CHAPTER 5

Solar Photovoltaic Systems

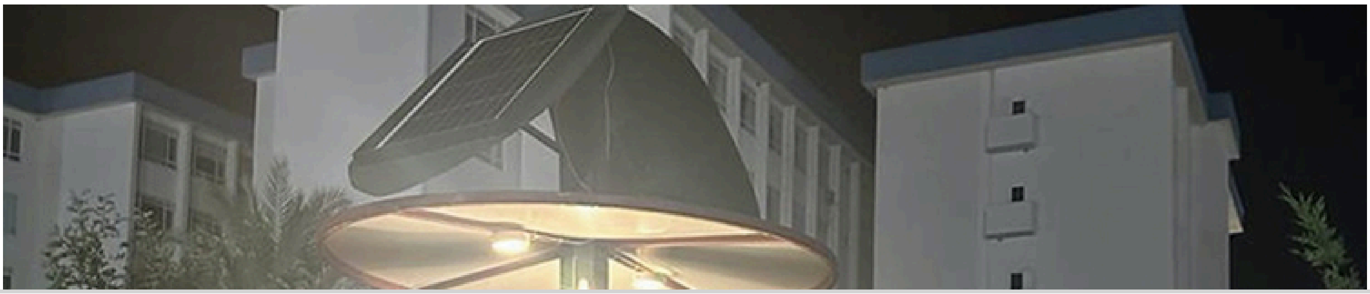
5-1 PHOTOVOLTAIC EFFECT

Solar cells or photovoltaic (PV) cells are devices that convert solar radiation into electricity directly. Solar cells have no moving parts or components, and they have a lightweight structure. A PV cell operates on the principle of *photovoltaic effect*. When photons from solar light are incident on a suitable material, electrons are released, which in turn generate voltage difference or electric current.

Becquerel noted the photoelectric effect for the first time in 1839. He observed this when light was incident on an electrode in a solution. The operating principle of a PV cell was discovered by Adams and Day in 1877 in solids with selenium as the material. Coblenz discovered the generation of voltage between the dark and illuminated regions of semiconducting crystals in 1919. Ohl discovered the photoelectric effect at a *p*-*n* junction of two semiconductors in 1941. Researchers at RCA and Bell Laboratories achieved a conversion efficiency of 6 percent in 1954 by working on *p*-type and *n*-type semiconductors.

PV cells are found in small devices such as calculators and watches, medium-size systems such as water pumps, traffic signs, satellites, space vehicles, residential units, and large systems such as power stations for utility grids (Fig. 5-1). Some advantages of PV systems include high reliability with no moving parts and lightweight structure, low operating and maintenance costs, flexibility in sizing, and no water consumption. Some disadvantages are relatively high initial cost, intermittent nature of solar energy, additional costs for energy storage, and dust collection on panel surfaces reducing system performance.

(*a*)



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(b)

Figure 5-1 (*a*) A grid-connected PV system. (*b*) A cell phone charging station plus nighttime lighting powered by two 60-W solar panels.

An understanding of the operation of solar cells requires physics of atomic theory and semiconductor theory. We learned from physics that an atom consists of a nucleus containing protons and neutrons and equal number of electrons orbiting about the nucleus. For the silicon element, the atomic number is 14, which is equal to the number of photons or electrons. Protons are contained in the nucleus while electrons are in orbitals or *bands* with respect to the nucleus. Inner bands are filled while outer bands may be partially filled (Hodge, 2010).

The energy of an electron depends on the band that it occupies. The most outside band an electron can be found is called the *valence band*. The chemical characteristics of an element depend on the number of electrons in the valence band. For a chemically inert element, the valence band is filled. In silicon, the valence band can accommodate a maximum of eight electrons, but it has four electrons.

When the electron bond in the valence band is strong, the neighboring atoms share electrons so that valence bands are filled. This is called the *covalent bond*. The electrons in a valence band may attach themselves to a neighboring atom if their bond is not strong. As a result, the donor atom becomes a positively charged ion and the neighboring atom becomes a negatively charged ion. The two atoms form an *ionic bond*.

When the electrons in the valence band become too energetic, they jump into a band too far from the nucleus. This remote band is called the *conduction band*. The energy difference between an electron in the valence band and an electron in conduction band is called the *band gap energy*. A small amount of energy is sufficient to move electrons away from the atom when they are in the conduction band. This is the mechanism of heat and electrical conduction.

The common unit for band gap energy is electron-volt, eV. Note that $1 \text{ eV} = 1.602 \times 10^{-19}$ J. Insulators, conductors, and semiconductors are characterized by their band gap energies (Kreith and Kreider, 2011).

Conductors have very low band gap energies because their atoms have relatively empty valence bands with some electrons in the conduction band. Metals such as gold, copper, and iron are good conductors.

Insulators have high band gap energies because their atoms have full valence bands. Band gap energies for insulators are greater than 3 eV. Glass is an example of an insulator. Electrons in an insulator atom do not flow under the application of voltage or current.

Semiconductors have partially filled valence bands, and their band gap energies are less than 3 eV. Silicon is an example of semiconductor.

The band gap energy values for common semiconductor materials for PV cell applications are as follows (Hodge, 2010):

1.01 eV	copper indium diselenide
1.11 eV	silicon
1.27 eV	indium phosphide
1.40 eV	gallium arsenide

1.44 eV	cadmium telluride
2.24 eV	gallium phosphide
2.42 eV	cadmium sulfide

Silicon is a semiconductor material and commonly used in PV cells. There are four electrons in the valence band in silicon atoms. For PV cell applications, pure silicon, called an *intrinsic semiconductor*, is not used. Instead, silicon is doped with a small amount of another material (*dopant*) to yield an *extrinsic semiconductor*.

When the dopant has more electrons in the valence band compared to the number of electrons in silicon, the resulting material is an *n-type* (negative-type) *semiconductor*. Phosphorus has five valence electrons (one more than silicon atom), and it is used as a dopant to create a free electron, producing an *n*-type material. When the dopant has a smaller number of electrons in the valence band compared to pure silicon, the resulting material is a *p-type* (positive-type) *semiconductor*. A *p*-type semiconductor having fewer electrons in the valence band is also called having an excess of *holes*. Boron has three valence electrons (one less than silicon atom), and it is used as the dopant to create a shortage of electron (creating a hole), producing a *p*-type material. Despite having absence of electrons in the valence band, the semiconductor is electrically neutral. An *n*-type semiconductor is also electrically neutral despite having excess electrons in the valence band.

An *n*-type semiconductor acquires positive charge because it has tendency to lose electrons and gain holes. A *p*-type semiconductor acquires negative charge because it has tendency to lose holes and gain electrons. As a result of doping silicon with two different dopants, *n*-type and *p*-type semiconductors are obtained. Combining *n*-type and *p*-type semiconductors result in a *p-n* junction. Forming of the junction enhances the flow of electrons and holes. The negative charge on *p*-type semiconductor and positive charge on *n*-type semiconductor are responsible for preventing electrons and holes from crossing the junction.

The operation of a PV cell designated by a *p-n* junction is shown in Fig. 5-2. Photons from solar radiation penetrate the *p-n* junction and strike silicon atoms. If the energy level of the photon is sufficiently high, the electron in the valence band acquires more energy than the band gap energy, and the electron will jump to the conduction band. This initiates an electron flow and an electric current flow. As a result, energy in photons of solar light is converted to electrical energy.

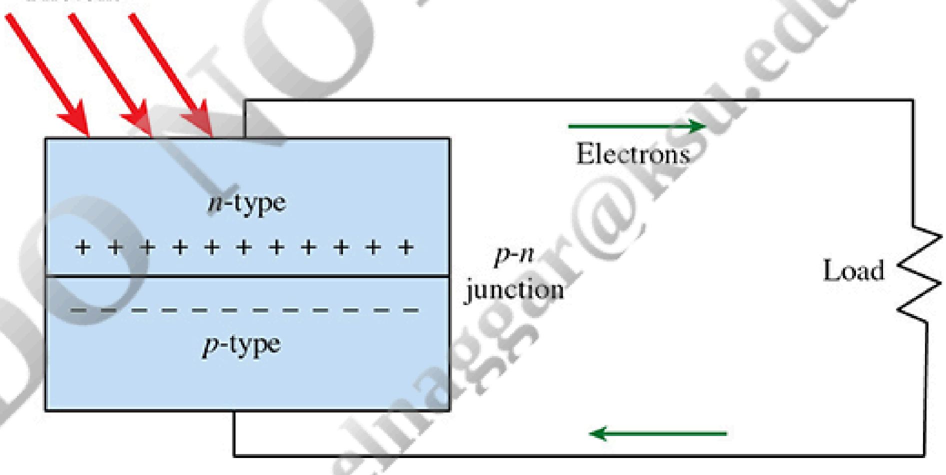


Figure 5-2 Photovoltaic cell operation. Electrons flow from the *n*-type semiconductor to the *p*-type semiconductor through the load.

If the energy of photon is less than the band gap energy, the electron has insufficient energy to jump into the conduction band. This excess energy in the electron is converted to excess kinetic energy, which is converted to heat, manifesting itself as a rise in temperature of the PV system. This shows that only the photons of solar radiation having a minimum band gap energy contribute to the electricity production. The energy of a photon depends on the wavelength of solar light. The higher the wavelength, the lower the energy level of the photon. Therefore, in PV cells, only low-wavelength spectrum of solar radiation contributes to the PV energy conversion.

A single photon can only move a single valence electron to the conduction band. When the photon possesses more energy than the band gap energy, the part of energy that is equal to the gap energy is used to move the electron while the excess energy is converted to heat. Therefore, the excess energy of the photon does not contribute to the electricity production.

As discussed in Chap. 3, electromagnetic waves transport energy just like other waves, and all electromagnetic waves travel at the *speed of light* in a vacuum, which is $c_0 = 2.9979 \times 10^8$ m/s. Electromagnetic waves are characterized by their *frequency* v or *wavelength* λ. These two properties in a medium are related by

$$\lambda = \frac{c}{\nu} \tag{5-1}$$

where c is the speed of propagation of a wave in that medium. The speed of propagation in a medium is related to the speed of light in a vacuum by $c = c_0/n$, where n is the *index of refraction* of that medium. The refractive index is essentially unity for air and most gases, about 1.5 for glass, and 1.33 for water. The commonly used unit of wavelength is the *micrometer* (μm) or micron, where 1 μm = 10^{-6} m. It has proven useful to view electromagnetic radiation as the propagation of a collection of discrete packets of energy called photons or quanta, as proposed by Max Planck in 1900 in conjunction with his *quantum theory*. In this view, each photon of frequency ν is considered to have an energy of

$$e = h\nu = \frac{hc}{\lambda} \tag{5-2}$$

where $h = 6.626069 \times 10^{-34}$ J·s is *Planck's constant*. Note from the second part of Eq. (5-2) that the energy of a photon is inversely proportional to its wavelength. Therefore, shorter-wavelength radiation possesses larger photon energies (Çengel and Ghajar, 2020).

EXAMPLE 5-1 Maximum Wavelength of Solar Radiation for PV Cells

The band gap energy values are 1.11 eV for silicon and 1.40 eV for gallium arsenide. What are the maximum wavelengths of solar radiation for which solar radiation can be converted to electrical energy for silicon and gallium arsenide?

SOLUTION The energy of each photon is $e = \frac{hc}{\lambda}$ where $h = 6.626069 \times 10^{-34}$ J·s and $c = 2.9979 \times 10^8$ m/s. For silicon, the band gap energy is 1.11 eV. Solving for the wavelength, we obtain

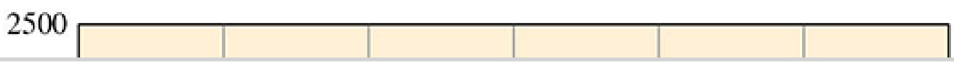
$$\lambda = \frac{hc}{e} = \frac{(6.626069 \times 10^{-34}\ \text{J·s})(2.9979 \times 10^8\ \text{m/s})}{1.11\ \text{eV}}\left(\frac{1\ \text{eV}}{1.602 \times 10^{-19}\ \text{J}}\right)$$
$$= 1.12 \times 10^{-6}\ \text{m}$$
$$= \mathbf{1.12\ \mu m}$$

Repeating the calculation for gallium arsenide, we find

$$\lambda = \frac{hc}{e} = \frac{(6.626069 \times 10^{-34}\ \text{J·s})(2.9979 \times 10^8\ \text{m/s})}{1.40\ \text{eV}}\left(\frac{1\ \text{eV}}{1.602 \times 10^{-19}\ \text{J}}\right)$$
$$= 0.885 \times 10^{-6}\ \text{m}$$
$$= \mathbf{0.885\ \mu m}$$

Therefore, the maximum wavelength of solar radiation for PV energy conversion is 1.12 μm for silicon and 0.885 μm for gallium arsenide. ▲

This example shows that photons of solar radiation should have a maximum wavelength of 1.12 μm to convert solar light to electricity when silicon is used as the semiconductor material (Fig. 5-3). Remember that the energy of a photon is inversely proportional to its wavelength. Solar radiation wavelengths greater than 1.12 μm do not have sufficient energy in photons to move a valence electron and initiate the current flow. When the wavelength is less than 1.12 μm, the difference between the photon energy from the solar light and the band gap energy of the silicon is the excess energy, which is also wasted. These characteristics explains why the conversion efficiency of solar radiation to electricity by PV effect is relatively low.



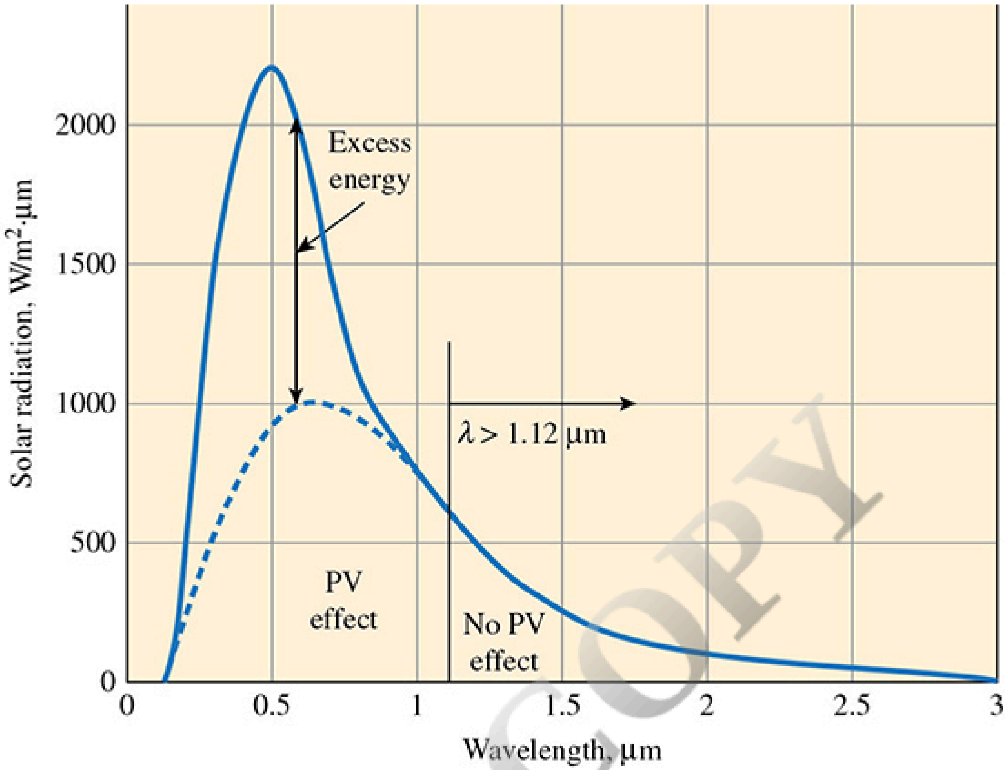


Figure 5-3 There is no electricity generation when the wavelength of solar radiation is greater than 1.12 µm when silicon is used as the semiconductor material. When the wavelength is less than 1.12 µm, the difference between the photon energy from the solar light and the band gap energy of the silicon is the excess energy. (*Adapted from Hodge, 2010.*)

As discussed in Chap. 3, the electromagnetic spectrum of solar radiation falls between the wavelengths of 0.3 and 3.5 µm. About 40 percent of solar radiation is in visible range (between 0.4 and 0.7 µm) with peak radiation at a wavelength of 0.48 µm, which corresponds to the green portion of the visible spectrum. The visible spectrum of solar radiation contributes the most to the PV energy conversion. About 52 percent of solar radiation falls into near-infrared region with a wavelength range of 0.7 to 3.5 µm. The contribution of this infrared region to electricity generation by PV effect is very low. Ultraviolet region of solar radiation falls in wavelengths between 0.3 and 0.4 µm, and its contribution to PV energy conversion is small.

The conversion efficiency of a solar cell may be defined as the electrical power output (in W) divided by the incident solar radiation:

$$\eta_{\text{cell}} = \frac{\dot{W}_{\text{out}}}{AG_{\text{solar}}} \qquad (5\text{-}3)$$

where A is the area of the solar cell in m^2 and G_{solar} is the solar irradiation in W/m^2.

EXAMPLE 5-2 Maximum Efficiency of a Silicon Solar Cell

Solar radiation is incident on a 1-m^2 silicon solar cell at a rate of 1000 W/m^2·µm at a wavelength of 0.48 µm. Determine the maximum efficiency of this solar cell at this wavelength.

SOLUTION The rate of solar radiation incident is

$$G = AG_{\text{solar}} = (1000\ \text{W/m}^2)(1.0\ \text{m}^2) = 1000\ \text{W}$$

Each photon with a wavelength λ has an energy of

$$e = \frac{hc}{\lambda} = \frac{(6.626069\times10^{-34}\ \text{J}\cdot\text{s})(2.9979\times10^{8}\ \text{m/s})}{0.48\ \mu\text{m}}\left(\frac{1\ \mu\text{m}}{1\times10^{-6}\ \text{m}}\right) = 4.138\times10^{-19}\ \text{J}$$

The rate of photons incident on the PV cell is

$$n_{\text{photon}} = \frac{G}{e} = \frac{1000 \text{ J/s}}{4.138 \times 10^{-19} \text{ J}} = 2.417 \times 10^{21} \text{ photons/s}$$

Each photon will move one electron and, therefore, the number of electrons are equal to the number of photons. The band gap energy of silicon is 1.11 eV. Then the maximum electrical power output is

$$\dot{W}_{\text{out,max}} = n_{\text{photon}} e = (2.417 \times 10^{21} \text{ photons/s})(1.11 \text{ eV})\left(\frac{1.602 \times 10^{-19} \text{ J}}{1 \text{ eV}}\right) = 430 \text{ W}$$

The maximum efficiency at this wavelength is the maximum electrical power output divided by the incident solar radiation:

$$\eta_{\lambda,\text{cell,max}} = \frac{\dot{W}_{\text{out,max}}}{AG_{\text{solar}}} = \frac{430 \text{ W}}{(1 \text{ m}^2)(1000 \text{ W/m}^2)} = 0.430 = \mathbf{43.0\%}$$

This is the maximum conversion efficiency of a silicon solar cell when solar radiation is incident at a wavelength of 0.48 μm. The maximum efficiency will be different at different wavelengths because photon energy depends on the wavelength. The value of maximum efficiency is 100 percent when the wavelength is 1.12 μm. The maximum efficiency is zero when the wavelength is greater than 1.12 μm. ▲

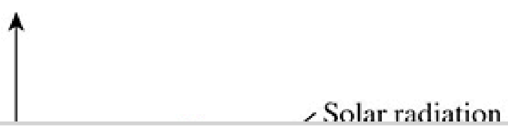
The overall maximum efficiency of a solar cell can be determined by integrating the cell efficiency at each wavelength over the entire solar irradiation spectrum:

$$\eta_{\text{cell,max}} = \frac{\int \eta_{\lambda,\text{cell,max}} G_\lambda \, d\lambda}{\int G_\lambda \, d\lambda} \tag{5-4}$$

where $\eta_{\lambda,\text{cell}}$ is the maximum cell efficiency at a given wavelength and G_λ is the solar irradiation at the given wavelength.

Actual efficiencies of solar cells are less than the maximum efficiencies based on Eq. (5-4). Some of the reasons are reflection of solar radiation from the cell surface, shading of the cell due to electrical contacts, internal electric resistance of the cell, and recombination of electrons and holes not contributing to electric flow. Using antireflective (AR) coatings on PV panels are now a standard practice to minimize reflection of solar light. This can reduce the reflection from 30 percent to 3 percent for a silicon cell. Undesired recombination of electrons and holes can be reduced by using hydrogen alloys in polycrystalline and amorphous cells (Kreith and Kreider, 2011).

Mismatch of the photon energy of the solar radiation and the band gap energy of the cell material results in relatively low maximum efficiencies for the solar cell. An effective solution to this issue is using multijunction solar cells for which two or more thin layers of solar cells are stacked on top of each other. This is shown in Fig. (5-4). Material *a* is used as the top layer, and the material *b* as the bottom layer. Material *a* will not produce PV effect when the wavelength is greater than λ_a. That is, only the area A1+A2 contributes to the solar radiation conversion to electricity. Material *b* has different characteristics such that its maximum wavelength for the PV effect is λ_b. By adding a second cell layer, a wider range of wavelength for solar radiation becomes available for energy conversion. The solar radiation with wavelength greater than λ_a will pass through layer *a* but absorbed by layer *b* for wavelengths up to λ_b. As a result, a greater area in the spectrum (A1+A2+A3) contributes to the solar radiation conversion to electricity. Multijunction solar cells allow higher cell efficiencies in comparison to the cell efficiencies using a single layer of material *a* or a single layer of material *b* by utilizing a wider spectrum of solar radiation in PV energy conversion. Using more layers would result in higher cell efficiencies. However, using very thin layers of crystalline and polycrystalline cells on top of each other has some serious challenges. This concept is mainly used for thin-film amorphous solar cells (Goswami et al., 2000). Different types of solar cells are described later in the chapter.



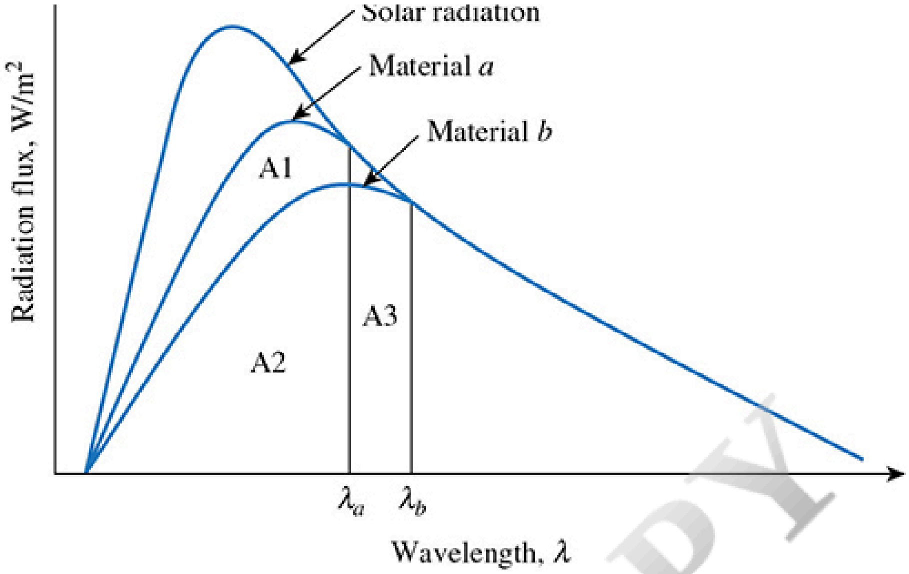


Figure 5-4 Photovoltaic energy conversion in multijunction solar cells. (*Adapted from Goswami et al., 2000.*)

5-2 ANALYSIS OF SOLAR CELLS

Electrical analysis of PV cells is presented by following the simple model described in Hodge (2010) and Culp (1991). The cell involves a *p*-type semiconductor and an *n*-type semiconductor. Silicon is commonly used as a semiconductor material in solar cells. The silicon is doped with phosphorus to produce the *n*-type semiconductor, while it is doped with boron to produce the *p*-type semiconductor. There is a current density flow at the *p*-*n* junction of a solar cell (Fig. 5-5).

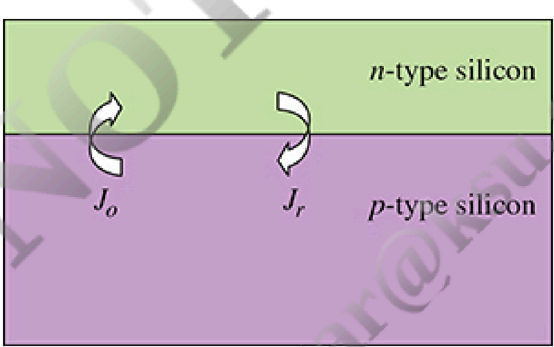


Figure 5-5 A simplified model for current density at *p*-*n* junction. (*Adapted from Hodge, 2010.*)

The *current density* J is defined as the current I over the cell surface area A. The current density flow from *n*-type semiconductor to *p*-type semiconductor is denoted by J_r and is called the *light-induced recombination current*, and that from *p*-type to *n*-type is denoted by J_o and is called the *dark current* or *reverse saturation current*. In an illuminated solar cell, J_r is proportional to J_o according to the relation

$$J_r = J_o \exp\left(\frac{e_o V}{kT}\right) \tag{5-5}$$

where $e_o = 1.6 \times 10^{-19}$ J/V is equal to the charge of one electron, $k = 1.381 \times 10^{-23}$ J/K is Boltzmann's constant, V is voltage, and T is the cell temperature. The junction current density J_j is equal to the algebraic sum of J_r and J_o:

$$J_j = J_r - J_o = J_o\left[\exp\left(\frac{e_o V}{kT}\right) - 1\right] \tag{5-6}$$

The equivalent circuit for a solar cell is given in Fig. 5-6. The current output density J_s flows through the junction or load.

The load current density J_L is given by

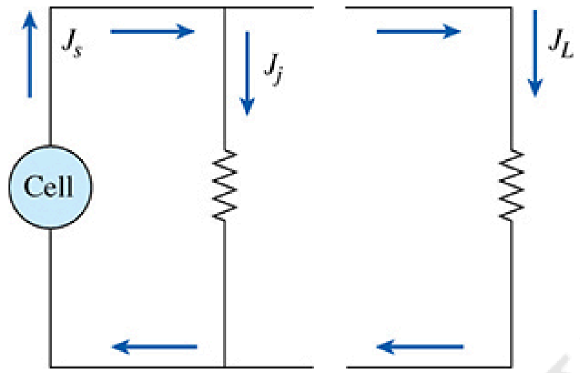


Figure 5-6 Equivalent circuit for solar cell. (*Adapted from Hodge, 2010.*)

$$J_L = J_s - J_j = J_s - J_o\left[\exp\left(\frac{e_o V}{kT}\right) - 1\right] \tag{5-7}$$

The voltage is zero, $V = 0$, when the cell is short-circuited, and thus $J_s = J_L$. The cell output is through the junction when the circuit is open and $J_L = 0$. The voltage in this case is called the open circuit voltage, V_{oc}. Equation (5-7) can be solved for V_{oc} to yield

$$V_{oc} = \frac{kT}{e_o}\ln\left(\frac{J_s}{J_o} + 1\right) \tag{5-8}$$

An expression for the ratio of the load current density J_L to short circuit current density J_s may be obtained by dividing Eq. (5-7) by J_s:

$$\frac{J_L}{J_s} = 1 - \frac{J_o}{J_s}\left[\exp\left(\frac{e_o V}{kT}\right) - 1\right] \tag{5-9}$$

The power output delivered to the load is

$$\dot{W} = J_L V A \tag{5-10}$$

where A is the cell area. Substituting J_L from Eq. (5-9) into Eq. (5-10) gives

$$\dot{W} = VAJ_s - VAJ_o\left[\exp\left(\frac{e_o V}{kT}\right) - 1\right] \tag{5-11}$$

Differentiating Eq. (5-11) with respect to voltage V and setting the derivative equal to zero gives the maximum load voltage for the maximum power output:

$$\exp\left(\frac{e_o V_{max}}{kT}\right) = \frac{1 + J_s/J_o}{1 + \frac{e_o V_{max}}{kT}} \tag{5-12}$$

Note that the maximum voltage V_{max} is implicit in this equation. A trial-and-error approach or an equation solver is needed to solve for V_{max}. The maximum power output of the cell is

$$\dot{W}_{max} = \frac{AV_{max}(J_s + J_o)}{1 + \frac{kT}{e_o V_{max}}} \quad (5\text{-}13)$$

The conversion efficiency of a solar cell can be expressed as the power output divided by the incident solar radiation:

$$\eta_{cell} = \frac{\dot{W}}{AG} \quad (5\text{-}14)$$

where G is the solar irradiation. Using the maximum power output expression in Eq. (5-13), the maximum conversion efficiency of a solar cell can be written as

$$\eta_{cell,max} = \frac{\dot{W}_{max}}{AG} = \frac{AV_{max}(J_s + J_o)}{AG\left(1 + \frac{kT}{e_o V_{max}}\right)} = \frac{V_{max}(J_s + J_o)}{G\left(1 + \frac{kT}{e_o V_{max}}\right)} \quad (5\text{-}15)$$

Equation (5-9) along with Eq. (5-8) can be used to plot the current density ratio J_L/J_s as a function of load voltage for a specified value of open circuit voltage V_{oc}. Also, Eqs. (5-12) and (5-13) can be used to plot power output normalized with respect to maximum power against load voltage. The plots in Fig. 5-6 are obtained with V_{oc} = 0.55 V and T = 300 K. Note that a high-quality silicon solar cell can produce an open circuit voltage of about 0.6 V. For the short circuit case ($J_L = J_s$ or $J_L/J_s = 1$), the voltage is zero, and the power output is zero. For the open circuit voltage case ($J_L = 0$), the voltage is 0.55 V, and the power output is also zero. The maximum power occurs at a voltage close to open circuit voltage, which is 0.47 V in this case. The current density ratio remains close to one until the open circuit voltage is approached. Then it decreases rapidly before it becomes zero at the open circuit case. The trends and characteristics shown in Fig. 5-7 are typical of most solar cells.

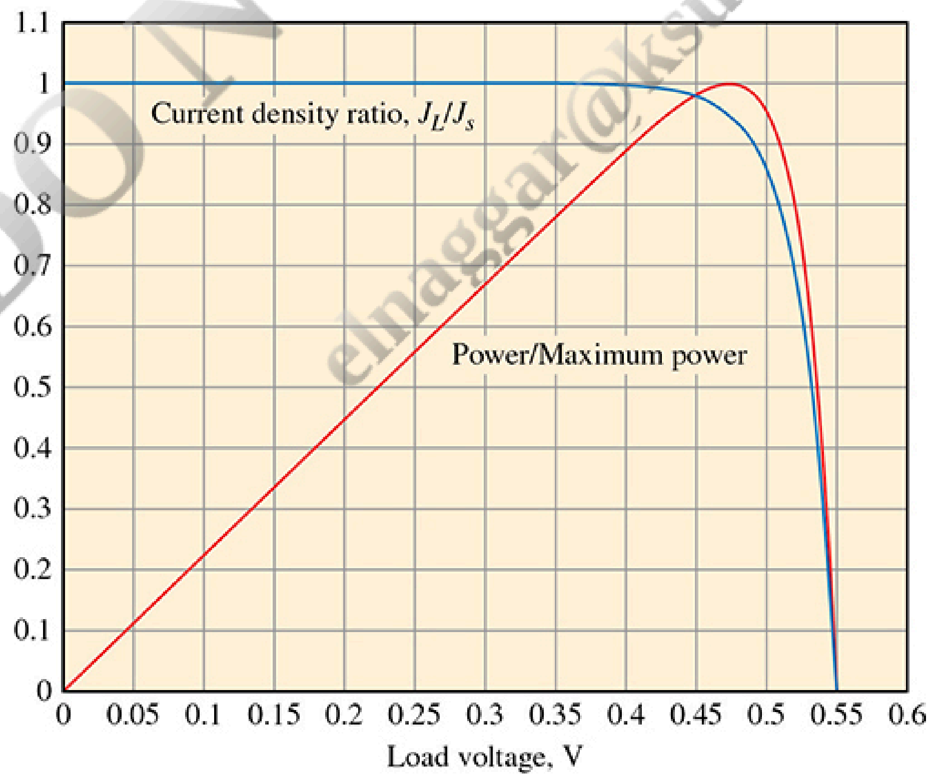


Figure 5-7 Current density ratio J_L/J_s and power output ratio $\dot{W}/\dot{W}_{max}$ in a solar cell as a function of load voltage.

The power output from a photovoltaic cell is proportional to solar radiation absorbed by the cell. It turns out that as the

EXAMPLE 5-3 Analysis of a Solar Cell

A solar cell has an open circuit voltage value of 0.62 V with a reverse saturation current density of 2.253×10^{-9} A/m^2.

(*a*) For a temperature of 20°C, determine the load voltage at which the power output is maximum.

(*b*) If the solar irradiation is 770 W/m^2, determine the efficiency of the solar cell at a load voltage of 0.5 V.

(*c*) Determine the cell area for a power output of 500 W at a load voltage of 0.5 V.

SOLUTION (*a*) The current output density is determined from Eq. (5-8) to be

$$V_{oc} = \frac{kT}{e_o}\ln\left(\frac{J_s}{J_o}+1\right)$$

$$0.62\text{ V} = \frac{(1.381\times10^{-23}\text{ J/K})(293\text{ K})}{1.6\times10^{-19}\text{ J/V}}\ln\left(\frac{J_s}{2.253\times10^{-9}\text{ A/m}^2}+1\right)$$

$$J_s = 100\text{ A/m}^2$$

The load voltage at which the power output is maximum is determined from Eq. (5-12) to be

$$\exp\left(\frac{e_o V_{max}}{kT}\right) = \frac{1+J_s/J_o}{1+\dfrac{e_o V_{max}}{kT}}$$

$$\exp\left(\frac{(1.6\times10^{-19}\text{ J/V})V_{max}}{(1.381\times10^{-23}\text{ J/K})(293\text{ K})}\right) = \frac{1+(100\text{ A/m}^2/2.253\times10^{-9}\text{ A/m}^2)}{1+\dfrac{(1.6\times10^{-19}\text{ J/V})V_{max}}{(1.381\times10^{-23}\text{ J/K})(293\text{ K})}}$$

$$V_{max} = \mathbf{0.5414\text{ V}}$$

(*b*) The load current density is determined from Eq. (5-9):

$$\frac{J_L}{J_s} = 1-\frac{J_o}{J_s}\left[\exp\left(\frac{e_o V}{kT}\right)-1\right]$$

$$\frac{J_L}{100\text{ A/m}^2} = 1-\frac{2.253\times10^{-9}\text{ A/m}^2}{100\text{ A/m}^2}\left[\exp\left(\frac{(1.6\times10^{-19}\text{ J/V})(0.5\text{ V})}{(1.381\times10^{-23}\text{ J/K})(293\text{ K})}\right)-1\right]$$

$$J_L = 99.12\text{ A/m}^2$$

The power output per unit area of the cell is

$$\dot{W}/A = J_L V = (99.12\text{ A/m}^2)(0.5\text{ V})\left(\frac{1\text{ W}}{1\text{ AV}}\right) = 49.56\text{ W/m}^2$$

Then, the cell efficiency becomes

$$\eta_{cell} = \frac{\dot{W}/A}{G} = \frac{49.56\text{ W/m}^2}{770\text{ W/m}^2} = 0.0644\text{ or }\mathbf{6.44\%}$$

(*c*) Finally, the cell area for a power output of 500 W is

$$A = \frac{\dot{W}}{\dot{W}/A} = \frac{500\ \text{W}}{49.56\ \text{W/m}^2} = \mathbf{10.1\ m^2} \quad \blacktriangle$$

5-3 PHOTOVOLTAIC TECHNOLOGIES AND SYSTEMS

Some well-known solar cell types and technologies include monocrystalline, polycrystalline, amorphous, thin-film, gallium arsenide, and multijunction (Gevorkian, 2007). The first three technologies involve silicon as the semiconductor materials.

Monocrystalline solar cell: The cells are produced from pure silicon by a process called the floating zone technique. Monocrystalline silicone grows on a seed out of a silicone melt. The resulting silicone rods are sliced into thin wafer disks (between 0.2 and 0.4 mm thickness). The wafers are further processed by grinding, polishing, cleaning, doping with impurities, and antireflective coating. Manufacturing of monocrystalline silicon cells is expensive, but they have the highest efficiency with respect to other cell technologies.

Polycrystalline solar cell: This is also called a multicrystalline solar cell. The silicon is produced in the form of an ingot as the silicon melt is cooled slowly. Grain boundaries are formed that separate the crystalline regions of the silicon ingot. The polycrystalline solar cell manufactured by this method has a lower efficiency than the monocrystalline solar cell due to the gaps in the grain boundaries. Polycrystalline solar cell is preferred by most cell manufacturers due to its lower manufacturing cost.

Amorphous solar cell: An amorphous silicon film is manufactured by depositing a thin layer of silicon on a carrier material and doping with suitable materials. The glass plates house the silicon film. The main advantage of the amorphous solar cell is that it is relatively simple and inexpensive to manufacture. The disadvantages with respect to other technologies include lower efficiency, larger installation surface, and continuous degradation over its lifetime.

Thin-film solar cell: This solar cell technology uses thin crystalline layers of cadmium telluride or copper indium diselenide deposited on the surface of a carrier base. The process is simple and inexpensive and has high cell efficiencies. However, these solar cells use a lot of space, which makes it unsuitable for a variety of applications. Their lifespan is short, and there are additional expenses due to cables and support structures.

Gallium arsenide solar cell: Multiple research institutions have active research programs in developing gallium arsenide solar cell technology. The interest is due to its high efficiency compared to other solar cell technologies. The process is very expensive, however, because gallium deposits are hard to find. They have some special uses such as space applications.

Multijunction cell: This technology involves the use of two cells, one on top of another. Silicon cell and gallium arsenide cell may be used. The result is higher efficiency compared to single cell systems.

Solar radiation incident on a solar energy conversion system originates from the sun. The upper limit for the efficiency of a solar thermal system for power generation may be determined from the Carnot efficiency by using the effective surface temperature of the sun (5780 K) and an ambient temperature of 298 K:

$$\eta_{\text{cell,max}} = 1 - \frac{T_L}{T_H} = 1 - \frac{298\ \text{K}}{5780\ \text{K}} = 0.948 = 94.8\%$$

The Carnot limit does not apply to solar cells because they are not heat engines. However, for the reasons explained in the previous section, the theoretical efficiency limit is about 34 percent for a single-junction solar cell. This limit can be exceeded by multijunction solar cells. If an infinite number of junctions is used with a high concentration of solar radiation, the limit becomes 86 percent (De Vos, 1980).

Silicon has been commonly used in solar cells, but commercial silicon solar cells have relatively low efficiencies (between 15 and 25 percent). Other materials have been tested extensively to increase solar cell efficiencies. They include cadmium telluride, cadmium sulfide, copper indium diselenide, gallium arsenide, gallium phosphide, and indium phosphide. Copper indium diselenide and gallium arsenide are among the most promising materials. An efficiency of 40 percent has been approached for gallium arsenide solar cells in a laboratory environment. Using the multijunction design with high solar irradiation has resulted in a research efficiency of 43 percent. However, the high cost of high-efficiency solar cells remains a concern.

Halide perovskites are a family of materials with the potential of high efficiency and low manufacturing costs in solar cells. Extensive research work underway in improving efficiencies of perovskite solar cells. Efficiencies as high as 25.5 percent were reported by combining a two-dimensional perovskite layer with a three-dimensional perovskite layer. The main concern for perovskite solar cells is their limited stability and corresponding short lifetime (NREL, 2022).

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A single solar cell produces a small amount of voltage and current. Solar cells can be connected in series and parallel arrangement to increase voltage and current. When identical cells are connected in series, the current remains the same, but the voltages are added, just like DC circuits in series. For parallel arrangement of identical cells, the voltage remains the same while the currents are added (Fig. 5-8). Therefore, the series arrangement should be used to increase the voltage and the parallel arrangement should be used to increase the current. When two dissimilar cells are connected in series, the voltages are added ($V = V_1 + V_2$) while the current for the cell network is between the two current values ($I_1 < I < I_2$), but closer to I_1. When two dissimilar cells are connected in parallel, the currents are added ($I = I_1 + I_2$) while the voltage takes a value between the two voltage values ($V_1 < V < V_2$), but closer to V_1.

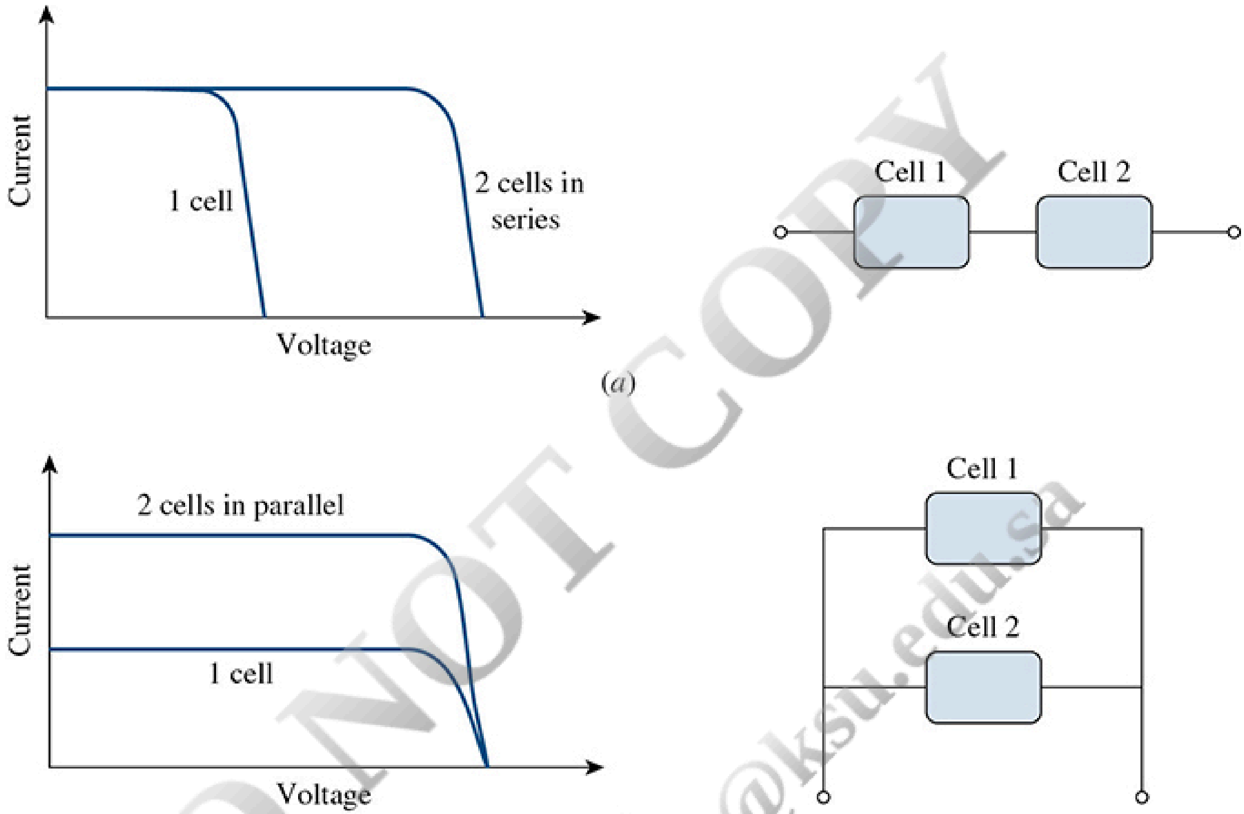
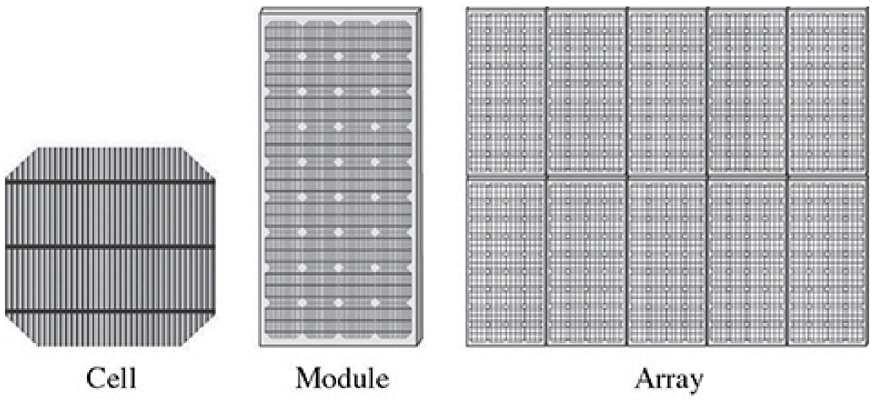
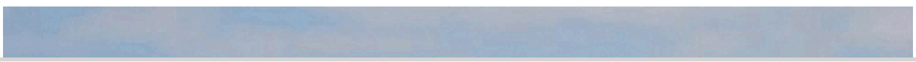


Figure 5-8 Series and parallel arrangements of identical solar cells. (*a*) Voltage is added in series arrangement. (*b*) Current is added in parallel arrangement.

A single solar cell produces only 1 to 3 W of power. Multiple cells should be connected to form modules, and modules should be connected into arrays so that reasonable amounts of power can be generated (Fig. 5-9). This way, both small and large PV systems can be installed, depending on the demand (Fig. 5-10).

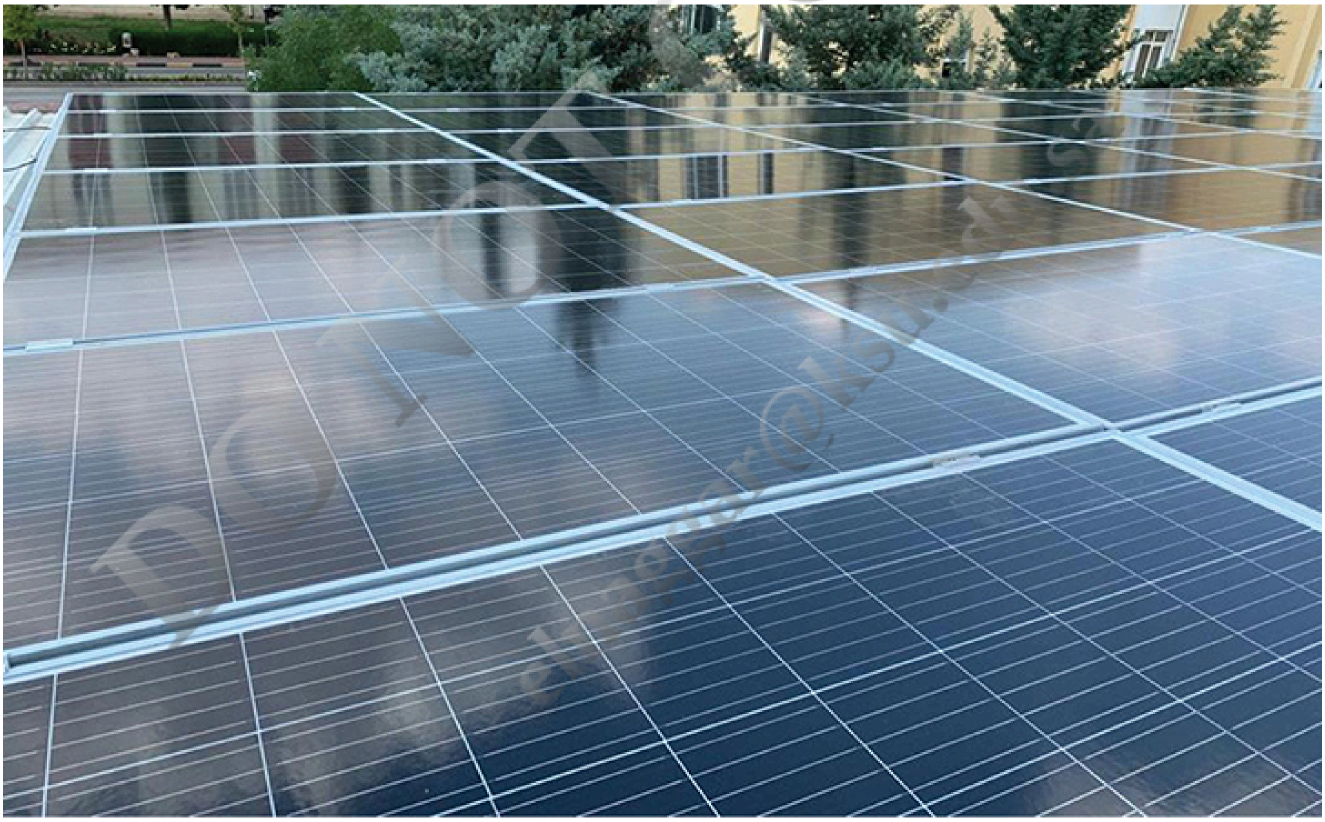


(*a*)



(*b*)

Figure 5-9 (*a*) A photovoltaic system typically consists of arrays, which are obtained by connecting modules, and modules consist of individual cells. (*DOE/EERE.*) (*b*) Solar arrays. (*Fotosearch/Photo Library RF.*)



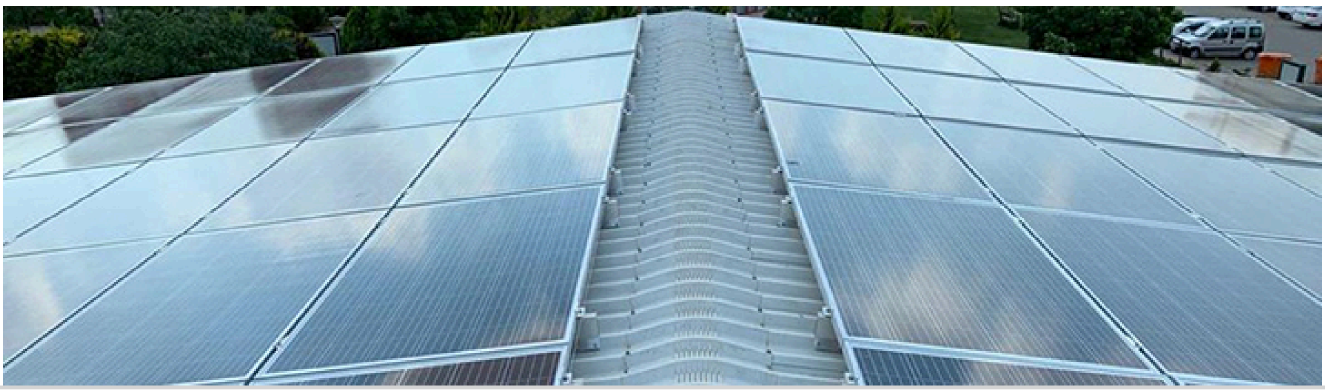


Figure 5-10 Solar array examples. (*Photos by Adem Atmaca*.)

EXAMPLE 5-4 Arrangement of Solar Cells

Consider a commercial solar cell with the following specifications:

Open circuit voltage = 0.60 V

Open circuit current = 5.1 A

Maximum power = 2.2 W

Voltage at maximum power = 0.48 V

Current at maximum power = 4.6 A

Efficiency = 18 percent

A module of these solar cells is to be constructed to provide a voltage output of 12 V and a power output of 275 W.

(*a*) How many cells should be used to satisfy the power output?
(*b*) How many cells should be arranged in series to satisfy the voltage output?
(*c*) How many rows of the cells in series should be used?
(*d*) If the testing of this solar cell is made for a solar radiation value of 800 W/m^2, what is the required area of this module?

SOLUTION (*a*) The total number of cells to provide a power output of 275 W is

$$n_{\text{cell, total}} = \frac{\dot{W}_{\text{total}}}{\dot{W}_{\text{one cell}}} = \frac{275\ \text{W}}{2.2\ \text{W}} = \mathbf{125\ cells}$$

(*b*) In series arrangement, the voltages are added. Then the number of cells in series should be

$$n_{\text{cell, series}} = \frac{V_{\text{total}}}{V_{\text{one cell}}} = \frac{12\ \text{V}}{0.48\ \text{V}} = \mathbf{25\ cells}$$

(*c*) Each line has 25 cells while the total number of cells is 125. Then, the number of the rows will be

$$n_{\text{row}} = \frac{n_{\text{cell, total}}}{n_{\text{cell, series}}} = \frac{125\ \text{cells}}{25\ \text{cells}} = \mathbf{5\ rows}$$

(*d*) The efficiency of this solar cell is specified to be 18 percent. Using the definition of the cell efficiency, we find the area of the module as

$$\eta_{\text{cell}} = \frac{\dot{W}_{\text{out}}}{AG_{\text{solar}}} \rightarrow 0.18 = \frac{275\ \text{W}}{A(800\ \text{W/m}^2)} \rightarrow A = \mathbf{1.91\ m^2} \quad \blacktriangle$$

Characteristics of commercial PV modules are shown in Fig. 5-11, taken from the brochures of Akademi Energy (http://enerji.gantep.edu.tr). They are useful for technical specifications and practical information on PV systems. The PV (http://enerji.gantep.edu.tr). They are useful for technical specifications and practical information on PV systems. The PV module consists of 60 cells with 10 rows, each row with 6 cells in series.

Mechanical Characteristics	
Solar Cell	Mono/Poly
No. of Cells	60 (6 × 10)
Dimensions	1658 × 996 × 35 mm
Weight	19.5 kgs
Front	Glass 3.2 mm tempered glass
Frame	Anodized aluminium alloy
Junction Box	IP 68 rated (3 by pass diodes)
Output Cables	4.0 mm^2, symmetrical length (–) 900 mm and (+) 900 mm
Connectors	MC4 compatible
Mechanical load test	5400 Pa

MONO	GAP-310M		GAP-315M		GAP-320M		GAP-325M		GAP-330M	
	STC	NOCT	STC	NOCT	STC	NOCT	STC	NOCT	STC	NOCT
Maximum Power (Pmax)	310W	229W	315W	233W	320W	237W	325W	241W	330W	245W
Open Circuit Voltage (Voc)	39.80V	37.28V	40.12V	37.72V	40.43V	38.15V	40.74V	38.59V	41.05V	39.01V
Short Circuit Current (Isc)	10.05A	7.94A	10.12A	7.98A	10.19A	8.02A	10.26A	8.06A	10.33A	8.10A
Voltage at Maximum Power (Vmpp)	32.56V	30.57V	32.85V	30.94V	33.13V	31.31V	33.40V	31.67V	33.67V	32.03V
Current at Maximum Power (Impp)	9.52A	7.49A	9.59A	7.53A	9.66A	7.57A	9.73A	7.61A	9.80A	7.65A
Module Efficiency (%)	18.77%		19.08%		19.38%		19.68%		19.98%	

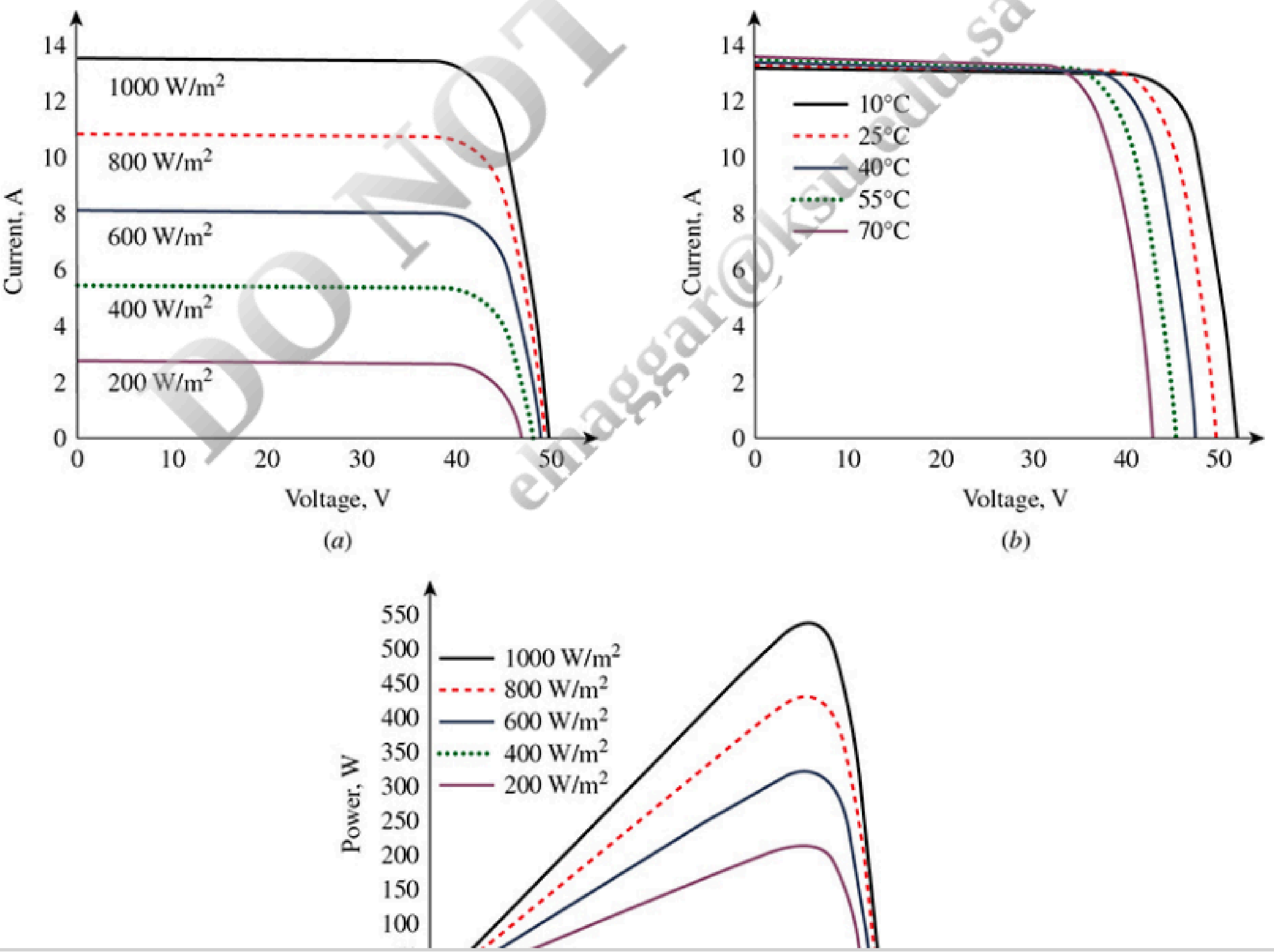
POLY	GAP-275P		GAP-280P		GAP-285P		GAP-290P		GAP-295P	
	STC	NOCT	STC	NOCT	STC	NOCT	STC	NOCT	STC	NOCT
Maximum Power (Pmax)	275W	204W	280W	208W	285W	212W	290W	216W	295W	220W
Open Circuit Voltage (Voc)	38.27V	36.03V	38.57V	36.32V	38.84V	36.59V	39.14V	36.86V	39.41V	37.13V
Short Circuit Current (Isc)	9.37A	7.41A	9.45A	7.49A	9.54A	7.57A	9.62A	7.65A	9.71A	7.73A
Voltage at Maximum Power (Vmpp)	30.88V	29.39V	31.15V	29.63V	31.39V	29.86V	31.66V	30.08V	31.90V	30.30V
Current at Maximum Power (Impp)	8.91A	6.94A	8.99A	7.02A	9.08A	7.10A	9.16A	7.18A	9.25A	7.26A

Module Efficiency (%)	16.65%	16.96%	17.26%	17.56%	17.86%

Figure 5-11 Mechanical and technical characteristics of commercial PV modules. (*Courtesy of Akademi Energy, http://enerji.gantep.edu.tr*.)

There are three tables in Fig. 5-11. The first table gives mechanical characteristics of the solar module. The other two tables specify technical characteristics of monocrystalline and polycrystalline cells. The standard test conditions (STC) are based on a solar irradiance of 1000 W/m^2, a spectrum of AM 1.5, and a cell temperature of 25°C. Spectrum AM 1.5 refers to two standard terrestrial solar irradiance spectra. The nominal operating cell temperature (NOCT) conditions are as follows: solar irradiance = 800 W/m^2, ambient temperature = 20°C, wind speed = 1 m/s. The maximum power, voltage and current at maximum power, open circuit voltage, open circuit current, and the module efficiency are specified. As the power output increases, the voltage and current values increase, as expected, since power is equal to the product of voltage and current. The efficiency also increases at higher power outputs. The maximum power at NOCT conditions is lower than the that at STC because the power is based on an irradiance value of 1000 W/m^2 at STC while it is based on a value of 800 W/m^2 at NOCT.

The performance of a commercial PV module at various voltage values is given in Figs. 5-12*a–c*. Fig. 5-12*a* gives the effect of solar irradiance, and Fig. 5-12*b* gives the effect of cell temperature on the cell performance. The cell performance is given by the current-voltage curve. Fig. 5-12*c* is on the effect of solar irradiance on the power output. The higher the solar irradiance, the higher the power output. As the solar irradiance increases, the current and the power output increase as the open circuit voltage increases slightly. The performance of the solar module decreases at higher cell temperatures resulting in lower values of open circuit voltage and maximum power output. It is desirable to match the load to the best operating point in the current-voltage curve, which is the point for maximum power. The maximum power occurs at the knee of the current-voltage curve.



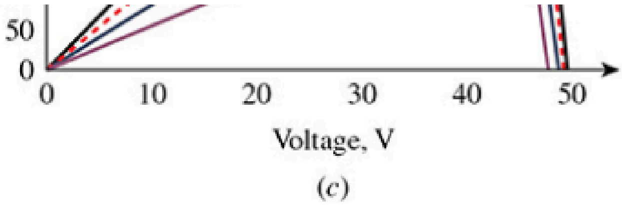


Figure 5-12 Effects of solar irradiance and temperature on the cell performance and power-voltage curve at different solar irradiance values for a commercial PV module (*Akademi Energy*, *http://enerji.gantep.edu.tr*.).

5-4 ENERGY PRODUCTION FROM PHOTOVOLTAIC SYSTEMS

The energy production from a PV system can be estimated using different methods, some detailed and more accurate, and some simple and less accurate. Free and commercial software with built-in solar data for various locations on the earth are also available. The characteristics of a PV system and solar radiation data in the location of interest affect such an estimate. A simplified approach for the estimation of energy production for an average day in a specified location is based on the following formula:

$$\text{Energy production} = n_{\text{days}}\eta_{\text{system}}\eta_{\text{cell}}AG_{\text{solar}} \tag{5-16}$$

Here, n_{days} is the number of days, η_{cell} is the solar cell efficiency, A is area of the solar array, and G_{solar} is the solar irradiation per unit area per day (typically in MJ/m^2·day or kWh/m^2·day). Also, η_{system} is the combined efficiency of the PV system, which accounts for efficiencies of the components other than the PV cell, such as the inverter, battery, and distribution system.

EXAMPLE 5-5 Energy Production from a PV Array

A PV array uses 20 commercial PV modules each with an area of 1.85 m^2, a typical power output of 350 W, and a solar module efficiency of 19 percent. The system efficiency may be taken as 75 percent. This PV array is installed in Atlanta, Georgia. The average daily solar radiation on a horizontal surface in Atlanta is given in Table 3-6, in MJ/m^2·day, as follows:

January	9.31	July	22.15
February	12.26	August	20.56
March	16.13	September	17.49
April	20.33	October	14.54
May	22.37	November	10.56
June	23.17	December	8.52
		Average	16.43 MJ/m^2·day

(*a*) Estimate the amount of energy production from this solar array per year in Atlanta, in kWh.
(*b*) If the price of electricity is \$0.15/kWh, what is the annual potential revenue from this PV array?
(*c*) If the initial cost of this PV system is specified as \$2/W, what is the simple payback period?

SOLUTION (*a*) Each PV module has an area of 1.85 m^2. The total area for 20 such modules is

$$A_{\text{total}} = (20)(1.85 \text{ m}^2) = 37 \text{ m}^2$$

We now calculate amount of energy production for the month of January:

$$\text{Energy production (Jan)} = n_{\text{days}}\eta_{\text{system}}\eta_{\text{cell}}AG_{\text{solar}}$$

$$= (31 \text{ days})(0.75)(0.19)(37 \text{ m}^2)(9.31 \text{ MJ/m}^2\cdot\text{day})\left(\frac{1 \text{ kWh}}{3.6 \text{ MJ}}\right)$$

$$= 423 \text{ kWh}$$

We repeat the calculations at other months and obtain the energy production in each month and for an entire year, as shown in the following table.

January	423	July	1006
February	503	August	933
March	732	September	768
April	893	October	660
May	1016	November	464
June	1018	December	387
		Total	**8803 kWh**

Alternatively, we can calculate annual energy production by using the annual average solar radiation value for Atlanta (16.43 MJ/m^2·day):

$$\text{Energy production (total)} = n_{\text{days}}\eta_{\text{system}}\eta_{\text{cell}}AG_{\text{solar}}$$

$$= (365 \text{ days})(0.75)(0.19)(37 \text{ m}^2)(16.43 \text{ MJ/m}^2\cdot\text{day})\left(\frac{1 \text{ kWh}}{3.6 \text{ MJ}}\right)$$

$$= 8783 \text{ kWh}$$

The results are sufficiently close, as expected.

(*b*) The price of electricity is \$0.15/kWh. Then, the annual potential revenue of this PV array is

$$\text{Potential revenue} = (\text{Annual energy production})(\text{Unit electricity price})$$

$$= (\$0.15/\text{kWh})(8803 \text{ kWh/yr})$$

$$= \mathbf{\$1320/yr}$$

(*c*) The total power output from 20 PV modules is

$$\dot{W}_{\text{total}} = (20)(350 \text{ W}) = 7000 \text{ W}$$

The initial cost of this PV system is specified as \$2/W. Then the initial cost of this PV system is

$$\text{Initial cost} = (\text{Annual energy production})(\text{Unit initial cost})$$

$$= (7000 \text{ W})(\$2/\text{W})$$

$$= \$14{,}000$$

The simple payback period of this system is

$$\text{Payback period} = \frac{\text{Initial cost}}{\text{Potential revenue}} = \frac{\$14{,}000}{\$1320/\text{yr}} = \mathbf{10.6 \text{ yr}}$$

This PV system will pay for itself in about 10 years. ▲

The design of a PV system for a particular application involves identification of the system configuration and the component requirements. Whether the load is DC or AC, the need for battery storage, and the availability of a backup energy source are among the options and criteria to consider. Once the system configuration is known, the next task is usually the selection of the size of the system and estimation of the amount of energy use.

EXAMPLE 5-6 Peak Load and Energy Consumption of a PV System

A PV system consisting of solar modules of 200 W power will be installed on a remote cabin with the following loads. Only one device other than the refrigerator runs at any one time during the day. Lights and TV run at the same time during the night. The refrigerator is on all the time, but it operates one-third of the time.

Device	Power rating, W	Daily operating period
Lights	80	4 h, nighttime
Refrigerator	400	on 24 h, operates 8 h
Microwave	400	1 h, daytime
Computer	250	3 h, daytime
Dishwasher	350	1 h, daytime
Oven	450	2 h, daytime
Television	300	4 h, nighttime

(*a*) Find the required capacity of the PV system and the number of modules.
(*b*) Find the daily energy consumption from the PV system.

SOLUTION (*a*) The required capacity of the system is equal to the total power requirement of the devices at the nighttime (peak load period) when the lights and TV are on, and the refrigerator is operating.

$$\text{Capacity} = 80 + 400 + 300 = \mathbf{780\ W}$$

Each solar module supplies 200 W, and thus, the required number of modules is

$$\text{Number of modules} = 780\ \text{W}/200\ \text{W} = 3.9 \approx \mathbf{4}$$

The result is rounded off to 4 modules.

(*b*) We need to consider the operation of all devices over a 24-h period to find the daily energy consumption.

$$\text{Energy consumption} = (80\ \text{W} \times 4\ \text{h}) + (400\ \text{W} \times 8\ \text{h}) + (400\ \text{W} \times 1\ \text{h}) + (250\ \text{W} \times 3\ \text{h}) + (350\ \text{W} \times 1\ \text{h}) + (450\ \text{W} \times 2\ \text{h}) + (300\ \text{W} \times 4\ \text{h}) = \mathbf{7120\ Wh}$$ ▲

Peak-Hours Approach to Estimate Energy Production

The energy yield performance of a solar array depends on characteristics of the PV array, power conditioning unit, and its components, as well as solar radiation data of the location. Here, we discuss an alternative method of the energy yield estimate using the peak-hours approach. The amount of electricity delivered from a PV array can be written as

$$\text{Energy production (kWh/day)} = \eta_{avg} A G \tag{5-17}$$

where A is the area of the PV array in m^2, G is the amount of solar radiation incident (i.e., insolation) per unit area per day in kWh/m^2·day, and η_{avg} is the average PV system efficiency over the day. The AC power output from the PV system may be expressed as

$$\text{Power}_{AC}\ (\text{kW}) = \eta_{1\text{-sun}} \times A \times (1\text{-sun}) \tag{5-18}$$

where $\eta_{1\text{-sun}}$ is the PV system efficiency at 1-sun. 1-sun represents a power output of 1 kW per unit array area. That is, 1-sun = 1 kW/m^2. Remember that standard testing of PV modules is done at 1000 W/m^2. Solving Eq. (5-18) for the area A and substituting into Eq. (5-17) gives

$$\text{Energy production (kWh/day)} = \text{Power} \times \frac{G}{1\text{-sun}} \times \frac{\eta_{avg}}{\eta_{1\text{-sun}}} \tag{5-19}$$

Assuming the same efficiency for η_{avg} and $\eta_{1\text{-sun}}$,

$$\text{Energy production (kWh/day)} = \text{Power}_{AC} \times \frac{G}{1\text{-sun}} \tag{5-20}$$

PV manufacturers list STC power ratings of their PV modules, as shown in Fig. 5-11. These STC power ratings (DC power) may be converted into realistic AC power outputs by

$$\text{Power}_{AC} = \text{Derate factor} \times \text{Power}_{DC,STC} \tag{5-21}$$

The derate factor can be taken to be 0.70 to 0.75. Substituting Eq. (5-21) into Eq. (5-20), we obtain

$$\text{Energy production (kWh/day)} = \text{Derate factor} \times \text{Power}_{DC,STC} \times \frac{G}{1\text{-sun}} \tag{5-22}$$

The ratio G/1-sun in Eq. (5-22) is called peak-hours. For example, if the annual average solar insolation in a location is specified as 5.5 kWh/m^2·day, this ratio becomes

$$\frac{G}{1\text{-sun}} = \frac{5.5\ \text{kWh/m}^2\cdot\text{day}}{1\ \text{kW/m}^2} = 5.5\ \text{h/day}$$

In other words, a solar insolation of 5.5 kWh/m^2·day is equivalent to 5.5 hours of 1-kW solar insolation in a day or 5.5 peak hours. It is also called 5.5 h/day of peak sun. Using this terminology, Eq. (5-22) is sometimes given as

$$\text{Energy production (kWh/day)} = \text{Derate factor} \times \text{Power}_{DC,STC} \times \text{Peak-sun} \tag{5-23}$$

Equation (5-22) assumes that the system efficiency remains the same during the day. Note that grid-connected PV systems operate near the maximum power point (knee of the current-voltage curve) throughout the day. The power at this maximum point is proportional to solar radiation incident. As a result, the efficiency of the system remains reasonably constant. The system efficiency is higher in the mornings due to lower temperatures, which causes slight underestimation of energy production (Masters, 2013).

The National Renewable Energy Laboratory (NREL) developed the PVWATTS calculator for PV performance (available on their website). This calculator allows the estimate of overall derate factor based on other factors considering various system and operating conditions such as temperature. The accuracy of energy production estimate from Eq. (5-22) can be improved by obtaining overall derate factor from the PVWATTS calculator.

EXAMPLE 5-7 Energy Production Estimate by the Peak-Hours Approach

A PV array is installed in Houston, Texas, with a power rating of 10 kW (DC, STC). The annual average solar insolation is given in Table 3-6 for Houston as 15.90 MJ/m^2·day. Assuming a derate factor of 0.70, estimate the annual energy production using peak-hours approach.

production using peak-hours approach.

SOLUTION A solar insolation of 15.90 MJ/m^2·day is equal to 4.42 kWh/m^2·day since 1 kWh = 3600 kJ. The annual energy production by the peak-hours approach can be estimated from Eq. (5-22):

$$\text{Energy production} = \text{Derate factor} \times \text{Power}_{\text{DC,STC}} \times \frac{G}{\text{1-sun}} \times \text{Annual days}$$

$$= (0.70)(10\ \text{kW})\frac{4.42\ \text{kWh/m}^2\cdot\text{day}}{1\ \text{kW/m}^2}(365\ \text{day/yr})$$

$$= \mathbf{11{,}290\ kWh/yr}$$

5-5 PHOTOVOLTAIC SYSTEM CONFIGURATIONS

The heart of any PV system is solar cells, arranged into modules and arrays. A PV system incorporates various other components depending on the application. The application areas can be divided into two main categories as *off-grid* (*stand-alone*) and *grid-connected* systems.

An off-grid PV system may be as simple as a PV array feeding direct current (DC) power to a load. This is called a *direct-coupled* PV system (Fig. 5-13). These systems are used for low power uses. They only produce power when there is solar irradiation (Hodge, 2010).

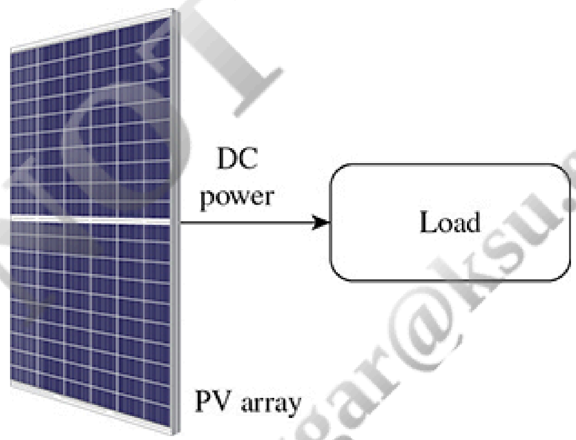
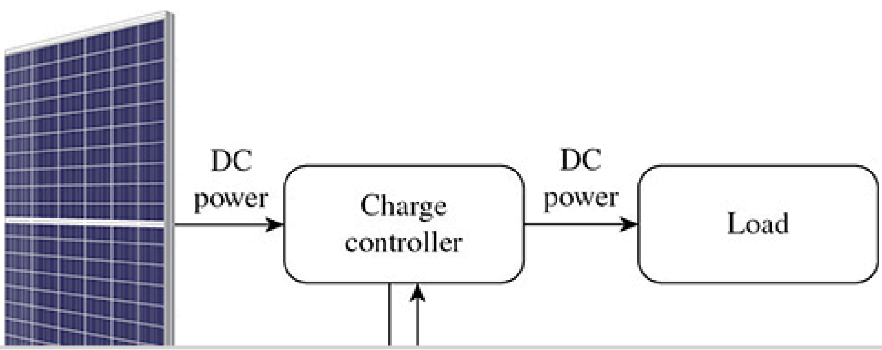


Figure 5-13 An off-grid direct-coupled PV system supplying DC power to a load.

For remote applications such as residences not connected to the grid, the PV system must have a battery storage for meeting loads during nighttime hours and cloudy periods. An off-grid system with battery storage is shown in Fig. 5-14. The system has flexibility to supply both DC power and AC (alternating current) power. The charge controller takes DC power from the PV array and directs to an application working with DC power. When there is excess power output from the PV array, the charge controller directs the power to the battery for storage. When there is no solar irradiation, the charge controller absorbs power from the battery and directs it to the DC load. For the operation of devices using AC power, an inverter must be used. The inverter receives DC power from the battery and converts it to AC power.



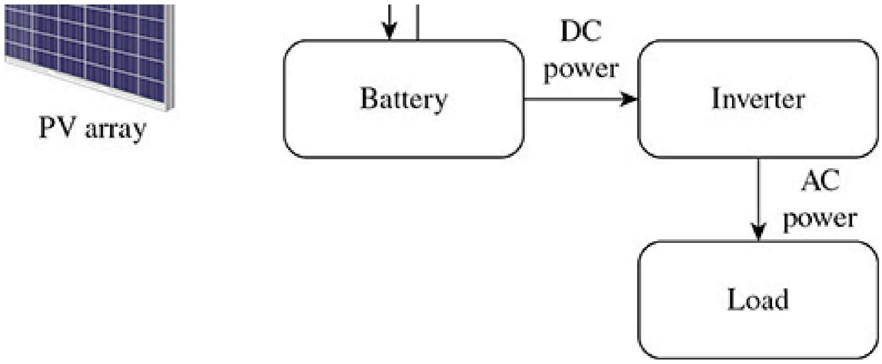


Figure 5-14 An off-grid PV system with energy storage. It is designed to supply both DC power and AC power.

Stand-alone PV systems can be used to power many different applications such as calculators, watches, street lighting, traffic signs, battery charging, telephones, radios, weather stations, and water purification (Fig. 5-15). These simple systems usually consist of a solar module, a charge controller, and a battery. Low-power stand-alone PV systems are usually cost-competitive to conventional methods such as conventional batteries, grid power, and small diesel generators. They also have advantages of reliability, durability, and, of course, no fuel cost.

Figure 5-15 A stand-alone solar panel used in a small bus converted to a caravan.

Water pumping in remote homes, villages, and farms is a common application of off-grid systems. In this application, the system is not equipped with a battery. Another important application of an off-grid PV system is supplying electricity to remote homes and villages. The cost of extending grid power to remote homes is usually much higher than the cost of PV installation. A commonly used alternative to PV power for water pumping and remote homes is diesel generators. Diesel generators are less expensive to install but the fuel cost and operating and maintenance expenses are very high compared to PV systems.

A disadvantage of the PV system is its inability to supply power during winter with long periods of cloudy days. An effective solution is a hybrid system consisting of a diesel generator and a PV array. The PV system is used to provide power most of the time when solar radiation or battery storage are available, and the diesel generator provides power at other times.

Grid-connected PV systems supply AC power at grid voltage, phase, and frequency for compatibility with the grid. Such a system is shown in Fig. 5-16. The inverter does not only convert DC power to AC power but also condition the power (works as a power conditioner) to make it compatible with the grid specifications. In this configuration, there is no waste of solar power because all the power produced from the PV array are transferred to the grid, and the applications use only the required amount of power from the grid.

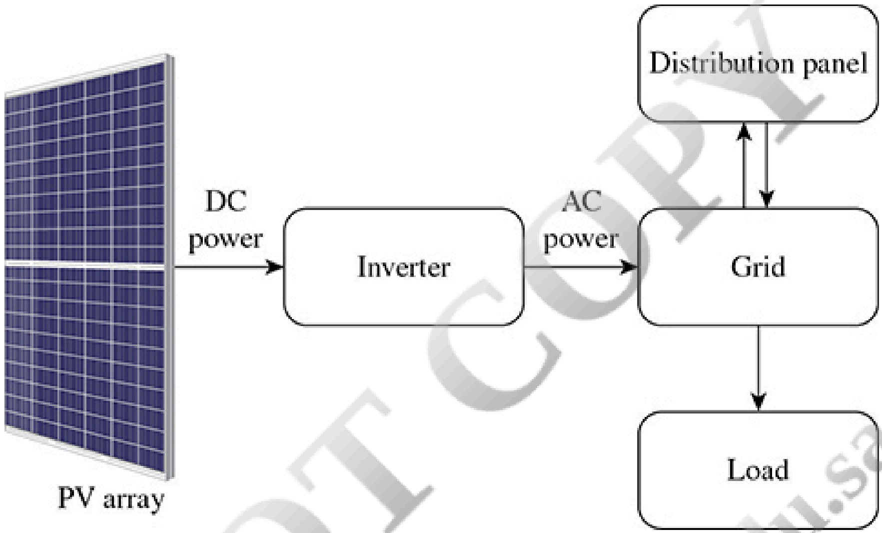


Figure 5-16 A grid-connected PV system.

A main advantage of grid-connected PV systems is the absence of a battery for energy storage. This greatly simplifies the overall system. They provide an effective and green method of peak shaving during the periods of peak demand from the utility. Most of the PV systems in the world are grid connected. The grid connected systems can be as small as a few kilowatts for residential applications, hundreds of kilowatts for industrial uses, and thousands of kilowatts for supplying power to utilities (Fig. 5-17).

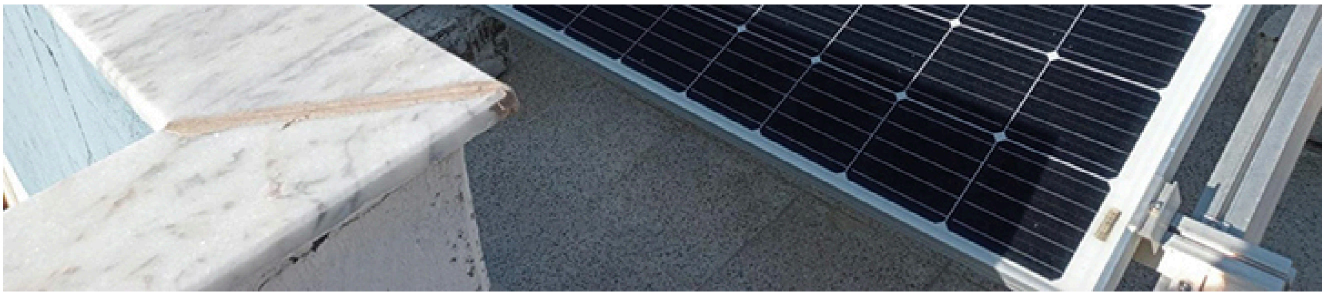


Figure 5-17 A grid-connected PV array on top of a campus building supplying power to the grid.

A battery can be added to a grid-connected PV system if the user demands power when the grid is down. This may be needed for industrial users to meet critical loads. The system becomes more complicated in this scenario with advanced controls to allow disconnecting and reconnecting to the grid.

Large installations of grid-connected PV systems are mostly owned by the utilities while the capacity is usually small for privately owned systems. There are significant variations in the specifications of the agreement between the private owner and the utility depending on the country, region, and the utility. In one case, the utility is required to pay for its levelized cost of producing 1 kWh of electricity. This is usually not attractive for the owner of the PV system because this cost is usually much lower than the rate the consumers pay for the electricity. Another example of the agreement between the owner and the utility is called *net metering*. In this arrangement, the consumption of the owner increases when power from the grid is used; and the consumption decreases when solar power is supplied to the grid. The same pricing (in $/kWh) is used for both the purchased electricity and sold electricity. Net metering is financially attractive for the PV owner. Some governments provide significant incentives to allow a profitable agreement for the PV owner to promote greater production of solar electricity.

Photovoltaic arrays can be installed at a fixed angle, or they can involve one-axis tracking or two-axis tracking capabilities. For fixed-angle systems, the best performance in the northern hemisphere is obtained when the arrays are placed with the azimuth south, and the tilt angle is selected to be equal to the latitude of the location. Most PV installations have no option of tracking the sun. One-axis tracking involves an axis of rotation at the north-south or east-west line. Two-axis tracking has an additional control of changing the tilt angle to track the sun. Passive tracking systems involving no motors or gears are also available, but they are not effective in windy areas. PV systems with tracking capabilities can produce 25 to 45 percent more power in the summer and can pump up to 50 percent more water compared to fixed PV systems (Nelson, 2011).

The lifespan of a solar cell is about 20 to 35 years. The collection of dust on panel surfaces over time reduces the performance of solar panels. There is no easy solution to this problem, and this is one of the main obstacles preventing widespread use of solar panels in some solar-rich countries. The cost of solar panels has been decreasing steadily over the years while the efficiencies have been increasing. As a result, PV systems are likely to remain as a main actor in green energy production.

5-6 COMPONENTS OF PHOTOVOLTAIC POWER SYSTEMS*

A *PV generator* consists of a number of PV modules that are electrically connected to each other. The PV generator is the core component of a PV power system, which utilizes PV modules as a power source to generate electrical energy. However, the PV power systems require a variety of other components in order to provide usable electrical energy for the energy consumers. The PV industry refer to all these components, equipment, and services (including labor) other than PV modules as the *balance of system* (BOS).

PV power systems can be categorized according to where the PV modules are installed, including but not limited to, installations on the ground, building roofs or even water. In this section, we focus on the PV generators and most important components of BOS such as inverters and batteries.

Another common categorization of PV power systems is based on the form of the electrical energy and where it is supplied, both of which depend on the requirements of the energy consumers. A PV power system supplies either DC or AC as a form of electrical energy. PV power systems that are not connected to the electricity grid are defined as *stand-alone*, in other words autonomous or *off-grid systems*. A PV power system supplying solely DC energy operates mostly as a stand-alone system. Stand-alone PV systems can also provide AC energy. On the other hand, PV power systems that are connected to the electricity grid feed only AC energy into the grid. Such PV power systems are defined as *grid-connected* or *on-grid systems*.

PV Generator

PV Generator

The power of a PV generator is defined in *watt-peak* (maximum power rating in watt) similar to that of a PV module and varies from a few watts (e.g. stand-alone systems for LED lighting) to several gigawatts (e.g. large grid-connected systems). In a PV generator, a number of PV modules are firstly connected in series to form a *string*. Here the principles of electrical circuitry apply: The voltage across a string is the sum of the voltages of individual PV modules, while the lowest current value of a particular PV module defines the total current that flows through the string. Therefore, PV modules with similar short-circuit currents should be connected in a string. Several strings with the same number of PV modules can later be connected in parallel to form a *PV array*, so that the string currents are added to each other, while the voltages across each string are supposed to be the same. Figure 5-18 reveals how the voltages and the currents of PV modules are added up when they are connected in series and parallel, respectively.

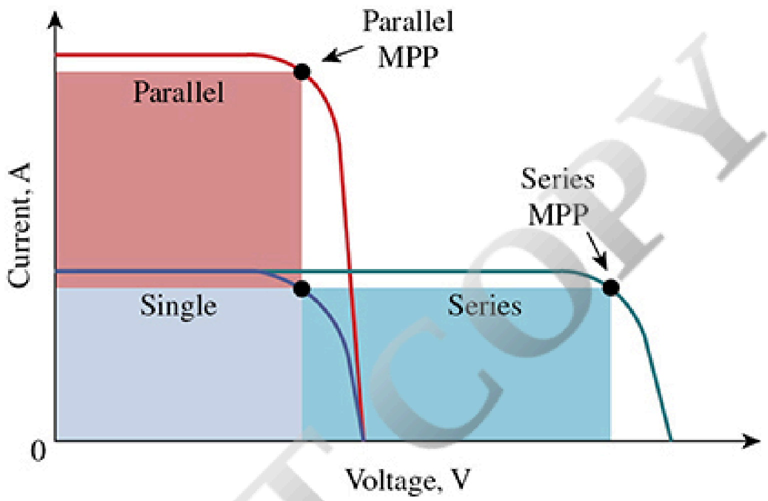
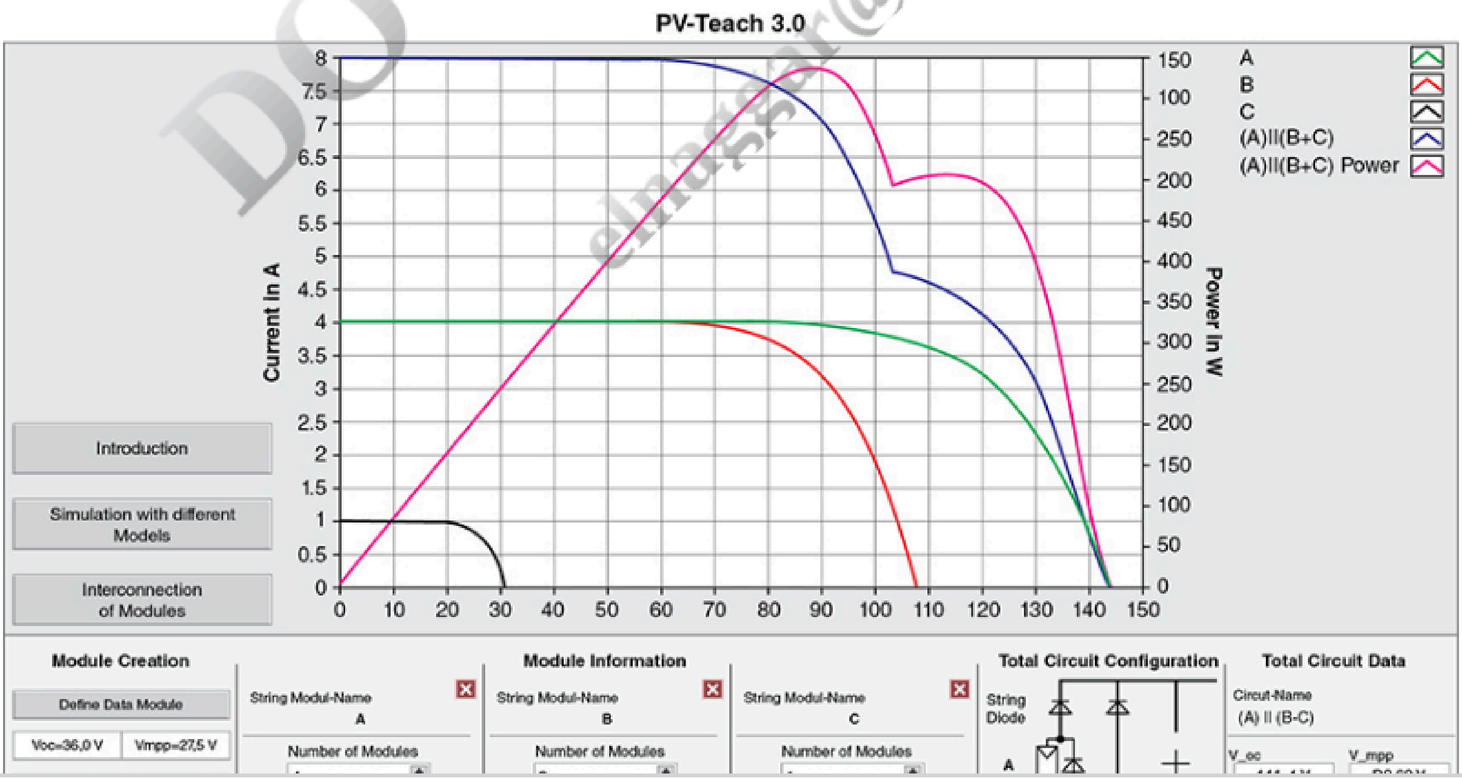


Figure 5-18 Current-voltage (I-V) characteristic curve of a PV array. MPP: Maximum Power Point.

PV modules of the same watt-peak value might have unidentical current and voltage values. In case such PV modules are combined in a PV array, the total power of the PV array is not equal to the sum of the individual PV module powers. This power loss in a PV generator is defined as a *mismatch loss*. Such losses also occur when a PV module in a PV array malfunctions or gets shaded, as well as when strings with different number of PV modules are connected in parallel to each other. The negative effects of mismatching and shading are so complex that it is better to calculate them by means of a simulation software, as shown in Fig. 5-19.



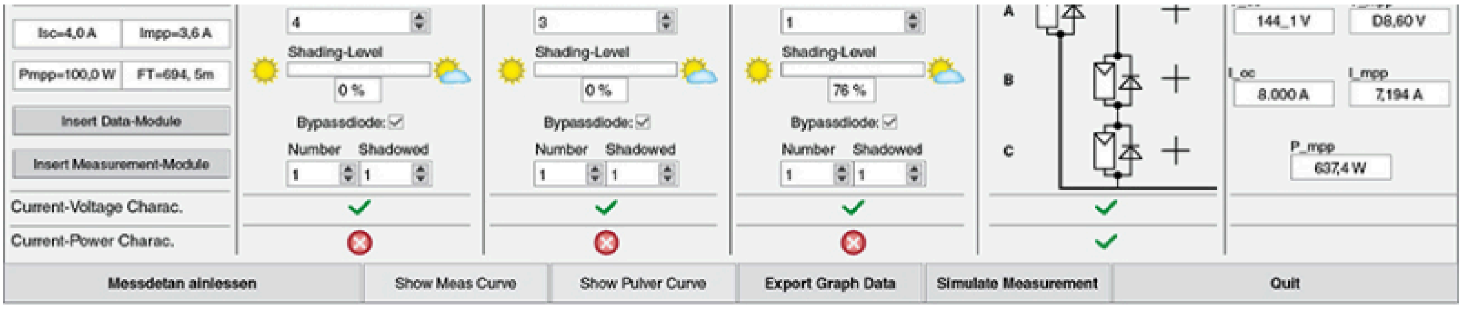


Figure 5-19 A screenshot of a simulation software depicting the losses of a PV array due to partial shading. (*The screenshot is from the free PV software PV-Teach accompanying the book by Mertens, 2018.*)

Inverter

A PV generator produces DC for starters, which cannot be fed into the electricity grid directly. The interconnected network for the distribution of electricity operates with either single- or three-phase AC depending on the energy consumers (industries, domestic customers, etc.). The voltage and frequency of the grid depend on the regions of the world. The inverter transforms the DC energy from the PV generator into AC energy depending on the requirements of the electricity grid and energy consumers. Inverters deliver either single- or three-phase AC.

Various inverter types and power classes are available depending on the concept and design of the PV power system. The most widespread types are explained as follows.

Central inverters are used for large PV systems and deliver three-phase electric power ranging from several hundred kilowatts to megawatts. The outputs of individual strings from the PV generator are connected in parallel in a generator connection box, also referred to as *junction box* (not to be confused with the junction box of a PV module) and the DC energy is fed into the DC side of the central inverter from the junction box. The main advantage of central inverters compared to other inverter concepts is the lower investment cost both for the inverter itself and rest of the BOS. On the other hand, the operation and maintenance (O&M) costs for central inverters are higher because of their complex structure. Their O&M is also very crucial since they supply considerable amount of power, which would cause elevated power losses in case of an inverter defect. Another disadvantage of central inverters is the fact that the mismatch losses of the PV system due to shading, PV module defects, or ageing, for example, would be higher than other inverter concepts because of the parallel connection of strings.

String inverters can be either in single-phase or three-phase depending on their power classes. In small residential PV systems, mostly single-phase string inverters up to 5 kW are deployed. In case the residence is connected to a three-phase electricity grid, a small-scale (mostly up to 5 kW) single-phase inverter can be connected to one phase of the grid, as long as the grid regulation permits (there is no such problem if the residence is connected to a single-phase electricity grid). This solution cannot be used for higher powers, because such a phase unbalance can cause problems for the electricity grid. Three-phase string inverters range up to 150 kW. In case the PV generator's power is higher than a single inverter, multiple inverters can be deployed, each of which operates independently. Multiple strings can be connected to a string inverter and each string can be controlled by an individual *maximum power point tracker* (MPPT). Therefore, PV systems with string inverters suffer less mismatch losses than the ones with central inverters. In case of an inverter defect, the power loss of the PV system is limited. A defective inverter can easily be substituted by a backup product in the field and repaired afterward.

String inverters enable more flexibility for design, engineering, and operation of PV systems. As for central inverters, lower investment cost at the expense of this flexibility is a tradeoff for megascale projects that the investors must decide. The rest of this discussion focuses on string inverters because they are more widely deployed than central inverters.

Maximum Power Point Tracking

Maximum power point (MPP) is a fundamental term for PVs that characterize solar cells, PV modules, strings, arrays, and generators. The maximum power point tracker (MPPT) is a device that is programmed for controlling the DC-DC converter to make sure that the PV generator is operated at its MPP. The MPP of a PV generator varies with ambient conditions such as irradiance and temperature, as well as with mismatch losses such as shading effects. The MPPT's task is to find the MPP on the current-voltage (I-V) curve of a PV generator under the conditions above-mentioned.

There are MPPT algorithms that aim to find the I_{MMP}; however, the most common method for MPPT is to tune the voltage of the PV generator until its V_{MPP} is found. The MPPT changes the duty cycle D of the DC-DC converter while measuring the output voltage and current of the PV generator simultaneously until the PV generator is operated at its MPP. It is especially challenging to track the MPP in case the PV generator is partially shaded. The illustrative current-voltage (I-V) and power-voltage (P-V) curves of a partially shaded PV generator are depicted in Fig. 5-20, where the P-V curve has various local maxima. It is the task of the MPPT algorithm to find the global MPP. String inverters complete this task easier than the central inverters. In case multiple strings are connected to a string inverter, it is more effective to control each string by an individual MPPT.

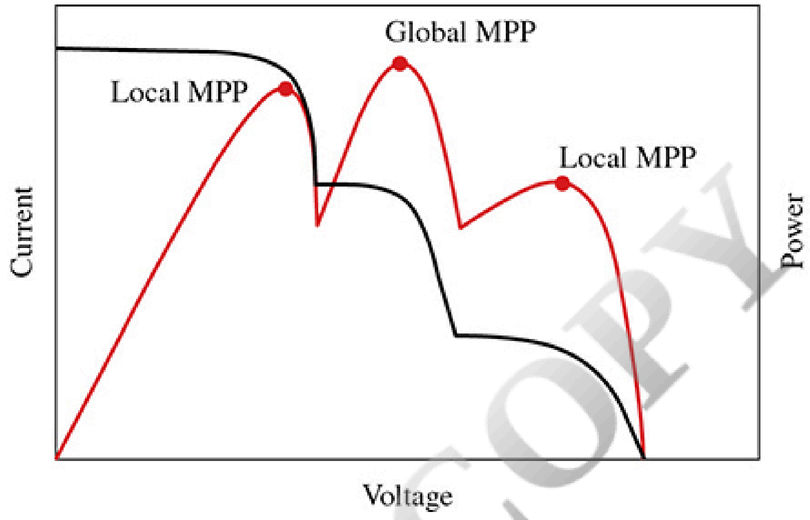


Figure 5-20 Current-voltage and power-voltage curves of a partially shaded PV generator with local and global MPPs.

Design of a Three-Phase String Inverter

Here, we consider a three-phase inverter design with a power class of 30 kW. In the first step, the DC-DC boost converter increases the DC voltage of the PV generator, if necessary. It is equipped with two MPP trackers, each of which having five input strings. Each MPPT operates its own PV array at its MPP independently, so that each PV array may:

- Consist of a different number of PV modules.
- Consist of different PV module types or power classes.
- Have PV modules with different installation conditions regarding orientation to the south and inclination from the horizontal plane.

However, each string within a PV array must:

- Consist of the same number of PV modules in series.
- Consist of the same PV module types and power classes.
- Have PV modules with the same installation conditions regarding orientation to the south and inclination from the horizontal plane.

The DC bus (also known as a link) capacitor provides a smooth DC bus voltage to the DC-AC inverter by eliminating the ripple currents and voltage transients. The DC-AC inverter converts the DC voltage into a sinusoidal AC voltage in compliance with the grid code. The low-pass filter attached to the DC-AC inverter suppresses the high-order harmonics of the AC voltage, so that the quality of the AC energy fed into the grid is increased.

The inverter has protective devices both on the DC and the AC side. The string fuses protect each string against return currents. In case of an earth fault or a short circuit in a string, the total current of all other parallel-connected strings that are not involved in the fault pass through the defective string. Such return currents may cause the risk of fire and damage to the PV generator. While a DC disconnect switch physically disconnects an individual PV array from the inverter, an AC disconnect switch physically disconnects the inverter from the electricity grid. An overvoltage protection system consisting of varistors, and surge protection devices (also known as surge arresters) are integrated in both DC and AC sides for protection against voltage peaks induced by lightning strikes, for example.

Batteries

Rechargeable (also known as secondary or storage) batteries can be used both in stand-alone and in grid-connected PV systems whenever the electrical energy from the PV generator needs to be stored. The term *rechargeable* is very vital, because the primary (single-use) batteries cannot be used in PV power systems, and thus are not relevant within the scope of this coverage. Rechargeable batteries, which are also known as accumulators, are electrochemical storages that can be charged, discharged into a load, and recharged many times.

An electric battery consists of electrochemical cells that can generate electrical energy from chemical reactions, as well as, initiate chemical reactions by using electrical energy. A battery converts chemical energy directly into electrical energy by means of a redox reaction. In a redox reaction, oxidation and reduction occur simultaneously. During this process, the reductant is transferring electrons to the oxidant and getting oxidized, while the oxidant is gaining electrons and getting reduced. This electrochemical reaction is reversible under electrical energy from an external source, so that the battery "accumulates" and stores energy. The amount of energy stored in a battery in comparison to its mass is denominated as energy density (or specific energy) and commonly expressed in watt-hours per kilogram (Wh/kg). A battery with a larger energy density than another one contains the same amount of energy although it has a smaller mass.

The operating principle of a battery is explained by the examples of lead-acid batteries and lithium-ion batteries. These two battery types are widely used for small-scale storages, which are the focus of this coverage. Megascale batteries are also available that can be used by utilities as a buffer between the intermittently produced electricity by the renewable energy sources and the difficult-to-predict electricity demands. Sodium-sulfur (NaS) batteries, redox flow batteries, and, to some extent, lithium-ion batteries can be used for this purpose.

Lead-Acid Battery

Invented during the second half of the 19th century, the lead-acid battery is the most established rechargeable battery technology. The electrochemical cells of a battery are electrically connected to each other. Each electrochemical cell consists of two half-cells connected in series and each half-cell consists of an electrode and an electrolyte. In a lead-acid battery, the negative electrode is made up of lead, while the positive electrode is made up of lead-dioxide. The half-cells are filled with sulfuric acid (H_2SO_4) solution as an electrolyte. The electrolyte is electrically conducting as it provides the flow of ions (anions and cations) between the electrodes. In case of a lead-acid battery, the electrolyte also participates in redox reactions inside the electrochemical cell. While the ions are conducted through the electrolyte, the electrons are conducted through an external conductor between the half-cells. A separator between the half-cells isolates the positive and negative electrodes but still allows the flow of ions between the electrodes.

Because lead sulfate at the surface of both electrodes decomposes during charging, sulfate ions are delivered back to the electrolyte from both electrodes. In case the battery is charged insufficiently or is not fully charged right after a deep discharge, the lead sulfate may partially remain at the electrodes, which may cause sulfation. Sulfation of the electrodes decreases their active masses and thus the capacity of the battery. On the other hand, a battery cell should not be overcharged. *Overcharging* occurs when the charging voltage is so high that excessive current is flown into the battery or when the battery is charged excessively even though it has become fully charged. In case of overcharging, the water inside the battery is electrolyzed so that oxygen gas is formed at the positive electrode and hydrogen gas is at the negative electrode. This process is known as *gassing* and may cause premature aging or even a risk of explosion of the battery.

There are various types of lead-acid batteries depending on the purpose of use. For small-scale stand-alone PV systems, *gel batteries* are usually preferred. In a gel battery, the sulfuric acid is thickened with mostly silica so that the electrolyte is gel-like. Compared to wet-cell (i.e., flooded-cell) batteries where the electrolyte is liquid as described above, gel batteries are completely sealed, have a much smaller risk of gas or electrolyte leakage, can be maintained infrequently, and have a longer lifespan. On the other hand, gassing should still be avoided or else the battery may dry out. Another disadvantage of gel batteries is that the mobility of the ions inside the electrolyte is limited because of thicker and less conductive electrolyte. Therefore, gel batteries cannot deliver high discharge currents like a starter battery in a car. However, they have a better deep-cycle characteristic than many other lead-acid battery types.

Compared to starter batteries, *deep-cycle batteries* can be deeply discharged on a regular basis and are less susceptible to degradation due to cycling. The latter prolongs the *battery lifespan*, which means the maximum number of charge-discharge cycles before the battery fails. This is also called the *cycle life*. Although possessing gel electrolytes and thicker plates (electrodes) compared to starter batteries extend the cycle life of deep-cycles batteries, it is also the reason why they cannot deliver discharge currents as high as starter batteries.

The capacity (C) of a lead-acid battery is measured in ampere hour (Ah), which is the amount of electric charge delivered under specific conditions. These conditions are explained by means of the characteristic curves of a commercial deep-cycle lead-acid gel battery with a nominal voltage of 12 V, as shown in Fig. 5-21.

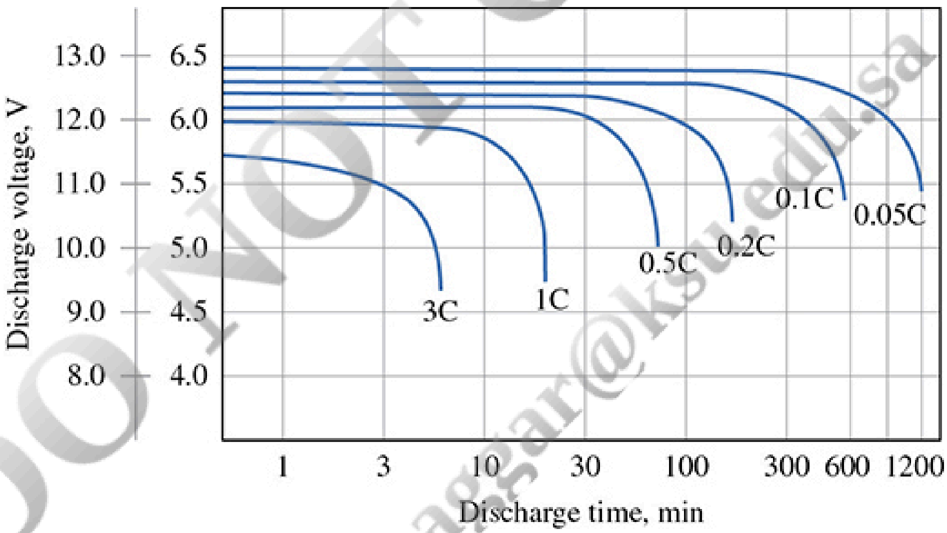


Figure 5-21 Correlation between discharge voltage, C-rate, and discharge time of a lead-acid battery at 25°C.

The capacity of a battery is always given at a certain C-rate. C-rate defines a correlation between the discharge current and the discharge time. For example, 1C means that a fully charged battery with a capacity of 144 Ah at 1C can theoretically provide a discharge current of 144 A for 1 hour. The nominal capacity of lead-acid batteries is usually given at 0.05C (C_{20}) or 0.1C (C_{10}) corresponding to a 20-h discharge or a 10-h discharge, respectively.

EXAMPLE 5-8 Discharge Current of a Lead-Acid Battery

A lead-acid battery is operated at 0.2C with a capacity of 215 Ah. What is the discharge current I5 if the battery is discharged by a constant current for 5 hours at 0.2C?

SOLUTION Because 0.2C (C_5) corresponds to a 5-h discharge, the constant discharge current I_5 is calculated as

$$I_5 = \frac{C_5}{\Delta t} = \frac{215\ \text{Ah}}{5\ \text{h}} = \mathbf{43\ A} \quad ▲$$

In the case of the battery shown in Fig. 5-21, only 0.05C corresponds to its theoretical discharge time, which is 20 hours. All other C-rates fall short of their individual discharge times. For example, 0.1C does not exactly correspond to 10 hours. As the C-rate increases, the deviation gets bigger: the discharge time at 0.2C is approximately 3 hours, even though it should have been 5 hours. Figure 5-21 also indicates that the operating voltage of a lead-acid battery is usually below its nominal voltage (12 V). The end-of-discharge voltages at various C-rates are also depicted in Fig. 5-21, meaning that in case of a longer discharge, the operating voltage falls below this level and the depth of discharge is dangerously high.

Depth of discharge (DoD) defines to which extent a battery is discharged compared to its fully charged state. The DoD is given in percentage and is the inverse of *state of charge* (SoC) of a battery, which defines to which extent a battery is charged. That is,

$$\text{DoD} = 100\% - \text{SoC} \tag{5-24}$$

EXAMPLE 5-9 Depth of Discharge of a Battery
Calculate the DoD and SoC of a battery with a nominal capacity of 260 Ah, which is discharged for 30 minutes at a constant current of 100 A.

SOLUTION The depth of discharge and state of charge of this battery are determined as

$$\text{DoD} = \frac{I\Delta t}{C} = \frac{(100\text{ A})(30\text{ min})\left(\frac{1\text{ h}}{60\text{ min}}\right)}{260\text{ Ah}} = 0.192 = \mathbf{19.2\%}$$

$$\text{SoC} = 100\% - \text{DoD} = 100\% - 19.2\% = \mathbf{80.8\%}$$

Therefore, 19.2 percent of the battery capacity is used and the remaining battery capacity is 80.8 percent. ▲

The DoD has a negative effect on battery life. In case the battery shown in Fig. 5-22 is fully discharged (DoD = 100%) on a regular basis, its capacity will reduce to 80 percent after only approximately 500 cycles.

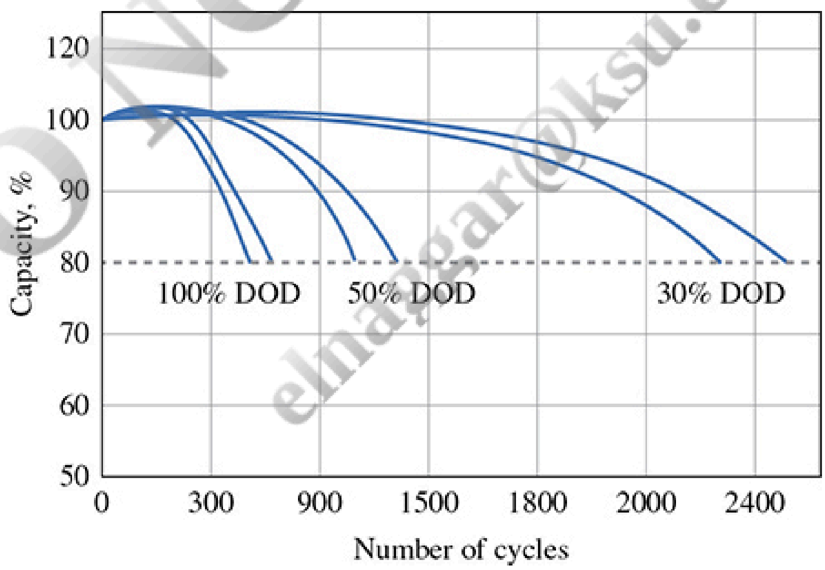
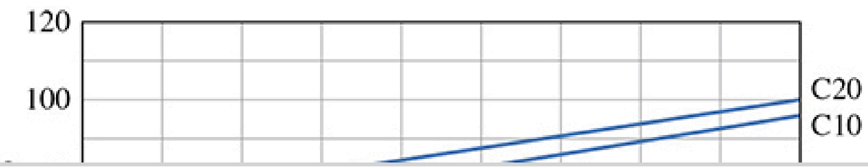


Figure 5-22 Correlation between capacity, depth of discharge, and cycle life of a lead-acid battery.

The usable capacity of a lead-acid battery strongly depends on its operating temperature. The battery capacity is reduced drastically when operating in subzero conditions. As depicted in Fig. 5-23, the capacity of most lead-acid batteries can be fully used at 25°C.



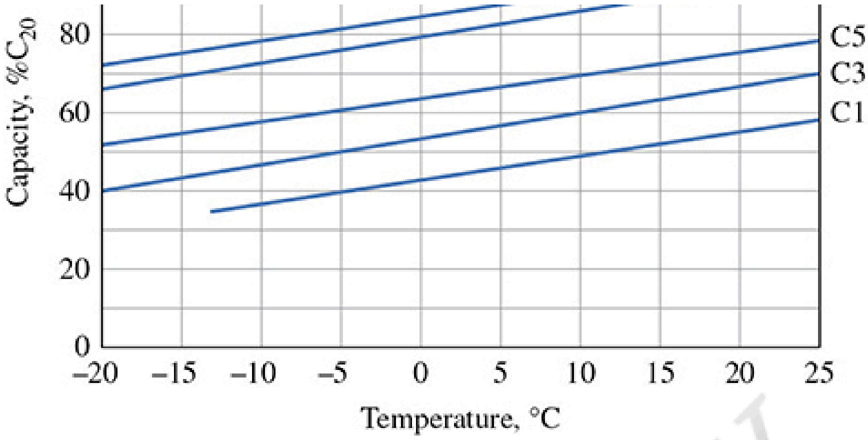


Figure 5-23 Correlation between usable capacity, C-rate, and ambient temperature of a lead-acid battery.

EXAMPLE 5-10 Effect of Temperature on the Capacity of a Battery
A lead-acid battery has a rated capacity of 250 Ah when operated at 0.1C and 25°C. It has a temperature behavior as shown in Fig. 5-23. How much of its rated capacity can be used when operated at 15°C?

SOLUTION The lead-acid battery shown in Fig. 5-23 can deliver 90 percent of its rated capacity C_{10} (0.1C) when operated at 15°C. Therefore,

$$C_{10(15°C)} = (250\ \text{Ah})(0.9) = \mathbf{225\ Ah} \quad \blacktriangle$$

Lithium-Ion Battery

The lithium-ion (Li-ion) battery is a technology of the 20th century, with Li-ion batteries being commercially available from 1991. The original lithium battery consisted of lithium metals as electrodes; however, this technology was abandoned because of fire and explosion incidents due to highly reactive lithium. Nowadays, lithium is used in form of ions in order to avoid dangerous reactions.

In a Li-ion battery, a positive electrode is coated onto aluminum, whereas a negative electrode is coated on copper, both of which serve as current collecting metals. There is a variety of Li-ion batteries with different chemical compositions of the electrodes and the electrolyte. In most of the cases, the main difference is the material used for the positive electrode. In Li-ion batteries that are used in PV power systems, the following materials are mostly used as the positive electrode:

- Lithium nickel manganese cobalt oxide ($LiNiMnCoO_2$), also known as an NMC battery
- Lithium nickel cobalt aluminum oxide ($LiNiCoAlO_2$), also known as an NCA battery
- Lithium iron phosphate ($LiFePO_4$), also known as an LFP battery

All Li-ion battery types above-mentioned use graphite as the negative electrode. Because of its good electrical conductivity, graphite is used in many other Li-ion batteries too. Exceptions are the Li-ion batteries using lithium titanate (Li_2TiO_3) or lithium silicates (typically in form of Li_4SiO_4), the latter of which is still being a matter of intensive research (Su et al., 2022). The most common electrolyte type is lithium hexafluorophosphate ($LiPF_6$) salt solved in a mixture of organic carbonate solvents such as ethylene carbonate (EC), dimethyl carbonate (DMC), and diethyl carbonate (DEC). Most of the electrode types above-mentioned operate reasonably within the $LiPF_6$ solution. Nevertheless, solvent-free solid polymer electrolytes or gel polymer electrolytes have been investigated as an alternative to liquid-type electrolytes (Xu, 2014). Such batteries are denominated as lithium-ion polymer battery, abbreviated to LiPo battery or lithium polymer battery.

Lithium iron phosphate (LFP) batteries have been widely deployed as energy storages for PV power systems in recent years. Compared to other Li-ion battery types, LFP batteries have the following drawbacks:

- Lower nominal voltage of 3.2 volts per battery cell, whereas those of NMC and NCA batteries are 3.6 volts per cell.
- Lower energy density of approximately 120 Wh/kg, whereas those of NMC and NCA are approximately 220 Wh/kg and 260 Wh/kg, respectively.

Despite all these drawbacks, LFP batteries are preferred because of the following:

- They have a longer lifespan of over 2000 cycles, which is at least twice as much as that of an NMC battery and four times as much as that of an NCA battery.
- They can discharge at much higher C-rates, which also allows that the discharge voltage remains nearly constant at different discharge rates.
- They are very safe regarding explosion and fire.

During the discharge process of an LFP battery, lithium ions and electrons come off from the negative electrode (anode). The lithium ions are transported to the positive electrode (cathode) through the separator, while the electrons migrate over an external electrical circuit to the cathode. Both the lithium ions and the electrons integrate into iron phosphates at the cathode.

While the battery is getting charged, the reactions described above run the other way around: the positive electrode becomes the anode and both the lithium ions and the electrons are transported from the anode to the cathode (negative electrode). The electrolyte plays a key role for the conductivity of lithium ions, which is crucial for the power output of the battery. Similar to lead-acid batteries, a separator made of thin and porous polymer foils prevents a direct contact of the electrodes while allowing the transport of lithium ions from one electrode to the other. The overcharging of the battery should be avoided in order to prevent the destruction of the battery cell.

Li-ion batteries have much longer cycle lives, much better DoD rates, and higher discharge voltages, C-rates, and energy densities than lead-acid batteries. While the lead-acid battery technology is very mature, the technology for various types of Li-ion batteries is developing further. Despite their high costs, Li-ions batteries have been taking the place of lead-acid batteries in PV power systems.

EXAMPLE 5-11 Replacing a Lead-acid Battery with a Li-ion Battery

A 12-volt lead-acid battery with a nominal capacity of 100 Ah and a mass of 26.2 kg shall be replaced by a Li-ion battery. An LFP battery cell with a nominal discharge voltage of 3.2 volts and a nominal capacity of 102 Ah, which weighs 2.7 kg, shall be used as replacement.

(*a*) Determine the total number of LFP battery cells required for the replacement.

(*b*) Calculate the total mass of LFP battery and the energy densities of both battery types.

SOLUTION (*a*) If four LFP battery cells are connected in series, the system voltage of the new battery will be equivalent to the required system voltage of 12 volts, calculated as

$$V = (4)(3.2\ \text{V}) = 12.8\ \text{V}$$

Because of series connection, the capacity of the LFP battery remains 102 Ah. Therefore, **four** LFP battery cells are required to replace the existing lead-acid battery.

(*b*) Four LFP battery cells are used. Then, the mass of LFP battery is

$$m = (4)(2.7\ \text{kg}) = \mathbf{10.8\ kg}$$

The energy provided by the lead-acid battery is

$$E = VC = (12\ \text{V})(100\ \text{Ah}) = 1200\ \text{Wh}$$

Note that the unit VA is equivalent to W. The energy density of the lead-acid battery is

$$E_g = \frac{E}{m} = \frac{1200\ \text{Wh}}{26.2\ \text{kg}} = \mathbf{45.8\ Wh/kg}$$

The energy provided by the LFP battery is

$$E = VC = (12.8\ \text{V})(102\ \text{Ah}) = 1306\ \text{Wh}$$

Thus, the energy density of the LFP battery is calculated as

$$E_g = \frac{E}{m} = \frac{1305.6 \text{ Wh}}{10.8 \text{ kg}} = \mathbf{120.9\ Wh/kg}$$

The calculations clarify that the LFP battery, which is much lighter (and also smaller) than the lead-acid battery, meets the requirements regarding the energy output much better. ▲

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PROBLEMS

PHOTOVOLTAIC EFFECT

5-1 What is the photovoltaic effect?

5-2 Give at least one application for small-size, medium-size, and large-size PV systems.

5-3 What are the advantages and disadvantages of PV systems?

5-4 What is the band gap energy?

5-5 Describe semiconductor materials in terms of their valence bands and band gap energies.

5-6 Describe the operation of a PV cell using terminologies including *p-n* junction, silicon, photon energy, valence band, conduction band, and band gap energy.

5-7 Why is the conversion efficiency of a silicon solar cell low? Explain using concepts of wavelength of solar radiation, photon energy, and band gap energy.

5-8 How does using multijunction solar cells increase cell efficiencies?

5-9 What are the maximum wavelengths of solar radiation for which solar radiation can be converted to electrical energy for copper indium diselenide and cadmium telluride? The band gap energy values are 1.01 eV for copper indium diselenide and 1.44 eV for cadmium telluride.

5-10 Solar radiation is incident on a silicon solar cell. What is the excess energy (amount of photon energy not contributing to energy conversion) in a photon from solar radiation at a wavelength of 0.75 μm?

5-11 Solar radiation is incident on a silicon solar cell. What is the excess energy (amount of photon energy not contributing to energy conversion) in a photon from solar radiation at a wavelength of 1.20 μm?

5-12 Solar radiation is incident on a 1-m^2 gallium arsenide solar cell at a rate of 800 $W/m^2 \cdot \mu m$ at a wavelength of 0.60 μm. Determine the maximum efficiency of this solar cell at this wavelength.

5-13 Solar radiation is incident on a 1-m^2 silicon solar cell at a rate of 1000 $W/m^2 \cdot \mu m$ at a wavelength of 0.45 μm. Determine the rate of photons incident on the solar cell and the rate of excess solar energy at this wavelength.

5-14 Solar radiation is incident on a silicon solar cell at a rate of 650 $W/m^2 \cdot \mu m$ at a wavelength of 1.12 μm. Determine the rate of photons incident on the solar cell and the maximum efficiency of this solar cell at this wavelength.

5-15 Solar radiation is incident on a silicon solar cell at a rate of 300 $Btu/h \cdot ft^2 \cdot \mu m$ at a wavelength of 0.70 μm. Determine the maximum efficiency of this solar cell at this wavelength.

5-16 Which of the following is not an advantage of PV systems?

5-16 Which of the following is not an advantage of PV systems?

(*a*) Lightweight
(*b*) High efficiency
(*c*) High reliability
(*d*) No water consumption
(*e*) Flexibility in sizing

5-17 Which of the following is not a disadvantage of PV systems?

(*a*) High operating and maintenance cost
(*b*) Low efficiency
(*c*) Need for energy storage
(*d*) Intermittent energy source
(*e*) Dust collection on panel surfaces

5-18 A material has high band gap energy, and their atoms have full valence bands. Electrons in the atom do not flow under the application of voltage or current. This material is most likely a(n)

(*a*) Conductor
(*b*) Semiconductor
(*c*) Insulator
(*d*) Intrinsic semiconductor
(*e*) Extrinsic semiconductor

5-19 When the dopant has a smaller number of electrons in the valence band compared to pure silicon, the resulting material is a(n)

(*a*) Intrinsic semiconductor
(*b*) Extrinsic semiconductor
(*c*) *n*-type semiconductor
(*d*) *p*-type semiconductor

5-20 Select the *incorrect* statement regarding PV energy conversion.

(*a*) The higher the wavelength, the lower the energy level of the photon.
(*b*) Only the low-wavelength spectrum of solar radiation contributes to the PV energy conversion.
(*c*) When the photon possesses more energy than the band gap energy, the excess energy is converted to heat.
(*d*) If the energy of photon is less than the band gap energy, the electron in the valence band will not jump into the conduction band.
(*e*) A single photon can move multiple valence electrons to the conduction band.

5-21 Which of the following is not a reason for actual efficiencies of solar cells being less than the maximum efficiencies?

(*a*) Recombination of electrons and holes not contributing to electric flow.
(*b*) Reflection of solar radiation from the cell surface.
(*c*) Internal electric resistance of the cell.
(*d*) Low temperature operation in winter.
(*e*) Shading of the cell due to electrical contacts.

ANALYSIS OF SOLAR CELLS

5-22 How is current density defined? What are light-induced recombination current and dark current or reverse saturation current?

5-23 What is the approximate maximum voltage a high-quality silicon solar cell can produce? Under what conditions is the power output zero? At what voltage level is the power output maximum?

5-24 A solar cell has an open circuit voltage value of 0.55 V with a reverse saturation current density of $J_o = 1.9 \times 10^{-9}$ A/m^2. For a temperature of 25°C, determine (*a*) the current output density J_s, (*b*) the load voltage at which the power output is maximum, and (*c*) the maximum power output of the cell for a unit cell area.

5-25 A solar cell has an open circuit voltage value of 0.60 V with a reverse saturation current density of $J_o = 3.9 \times 10^{-9}$ A/m^2. The temperature of the cell is 27°C, the cell voltage is 0.52 V, and the cell area is 28 m^2. If the solar irradiation is 485 W/m^2, determine the power output and the efficiency of the solar cell.

5-26 A solar cell has an open circuit voltage value of 0.60 V with a reverse saturation current density of $J_o = 4.11 \times 10^{-10}$ A/ft^2.

(*a*) For a temperature of 75°F, determine the load voltage at which the power output is maximum.
(*b*) If the solar irradiation is 220 Btu/h · ft^2, determine the efficiency of the solar cell at a load voltage of 0.56 V.
(*c*) Determine the cell area, in ft^2, for a power output of 500 W at a load voltage of 0.56 V.

5-27 Reconsider Prob. 5-26. What is the maximum conversion efficiency of this solar cell?

5-28 The competition car developed by a group of engineering students uses solar cells with a total area of 8 m^2. The solar radiation is incident on the cells at a rate of 860 W/m^2. The shaft power output from the car is measured by a dynamometer to be 540 W. What is the thermal efficiency of this solar car?

5-29 The unit for current density is

(*a*) W/m^2
(*b*) W/m^3

(*b*) W/m^3
(*c*) A/m^2
(*d*) A/m^3
(*e*) A/W

5-30 The theoretical efficiency limit for a single junction solar cell is considered to be about
(*a*) 34%
(*b*) 18%
(*c*) 50%
(*d*) 86%
(*e*) 95%

5-31 Which material is most commonly used in solar cells?
(*a*) Cadmium telluride
(*b*) Gallium arsenide
(*c*) Copper indium diselenide
(*d*) Silicon
(*e*) Cadmium sulfide

5-32 In a solar cell, the maximum power occurs at a voltage
(*a*) Equal to open circuit voltage
(*b*) Equal to zero
(*c*) Close to short circuit case
(*d*) Close to open circuit voltage
(*e*) Half of open circuit voltage

5-33 Which statement is not correct for solar cells?
(*a*) A high-quality silicon solar cell can produce an open circuit voltage of about 0.6 V.
(*b*) For the short circuit case, $J_L = J_s$.
(*c*) For the short circuit case, the voltage is zero.
(*d*) For the short circuit case, the power output is zero.
(*e*) For the open circuit voltage case, the power output is maximum.

5-34 In a solar cell, the load voltage is 0.5 V and the load current density is determined to be 80 A/m^2. If the solar irradiation is 650 W/m^2, the cell efficiency is
(*a*) 4.7%
(*b*) 6.2%
(*c*) 7.8%
(*d*) 9.1%
(*e*) 14.2%

PHOTOVOLTAIC TECHNOLOGIES AND SYSTEMS

5-35 List solar cell types and technologies. Which technologies have higher efficiencies with respect to others?

5-36 Can the Carnot efficiency be used as the upper limit for the efficiency of solar cells? Why?

5-37 What does a solar module consist of? What does a solar array consist of?

5-38 A PV system manufacturer lists the maximum power of a certain module as 273 W while the company lists the typical power as 365 W. Why is the typical power higher than the maximum power? Explain.

5-39 What is the effect of solar irradiation on the current, open circuit voltage, and maximum power?

5-40 What is the effect of cell temperature on the current, open circuit voltage, and maximum power?

5-41 Is it better to operate a solar cell in summer or in winter for the same solar irradiation? Why?

5-42 Consider a commercial solar cell with the following specifications:
Maximum power = 2.4 W
Voltage at maximum power = 0.53 V
Current at maximum power = 4.5 A
Efficiency = 20 percent
A module of these solar cells is to be constructed to provide a voltage output of 24 V and a power output of 150 W.
(*a*) How many cells should be used to satisfy the power output?
(*b*) How many cells should be arranged in series to satisfy the voltage output?
(*c*) How many rows of the cells in series should be used?
(*d*) What is the power rating of the solar module?
(*e*) If the testing of this solar cell is made for a solar radiation value of 1000 W/m^2, what is the required area of this module?

5-43 Consider a solar cell with the following specifications:
Typical power = 1.8 W

Typical power = 1.8 W
Voltage at typical power = 0.55 V
Current at maximum power = 3.3 A
Efficiency = 22 percent
A module of these solar cells is to be constructed to provide a voltage output of 8 V and a power output of 75 W.
(*a*) How many cells should be arranged in series to satisfy the voltage output?
(*b*) How many rows of the cells in series should be used?
(*c*) What is the power rating of the solar module?
(*d*) If the testing of this solar cell is made for a solar radiation value of 800 W/m^2, what is the required area of this module?

5-44 The silicon is produced in the form of an ingot as the silicon melt is cooled slowly. Grain boundaries are formed that separate the crystalline regions of the silicon ingot. Its efficiency is low due to the gaps in the grain boundaries. This type of solar cell is known as a(n) _______ solar cell.
(*a*) Amorphous
(*b*) Monocrystalline
(*c*) Polycrystalline
(*d*) Thin-film
(*e*) Multijunction

5-45 For monocrystalline fuel cells, the manufacturing cost is _______ and the efficiency is _______.
(*a*) High, low
(*b*) High, high
(*c*) Low, high
(*d*) Low, low

5-46 Two identical solar cells each with a voltage of 0.75 V and current of 4 A are connected in series. What is the voltage and current of this cell network?
(*a*) 0.75 V, 4 A
(*b*) 0.75 V, 8 A
(*c*) 1.5 V, 4 A
(*d*) 1.5 V, 8 A

5-47 Two identical solar cells each with a voltage of 0.75 V and current of 4 A are connected in parallel. What is the voltage and current of this cell network?
(*a*) 0.75 V, 4 A
(*b*) 0.75 V, 8 A
(*c*) 1.5 V, 4 A
(*d*) 1.5 V, 8 A

5-48 Two dissimilar solar cells with V_1 = 0.5 V, I_1 = 4 A and V_2 = 0.7 V, I_2 = 8 A are connected in series. What are the most likely values of the voltage and current for this cell network?
(*a*) 0.5 V, 4 A
(*b*) 0.6 V, 12 A
(*c*) 1.2 V, 12 A
(*d*) 1.2 V, 5 A
(*e*) 0.6 V, 6 A

5-49 For higher power output from a solar cell, the solar radiation should be _______ and the cell temperature should be _______.
(*a*) Higher, higher
(*b*) Higher, lower
(*c*) Lower, higher
(*d*) Lower, lower

ENERGY PRODUCTION FROM PHOTOVOLTAIC SYSTEMS

5-50 A PV array uses 50 commercial PV modules each with an area of 1.7 m^2, a typical power output of 320 W, and a solar module efficiency of 16 percent. The system efficiency may be taken as 70 percent. This PV array is installed in Las Vegas, Nevada. The average daily solar radiation on a horizontal surface in Las Vegas is given in Table 3-6, in MJ/m^2·day, as follows:

January	10.79	July	28.28
February	14.42	August	25.89
March	19.42	September	22.15
April	24.87	October	17.03
May	28.16	November	12.15
June	30.09	December	9.88

June	30.09	December	9.88
		Average	20.33 MJ/m²·day

(*a*) Estimate the amount of energy production from this solar array for each month and for the entire year in Las Vegas, in kWh.
(*b*) If the price of electricity is $0.22/kWh, what is the annual potential revenue from this PV array?
(*c*) If the initial cost of this PV system is specified as $2.5/W, what is the simple payback period?

5-51 A PV array has an area of 28 m^2 and a power capacity of 5 kW. The annual average daily solar radiation on a horizontal surface in a certain city is given as 4.95 kWh/m^2·day. The efficiency of the solar cell is 20 percent and the system efficiency may be taken as 65 percent. Estimate the amount of energy production from this PV system per year.

5-52 A PV array has an area of 15 m^2 and a power capacity of 2.4 kW. The annual average daily solar radiation on a horizontal surface in Miami, Florida is 17.38 MJ/m^2·day. The efficiency of the solar cell is 17 percent and the system efficiency may be taken as 70 percent. Estimate the amount of energy production from this PV system per year and calculate the capacity factor of this installation.

5-53 A PV array has an area of 650 ft^2 and a power capacity of 11 kW. The annual average daily solar radiation on a horizontal surface in a certain city is given as 1700 Btu/ft^2·day. The efficiency of the solar cell is 23 percent and the system efficiency may be taken as 60 percent. Estimate the amount of energy production from this PV system per year, in kWh and calculate the capacity factor of this installation.

5-54 A homeowner decides to install a PV cell system on the roof of his house to meet the electricity needs of the house. The capacity of the solar system is 6 kW and the cost of solar cells is $1.30/W. If the house owner currently pays an average of $125 for the electricity per month, determine how long it will take for the PV system to pay for itself. Assume the homeowner can meet approximately 80 percent of the electricity needs of the house with the solar system.

5-55 A PV array is installed in Hartford, Connecticut, with a power rating of 50 kW (DC, STC). The annual average solar insolation is given in Table 3-6 for Hartford as 13.74 MJ/m^2·day. Assuming a derate factor of 0.75, estimate the annual energy production using peak-hours approach.

5-56 Observations over a year period shows that a PV array installed in Las Vegas, Nevada, provided 45,000 kWh of electricity. The total power rating of the PV array is 28 kW (DC, STC). What is the overall derate factor of this PV system operation? Use the peak-hours approach.

5-57 A PV array is installed in a location with a power rating of 20 kW (DC, STC). If the annual average peak-hours or peak-sun value is 4.75 h/day and overall derate factor is 0.72, estimate the annual energy production by this PV system. What is the annual average insolation value in this location in MJ/m^2·day?

5-58 A PV array is installed in a location with a power rating of 5 kW (DC, STC). If the annual average peak-hours or peak-sun value is 3.5 h/day and overall derate factor is 0.7, estimate the annual energy production by this PV system.
(*a*) 12.3 kWh/yr
(*b*) 1230 kWh/yr
(*c*) 4470 kWh/yr
(*d*) 12,300 kWh/yr
(*e*) 36,800 kWh/yr

5-59 What is the annual average insolation value in a location with a peak-hour value of 4.3 h/day?
(*a*) 4.3 MJ/m^2·day
(*b*) 5.5 MJ/m^2·day
(*c*) 11.8 MJ/m^2·day
(*d*) 15.5 MJ/m^2·day
(*e*) 43.0 MJ/m^2·day

PHOTOVOLTAIC SYSTEM CONFIGURATIONS

5-60 What are the two general categories for the application areas of PV systems?

5-61 How do you compare water pumping powered by a PV system or a diesel generator?

5-62 List two advantages of grid-connected PV systems compared to off-grid systems.

5-63 What is the best placement of PV arrays in the northern hemisphere in terms of direction and tilt angle?

5-64 Which component is used to convert DC power to AC power in PV applications?
(*a*) Charge controller
(*b*) Battery
(*c*) Distribution panel
(*d*) PV array
(*e*) Inverter

5-65 Select the *incorrect* statement regarding the grid-connected PV systems.
(*a*) These systems include an inverter.
(*b*) They provide an effective method of peak shaving.
(*c*) They supply DC power or AC power to the grid.
(*d*) Large installations of grid-connected PV systems are mostly owned by the utilities.
(*e*) They supply power at grid voltage, phase, and frequency.

(*e*) They supply power at grid voltage, phase, and frequency.

COMPONENTS OF PHOTOVOLTAIC POWER SYSTEMS

5-66 What is a mismatch loss in a PV generator? Explain.

5-67 What is the function of an inverter in PV systems? Do the inverters deliver single-phase or three-phase AC? What are the common types of inverters?

5-68 What are the advantages and disadvantages of central inverters compared to string inverters?

5-69 What is the most common method for MPPT?

5-70 What is the function of rechargeable batteries in PV systems? Are they used in stand-alone or grid-connected PV systems?

5-71 How is energy density for a battery defined? What is its common unit?

5-72 What are the common types of batteries for PV systems? Which battery types can be used by utilities to meet demand during peak hours?

5-73 What is overcharging of a battery? What are the negative consequences of overcharging?

5-74 Give definitions for depth of discharge (DoD) and state of charge (SoC) for a battery. What is the relation between them?

5-75 What are the effects of higher values of depth of discharge (DoD) and lower values of temperature on the capacity of a battery?

5-76 List advantages and disadvantages of Li-ion batteries compared to lead-acid batteries.

5-77 A lead-acid battery is operated at 0.5C with a capacity of 144 Ah. What is the discharge current I_2 if the battery is discharged by a constant current for 2 hours at 0.5C?

5-78 Consider a lead-acid battery operating at 0.1C. If the constant discharge current is I_{10} = 20 A, what is the capacity of this battery?

5-79 Calculate the depth of discharge (DoD) and state of charge (SoC) of a battery with a nominal capacity of 180 Ah, which is discharged for 45 minutes at a constant current of 60 A.

5-80 The nominal capacity of a battery is 300 Ah and it is discharged at a constant current of 120 A. If this battery has an state of charge (SoC) value of 65 percent, what is the discharge time?

5-81 A lead-acid battery has a rated capacity of 175 Ah when operated at 0.05C and 25°C. It has a temperature behavior as shown in Fig. 5-23. How much of its rated capacity can be used when operated at 0°C?

5-82 A lead-acid battery has a rated capacity of 320 Ah when operated at 0.33C and 25°C. It has a temperature behavior as shown in Fig. 5-23. What are the usable capacities of this lead-acid battery when operated at 0.33C at a temperature of 10°C and 25°C?

5-83 A 24-volt lead-acid battery with a nominal capacity of 150 Ah and a mass of 40 kg shall be replaced by a Li-ion battery. An LFP battery cell with a nominal discharge voltage of 3.2 volts and a nominal capacity of 155 Ah, which weighs 4.2 kg, shall be used as replacement. Determine the number of LFP battery cells required for the replacement, the total mass of LFP battery, and the energy densities of both battery types.

5-84 A 12-volt lead-acid battery with a nominal capacity of 200 Ah and a mass of 25 kg shall be replaced by a Li-ion battery. An NMC battery cell with a nominal discharge voltage of 3.6 volts and a nominal capacity of 205 Ah, which weighs 3.3 kg, shall be used as replacement. Determine the number of NMC battery cells required for the replacement, the total mass of NMC battery, and the energy densities of both battery types.

5-85 Order the following components from the smaller power capacity to the larger ones:

I. Module
II. Cell
III. Array
IV. String

(*a*) I, II, III, IV
(*b*) I, II, IV, III
(*c*) II, I, III, IV
(*d*) II, I, IV, III
(*e*) IV, II, I, III

5-86 Which of the following is *not* an advantage of string inverters compared to central inverters?

(*a*) PV systems with string inverters suffer less mismatch losses.
(*b*) In case of an inverter defect, the power loss of the PV system is limited.
(*c*) String inverters enable more flexibility for design, engineering, and operation of PV systems.
(*d*) They can be either in single-phase or three-phase depending on their power classes.
(*e*) They involve lower investment cost both for the inverter itself and rest of the BOS.

5-87 The maximum power point (MPP) of a PV generator varies with which of the following:

I. Temperature
II. Irradiance
III. Mismatch losses

(*a*) I, II, and III
(*b*) I and II
(*c*) I and III
(*d*) II and III
(*e*) Only II

5-88 Which unit is commonly used to express the energy density of a battery?

(*a*) kW/kg
(*b*) Wh/kg
(*c*) kJ/kg
(*d*) kJ/m^3
(*e*) W/m^3

5-89 When a battery is charged extensively, the water inside the battery is electrolyzed so that oxygen gas and hydrogen gas are formed. This process is known as

(*a*) Undercharging
(*b*) Flooding
(*c*) Gassing
(*d*) Aging

(*d*) Aging
(*e*) Overcharging

5-90 The battery capacity _______ with higher values of depth of discharge (DoD) and _______ with lower values of temperature.
(*a*) Increases, increases
(*b*) Increases, decreases
(*c*) Decreases, increases
(*d*) Decreases, decreases

5-91 Select the *incorrect* notation regarding the capacity of a battery.
(*a*) 0.1C (C_{10})
(*b*) 0.5C (C_2)
(*c*) 0.05C (C_{20})
(*d*) 0.2C (C_5)
(*e*) None of these

5-92 The nominal capacity of lead-acid batteries is usually given at which of the following:
I. 0.05C (C_{20})
II. 0.1C (C_{10})
III. 0.2C (C_5)
(*a*) I, II, and III
(*b*) I and II
(*c*) I and III
(*d*) II and III
(*e*) Only II

5-93 Which of the following is *not* an advantage of LFP batteries compared to NMC and NMA batteries?
(*a*) Longer lifespan
(*b*) Discharging at higher C-rates
(*c*) Higher energy density
(*d*) Safer regarding explosion and fire

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*This section is contributed by Muammer Kabaçam. He is an engineer and general manager of a PV company with years of experience in PV projects.