why it is common practice to consider that all of the Sun's rays striking Earth's surface are parallel to each other (about 0.0049°).

   ____

   ____

   ____

3. Describe the general rule of thumb to be followed when installing fixed PV panels outdoors.

   ____

   ____

   ____

4. Which latitude corresponds to a solar altitude angle β_N of 75° if the solar declination δ is 20.1°?

   ____

   ____

   ____

5. At which period of the year are the Sun's rays perpendicular to Earth's surface at the Tropic of Cancer?

   ____

   ____

   ____

Sample

Extracted from

Instructor Guide

Exercise 6 Solar Panel Orientation

Answers to Procedure Step Questions

1. **Note to the instructor**:

   Some answers in this exercise depend on your geographical position and the time of year when the measurements are done. You must thus determine the answers that apply to your case. Typical answers corresponding to a latitude of +46° 53' 24.09" (≈46.9°) and obtained from measurements performed at a time close to solar noon on a clear day in September close to the equinox are given as an example in this instructor guide.

   Typical latitude: +46° 53' 24.09" (≈46.9°)

2. Altitude angle of the Sun β_N measured at a latitude of +46° 53' 24.09" (≈46.9°) on a clear day in September close to the equinox: 43.1° (90° - 46.9° + 0)

5. Tilt angle measured at a latitude of +46° 53' 24.09" and a time close to solar noon on a clear day in September close to the equinox: 46°

6. Altitude angle of the sun β_N for the tilt angle measured in the previous step: 44°

7. Yes

8. The values shown in the following table have been measured at a latitude of +46° 53' 24.09" and a time close to solar noon on a clear day in September close to the equinox.

Table 8. Short-circuit current I_{SC} versus Tilt angle error.

Tilt angle error (°)	I_{SC} (mA)	Tilt angle error (°)	I_{SC} (mA)
0	136.3	35	117.8
5	136.3	40	110.9
10	136.1	45	103.3
15	134.7	50	94.6
20	132.5	55	85.4
25	128.9	60	74.9
30	123.4		
Temperature of the PV panel during the measurements: 26°C (79°F)			

9. The values used to plot the following graph have been measured at a latitude of +46° 53' 24.09" and a time close to solar noon on a clear day in September close to the equinox.

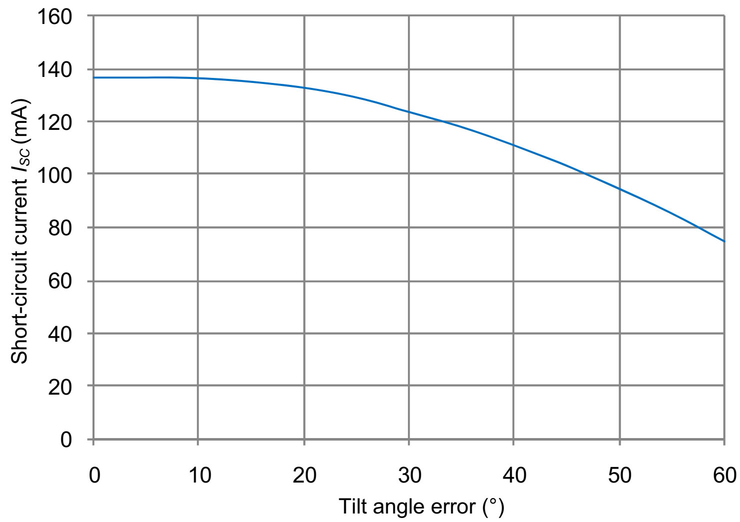


Figure 77. Short-circuit current *versus* Tilt angle error.

10. Yes

12. The values shown in the following table have been measured at a latitude of +46° 53' 24.09" and a time close to solar noon on a clear day in September close to the equinox.

Table 9. Short-circuit current versus Azimuth error.

Azimuth angle error (°)	I_{SC} (mA)	Azimuth angle error (°)	I_{SC} (mA)
0	136.3	35	112.2
5	135.5	40	105.3
10	134.1	45	97.4
15	131.8	50	88.3
20	128.1	55	79.5
25	123.6	60	66.1
30	118.4		
Temperature of the PV panel during the measurements: 26°C (79°F)			

13. The values used to plot the following graph have been measured at a latitude of +46° 53' 24.09" and a time close to solar noon on a clear day in September close to the equinox.

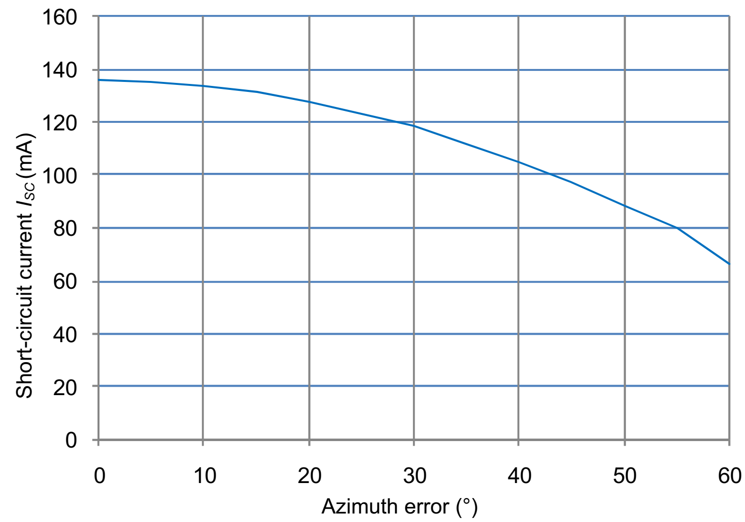


Figure 78. Short-circuit current I_{SC} versus Azimuth error.

14. Yes

Answers to Review Questions

1. solar noon.

2. Because the portion of sunlight that illuminates the complete surface of Earth is contained in a very small angular segment.

3. The general rule of thumb to be followed when installing fixed PV panels outdoors is to tilt the panels toward the equator at an angle with respect to the ground that is equal to the latitude at which the PV panels are located. The azimuthal orientation is South in the Northern Hemisphere, and North in the Southern Hemisphere.

4. $L = 90° - \beta_N + \delta = 90° – 75° + 20.1° = 35.1°$

5. At the summer solstice in the Northern Hemisphere (June 21)

Bibliography

MASTERS, Gilbert M., *Renewable and Efficient Electric Power Systems*, Hoboken: John Wiley & Sons, 2004, ISBN 0-471-28060-7