CHAPTER 11

Photovoltaic Systems

In Chapter 7, techniques for capturing and using solar energy to provide heat for domestic hot water and for space heating of buildings were introduced. By and large, these involve relatively simple, low-cost technologies and design concepts that can greatly reduce the need for conventional fuels at little or no extra cost. Indeed, simple passive solar design ideas such as careful building orientation, overhangs, and thermal mass have been effectively utilized throughout human history.

Relatively new on the scene are "rooftop" photovoltaic (PV) systems that convert sunlight directly into electricity—the highest quality, most versatile form of energy. Because buildings use almost three-fourths of U.S. electricity, the potential to meet some of that demand with PVs is intriguing. As will be discussed in this chapter, there are enough rooftops with appropriate solar exposure for PVs to supply over one-third of today's U.S. total electricity demand. Costs are still too high to make a dent in that potential without significant subsidies, but with rapidly increasing demand, and corresponding decreases in cost, we may well be able to wean ourselves of that necessity within the next decade or so.

In the next chapter, we will explore other solar energy systems for electricity generation, including concentrating parabolic troughs, Stirling engine dish systems, and, most importantly, wind turbines. The key advantage that building-integrated PVs have over these more centralized energy systems is that the electricity produced with PVs competes against the relatively expensive retail price of electricity, which homeowners and building operators pay, rather than the much lower wholesale price that large systems have to meet to in order to sell bulk electricity into the grid.

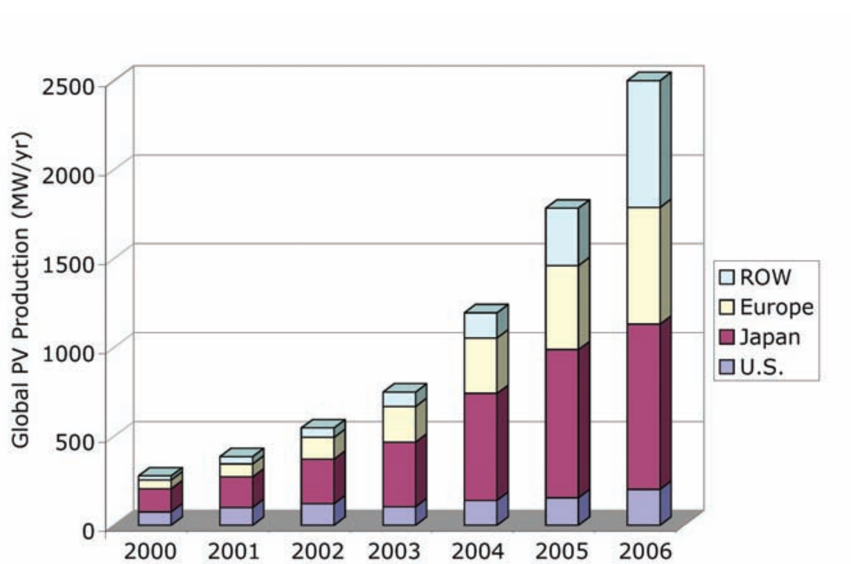
11.1 Introduction to Photovoltaics

Back in 1839, a 19-year-old French physicist, Edmund Becquerel, was able to cause a voltage to appear when he illuminated a metal electrode immersed in a weak electrolyte solution. That was the first known observation of what is now referred to as the photoelectric effect. Albert Einstein, in 1904, was the first to provide a theoretical explanation for the phenomenon, which led to his Nobel Prize in Physics in 1921. Then in 1916, in what has turned out to be a cornerstone of modern electronics in general, and PVs in particular, a Polish chemist, Jan Czochralski, developed a technique for fabricating pure single-crystal materials. His approach led to the modern-day Czochralski method for growing perfect crystals of silicon, the most commonly used PV materials today.

The first practical PV devices for power generation were developed as part of the space program in the late 1950s, for which their high cost was much less important than their low weight and high reliability. By the late 1980s, PVs began to be used in more mundane applications where utility power lines were not a cost-effective option; these uses included offshore buoys, highway lights, signs and emergency call boxes, rural water pumping, and small off-grid home systems. By the end of the twentieth century, however, as PV costs declined and efficiencies increased, it has been grid-connected, rooftop systems that have dominated sales. As shown in Figure 11.1, the global rate of production of PV modules has been growing at close to 40% per year. Japanese and European manufacturers provide half of that total, whereas the United States manufactures less than 10%. A milestone of sorts was reached in 2006 when the 2.5 GW of PV production used more tons of silicon than the entire microelectronics industry.

Annual installations of PVs in the last few years have been predominantly in three countries: Germany, Japan, and the United States, with Germany alone accounting for almost 40% of the total. Germany's aggressive Renewable Energy Law of 2000, which enables PV

figure 11.1 **Global Production of Photovoltaics**



Japanese and European manufacturers provide half of the total, whereas the United States and the rest of the world (ROW) provide the other half.

generators to sell their electricity for more than 50¢/kWh, has pushed that country to the forefront of global PV sales in spite of having only about half the annual average solar radiation of a typical site in California.

11.2 Basic Semiconductor Physics

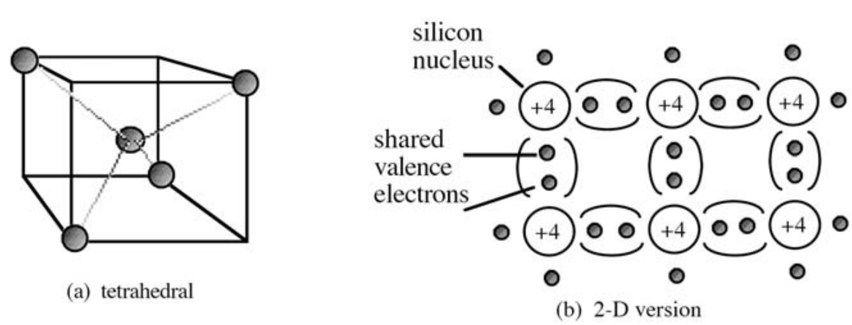
Einstein's revolutionary hypothesis that led to his Nobel Prize was that in certain circumstances light could be considered to consist of discrete particles, called photons, each carrying an amount of energy proportional to its frequency. Photons with high enough frequency can cause electrons in PV materials to break free of the atoms to which they are normally bound. If a nearby electric field is provided, those electrons can be swept toward a metallic contact where they can emerge as an electric current.

Although there are a number of promising PV materials under development, the starting point for almost all of the world's current PV devices, as well as almost all semiconductors used in electronic circuits, is pure crystalline silicon. Silicon has fourteen protons in its nucleus and fourteen orbital electrons. For all intents and purposes, the only electrons that matter are the four valence electrons in the outer orbit, so it is common practice to draw a silicon atom as if it has a +4 charge on its nucleus and four, tightly held, electrons that form covalent bonds with nearby silicon atoms as shown in Figure 11.2.

11.2.1 Hole-Electron Pairs

Crystalline silicon at absolute zero temperature would be a perfect electrical insulator. All of its electrons would be so tightly bound to their nuclei that none would be available to carry current, which means it would be useless as an electrical component. For an electron

figure 11.2



Crystalline silicon forms a three-dimensional tetrahedral structure (a), but it is easier to draw it as a two-dimensional flat array (b).

to do us some good, it must be able to contribute to current flow. To do so, it must acquire enough energy, called the *band-gap energy*, to free itself from its covalent bonds. Heating it up will free some electrons, but not very many. Exposing silicon to sunlight, however, can allow photons to provide the energy needed to free those electrons. Those photons must have at least as much energy as the band gap, which for silicon means that the wavelength of an incoming photon must be less than 1.11 microns (millionths of a meter). Solution Box 11.1 helps clarify the relationship between photon energy and wavelengths.

When a negatively charged electron leaves its nucleus, it also leaves behind a net positive charge, called a *hole*, associated with that nucleus. As suggested in Figure 11.3, if an electron from an adjacent silicon atom slides into that hole, the positive charge will appear to move. Imagine a room with every seat occupied. If someone (the electron) gets up to stretch his legs, an empty seat is created (a hole). Someone else may like that seat better and move into it, leaving her seat behind. The empty seat appears to move, just as a hole in silicon appears to move when a valence electron slips into a nearby hole. In a PV device, the trick is to get the electron to move away from the hole before the two have a chance to recombine. That is done by cleverly creating an internal electric field within the PV device that pushes holes in one direction and electrons in the other. The accumulating charge on opposite sides of the cell creates a voltage. Hook this up to a load and you have a solar-powered source of electricity.

11.2.2 The *p-n* Junction

Sunlight falling on a hunk of crystalline silicon will create hole-electron pairs; that is, negatively charged free electrons and positively charged holes. Both are capable of contributing to current flow. That's a great start to creating a device to convert sunlight into electricity. However if that is all you do, those electrons will quickly fall back into nearby holes and nothing will have been accomplished. To avoid recombination of holes and electrons, an internal electric field must be created within the device to separate the two charge carriers, sending holes toward one end of the device and electrons toward the other.

To create the needed electric field, two regions are established within the crystal. On one side of the dividing line separating the regions, pure (intrinsic) silicon is purposely contaminated with very small amounts of an element having five electrons in its outer orbit, such as phosphorus. Only about one phosphorus atom per 1000 silicon atoms is a typical amount of doping. When a pentavalent atom such as phosphorus forms covalent bonds with nearby silicon atoms, there is a leftover electron that is so loosely bound to its nucleus that it easily drifts off and becomes a free electron that can roam around the crystal. This side of the cell is referred to as being *n*-type material because there are now a fair number of free, negatively charged electrons that can move about. Meanwhile, the original +5 nucleus that the electron left behind becomes an immobile positive charge embedded in the crystal as shown in Figure 11.4(a).

On the other side of the device, about one atom of some trivalent element is added, such as boron, per 10 million atoms of silicon. When a trivalent atom forms covalent bonds in the crystal, it quickly grabs a fourth electron from a nearby silicon atom, creating an immobile negative

SOLUTION BOX 11.1

Light as Photons and Light as a Wave Phenomenon

SOLUTION

Light can be described as a continuous wave phenomenon characterized by wavelengths and frequencies, or it can be described as discrete packets of energy called photons. The relationship between the two is described by the following:

Eq. 11.1
$$E = hv = \frac{hc}{\lambda}$$

where E = the energy of a photon (J)
h = Planck's constant (6.626×10^{-34} J-s)
c = the speed of light (3×10^8 m/s)
v = the frequency (Hz)
λ = wavelength (m)

Because the energy of a photon is so low, it is often expressed in the more convenient units of electron-volts (eV), where 1 eV = 1.6×10^{-19} J. For our purposes, we can roll these various constants into a simple relationship between eV and wavelength:

Eq. 11.2
$$E\,(\text{eV}) = \frac{1.2424 \times 10^{-6}}{\lambda\,(\text{m})}$$

Notice the inverse relationship between wavelength and energy. Short wavelength radiation has more energy per photon than long wavelength radiation.

For example, find the maximum wavelength with sufficient energy to send an electron into the conduction band for silicon, which has a band gap of 1.12 eV.

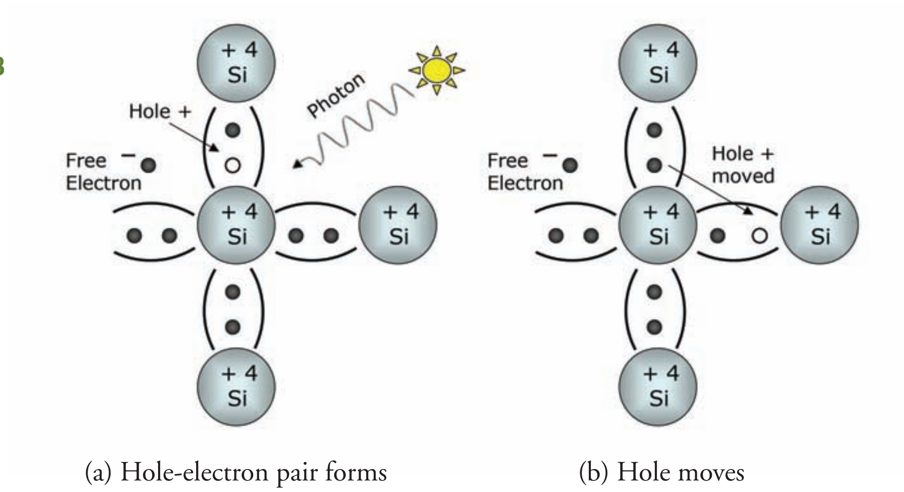
Solution:

A photon must have at least 1.12 eV to free an electron from its nucleus. In terms of wavelengths, that means the wavelength must be no more than

$$\lambda\,(\text{m}) = \frac{1.2424 \times 10^{-6}}{1.12\ \text{eV}} = 1.11 \times 10^{-6}\,\text{m} = 1.11\ \mu\text{m}$$

As we shall see soon, the band gap of a PV material and the wavelengths in the incoming solar spectrum limit the maximum theoretical efficiency of cells.

figure 11.3



(a) Hole-electron pair forms (b) Hole moves

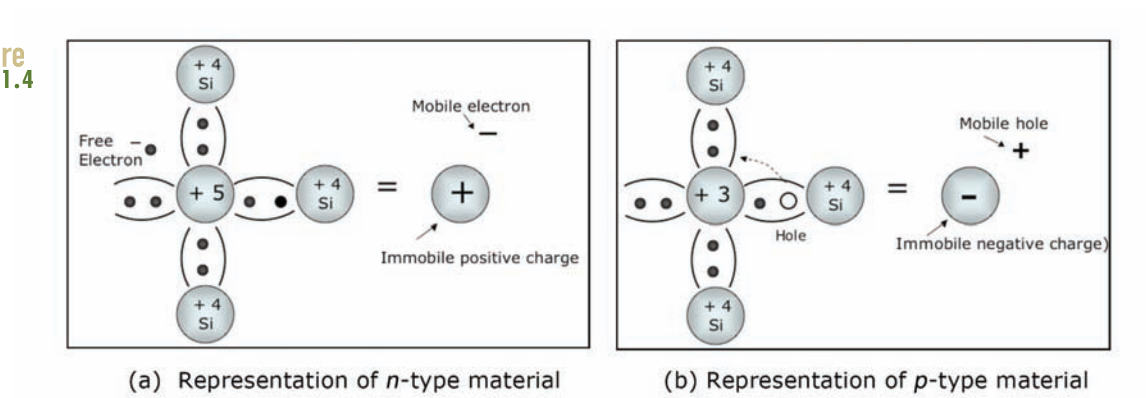
(a) A photon with sufficient energy can create a hole-electron pair. (b) A valence electron from an adjacent nucleus can slide into the hole, which gives the appearance of the positively charged hole moving. Both holes and electrons can move about in the crystal, so both can contribute to current flow.

charge in the vicinity of the +3 nucleus. Meanwhile, the silicon atom that lost an electron leaves behind a nice, movable, positively charged hole, as is suggested in Figure 11.4b. The crystal on this side of the device is called *p*-type because it has an abundance of positively charged carriers.

Both *n*-type and *p*-type materials have charged mobile carriers, which greatly increases the electrical conductivity. They're not as conductive as metals, but they are a lot more so than the original intrinsic silicon. Hence the name, *semiconductors*.

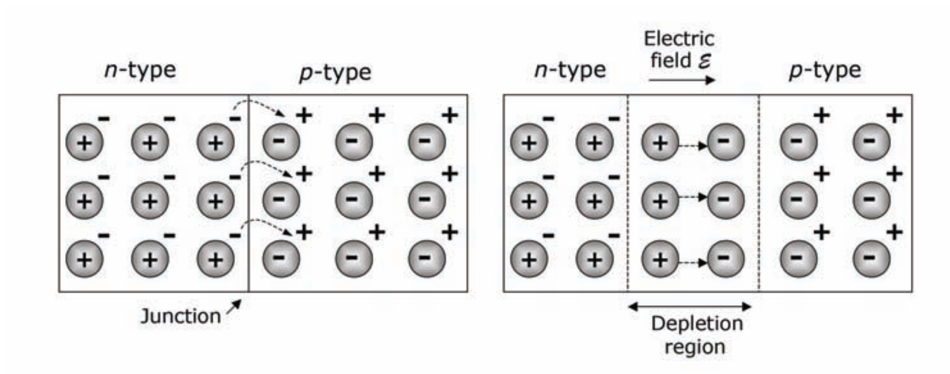
Now imagine what happens when some *n*-type material is put next to some *p*-type material, forming a *p*-*n* junction. With such a concentration of free electrons on the *n*-side

figure 11.4



An *n*-type material consists of immobile positive charges with mobile electrons whereas *p*-type materials have fixed negative charges and mobile, positively charged holes.

figure 11.5



(a) When first brought together (b) In steady-state

When *p*-type and *n*-type semiconductors are brought together (a), electrons diffuse from the *n*-region into the *p*-region filling holes and creating immobile charges on each side of the junction. The electric field created by those fixed charges opposes further diffusion, keeping holes on the *p*-side and electrons on the *n*-side (b).

of the junction, and hardly any on the other, there will be a tendency for those mobile electrons to drift over to check out the action on the *p*-side. As they cross over, those electrons leave behind immobile positive charges in the *n*-side. And, as they cross over, they will find themselves falling into holes on the *p*-side, creating immobile negative charges on that side of the junction. These immobile charged atoms in the *p*- and *n*-regions create an electric field that works against the continued movement of electrons across the junction. Almost instantaneously, the electric field reaches a level sufficient to stop any further diffusion of holes and electrons across the junction. Figure 11.5 shows the resulting stalemate.

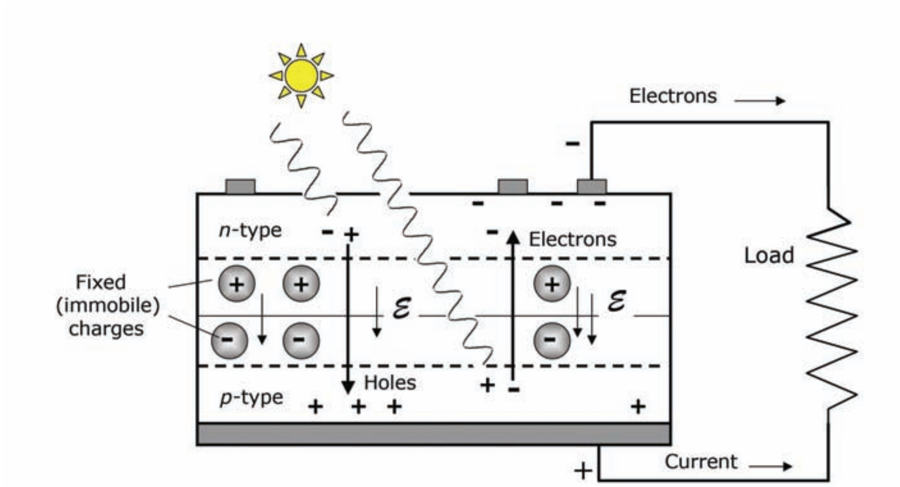
11.2.3 A Complete Solar Cell

We just about have everything we need now to understand how a PV cell works In essence, a PV cell is just a *p-n* junction that we will expose to sunlight. Photons with sufficient energy create hole-electron pairs. If those holes and electrons reach the vicinity of the depletion region, the electric field sweeps the electrons into the *n*-region and the holes into the *p*-region. This creates a voltage across the cell. When a load is connected to the cell, electrons will flow from the *n*-region through the load and return to the *p*-region. Power is delivered to the load as long as the sun shines on the cell. Figure 11.6 summarizes the whole thing.

11.3 Photovoltaic Efficiency

Now that we have a sense of how PVs work, we can begin to address a key question in terms of their performance. That is, what fraction of the sunlight hitting a PV will be collected and

figure 11.6



When photons create hole-electron pairs near the junction, the electric field in the depletion region sweeps holes into the *p*-side and electrons into the *n*-side of the cell. As shown, electron flow is clockwise through the load; conventional current is in the other direction.

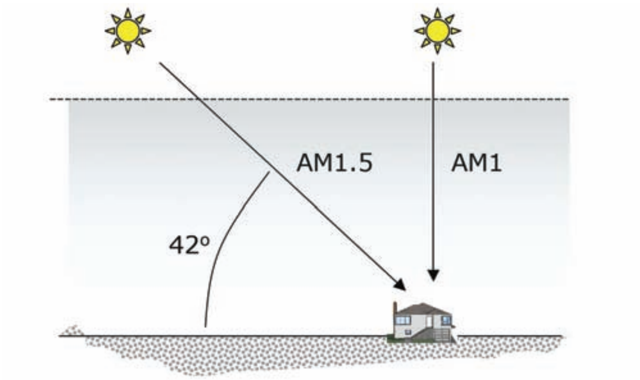
transformed into electrical power? The efficiency of a PV device depends on a number of factors, including the following:

1. The band-gap constraint, which has to do with some photons not having enough energy to create hole-electron pairs, whereas others have more energy than is needed to do so.
2. Photons that are not absorbed by the cell either because they are reflected off the face of the cell, or because they pass right through the cell, or because they are blocked by the metal conductors that collect current from the top of the cell.
3. Recombination of holes and electrons before they can be separated by the junction's electric field.
4. Internal resistance within the cell, which dissipates power.
5. Environmental effects such as temperature (which lowers efficiency) and the spectral distribution of sunlight striking the device, which varies depending on sun angles and sky clarity.

11.3.1 The Solar Spectrum

As was described in Chapter 4, the surface of the sun emits radiant energy with spectral characteristics that closely match that of a 5800 K blackbody. Some of those photons are absorbed by various constituents in the Earth's atmosphere so that by the time sunlight reaches the Earth's surface its spectrum is significantly distorted. The amount of sunlight reaching the Earth and its spectral characteristics depend on the *air mass ratio*, which is a measure of the amount of air the rays have to pass through before reaching the Earth's surface. With the

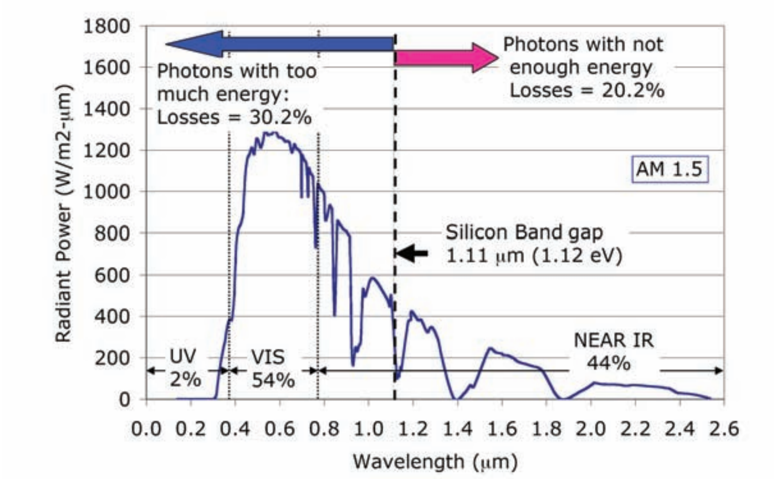
figure 11.7



PV performance measures usually assume sunlight passes through 1.5 times as much air before it reaches the Earth's surface (designated as AM1.5) as it would if the sun were directly overhead (AM1). AM1.5 is equivalent to the sun being about 42 degrees above the horizon.

sun directly overhead, the air mass ratio is defined to be 1, which is designated as AM1. It is standard practice to evaluate PV performance under AM1.5 conditions; that is, with the sun passing through an amount of air equivalent to 1.5 times as much as when the sun is directly overhead (Figure 11.7). Sunlight passing through clear AM1.5 skies has the spectral distribution shown in Figure 11.8.

figure 11.8 **The Clear-Sky Solar Spectrum at AM1.5**



For silicon, over half of the incoming solar energy is wasted because photons either don't have enough energy or they have more than is needed to create hole-electron pairs.

SOURCE: based on ERDA/NASA, 1977

11.3.2 Band Gap Impact on Photovoltaic Efficiency

Some photons coming from the sun don't have sufficient energy to cause an electron to jump into the conduction band, which means they don't contribute to the generation of electricity. Others have more energy than is needed, and because one photon can create only one hole-electron pair, any excess energy those photons carry above the band-gap energy is also wasted. How well a PV will work, therefore, depends on the wavelengths of the energy arriving from the sun as well as the band gap of the cells.

For silicon, the band gap is 1.12 electron-volts (eV), corresponding to a wavelength of 1.11 μm (see Solution Box 11.1 for the relationship between eV and wavelength). As shown in Figure 11.8, at AM1.5 about 20.2% of the available solar energy has wavelengths above 1.11 μm so those are not absorbed and cannot create hole-electron pairs. They simply pass right through the silicon. Wavelengths shorter than that are absorbed, but they have excess energy that simply heats the crystal and wastes another 30.2% of the sun's energy. Between the two, more than half of the sun's energy doesn't get turned into electricity.

Even this simple analysis can provide some insights into the importance of the band gap for various potential PV materials. Think of band gap as an indicator of the voltage that a cell will produce, and the number of hole-electron pairs created as current that will be delivered. And remember that power is the product of voltage and current. A high band gap material will deliver more voltage but less current than one with a lower band gap. And the other way around: lower band gap means lower voltage but higher current. So clearly there is a trade-off when it comes to power delivered, which is after all what we are after.

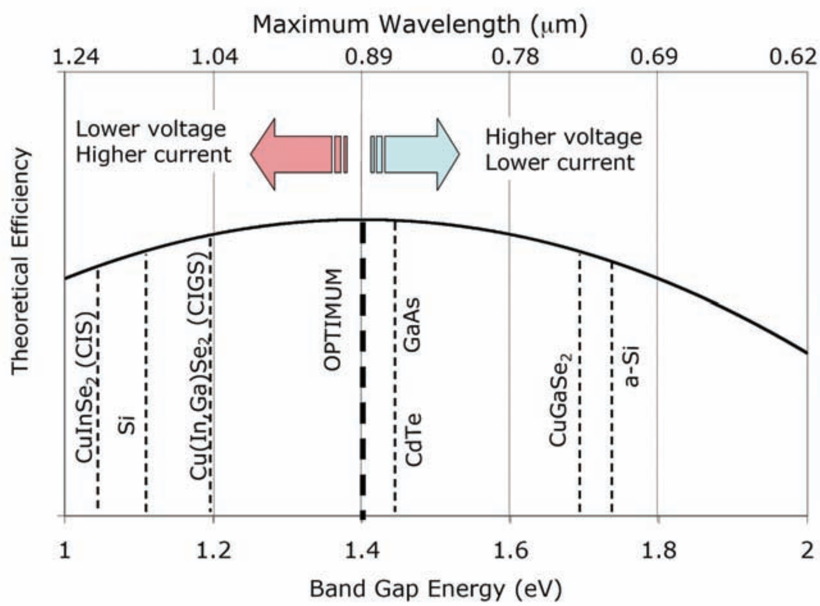
As Figure 11.9 indicates, there is an optimum band gap of about 1.4 eV (which means the maximum wavelength to create current is 0.89 μm). Also shown in the figure are various promising materials for PVs, including conventional silicon; a non-crystalline amorphous silicon (a-Si); cadmium telluride (CdTe); gallium arsenide (GaAs); copper gallium diselenide ($CuGaSe_2$); copper indium diselenide, or CIS cells, ($CuInSe_2$); and CIS cells with added gallium, $Cu(In,Ga)Se_2$, known as CIGS cells. Notice how the addition of gallium to CIS cells shifts the band gap a little closer toward the optimum.

11.3.3 Single-Junction PV Efficiency under Laboratory Conditions

A careful thermodynamic analysis of the maximum possible PV efficiency for single band gap materials under unconcentrated solar irradiance yields an upper limit of about 31% (Shockley and Queisser, 1961). Under laboratory conditions with cells not yet built into PV modules, the best solar cells now have efficiencies of about 25%.

Figure 11.10 shows an example of a single-crystal silicon PV that has been designed to maximize efficiency. Several features are worth commenting on. Notice there are no wire contacts on the front surface, which avoids the blockage of sunlight that those surface conductors normally cause. Instead, the contacts, both positive and negative, are positioned on the underside of the device. Also note the top surface is textured in such a way as to help any reflected sunlight to bounce down into the cell rather than away from it. Finally, a reflective surface on the underside

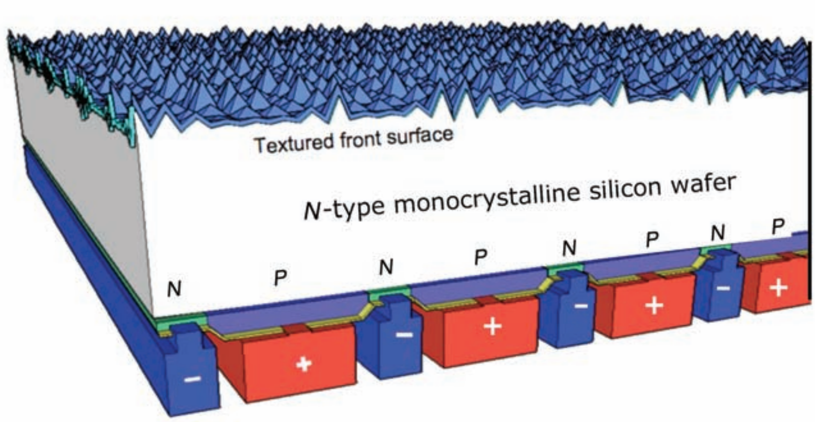
figure 11.9



Increasing the band gap increases cell voltage but reduces current, and vice versa. The product of voltage and current is power, which means there is an optimum band gap at which maximum power will be produced.

of the cell helps bounce photons back into the cell that otherwise might pass completely through the photovoltaic. This reflective feature allows the cell thickness to be reduced as well. With less silicon in each cell, the embodied energy needed to produce them is also reduced.

figure 11.10



Putting the electrical contacts on the underside of the cell and texturing the surface to bounce reflected sunlight into the cell, helps boost efficiency of this device to over 20%.

Source: courtesy of SunPower Corp.

11.3.4 Multijunction (Tandem) Cells to Increase Efficiency

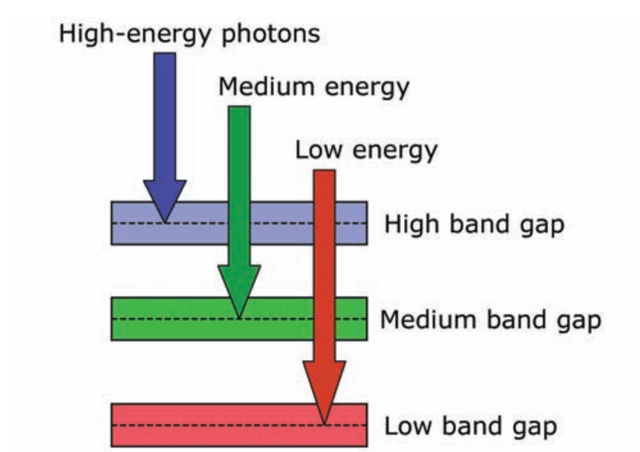
By carefully manipulating various alloys in some types of solar cells, the band gap can be adjusted to increase the cells' ability to capture different portions of the incoming solar spectrum. For example, the band gap of CIGS cells can be tuned to anything from about 1.04 eV to 1.68 eV. This suggests that perhaps a clever way to significantly increase PV efficiencies is to fabricate them with multiple *p-n* junctions, one on top of the other, with each tweaked to capture different wavelengths of solar energy. These multijunction, or tandem, cells are very promising. In fact, with an infinite combination of band gaps in a solar cell, the theoretical efficiency could be as high as 66%.

In multijunction cells, the uppermost junction is designed to have a high band gap so it will capture short-wavelength photons. Longer-wavelength photons are not absorbed so they pass right through to the next level. Subsequent junctions capture photons with longer and longer wavelengths (Figure 11.11).

11.4 Photovoltaic Fabrication

There are a number of different ways to fabricate PVs. One way to characterize these technologies is by the thickness of the cells. Relatively speaking, crystalline silicon cells tend to be very thick—on the order of 150–250 μm (micrometers), which is a bit thicker than a human hair. Most of today's commercially available PVs are these thick, crystalline silicon cells. An alternative approach to PV fabrication is based on thin films of semiconductor material, where "thin"

figure 11.11 An Example of a Triple-Junction (Tandem) Cell



Higher-energy photons (shorter wavelengths) are captured in the upper junction. Longer wavelength photons may be captured in subsequent junctions.

means something like 1–10 μm. Thin-film cells require much less semiconductor material and they are potentially easier to manufacture, so they offer the tantalizing promise of eventually being cheaper than crystalline silicon.

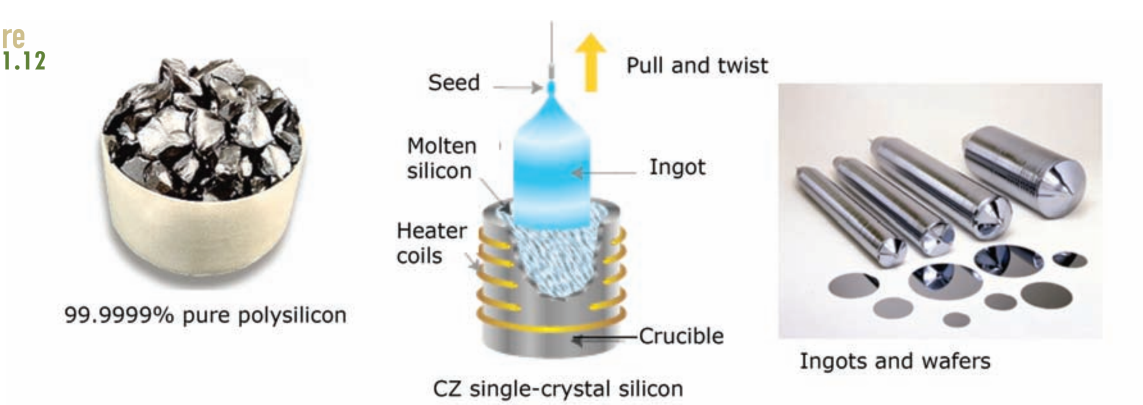
11.4.1 Crystalline Silicon Cells (*x*-Si)

Most solar cells are made of silicon, which is the second most abundant element in the Earth's crust. In its natural state it is usually in the form of silicon dioxide (SiO_2), or silica. That SiO_2 is first purified into a 99.9999% pure polysilicon form, which looks like the shiny rock-like material shown in Figure 11.12a.

The most commonly used technique for forming single-crystal silicon is based on the *Czochralski* (pronounced check-ralski), or CZ, method in which a small seed of solid, crystalline silicon about the size of a pencil is dipped into a molten vat of polysilicon. A tiny amount of *n*- or *p*-type material is added to the vat to dope the silicon one way or the other. As the seed crystal is slowly withdrawn from the vat, molten silicon atoms bond with atoms in the crystal and then solidify (freeze) in place. The result is a large cylindrical ingot of single-crystal silicon perhaps a meter or so long and 15 to 20 cm in diameter. As shown in Figure 11.9, the ingot is then sliced into wafers, the top layer of which is then doped in the other direction to create the necessary *p-n* junction.

Other, less expensive, approaches to manufacture crystalline silicon solar cells are providing tough competition for the CZ method. Single-crystal silicon can also be grown as a long, continuous ribbon from a silicon melt. Molten silicon can also be poured into a mold and allowed to solidify into a massive rectangular block that can be sliced into silicon wafers. The resulting wafers turn out to have a less well organized multicrystalline structure made up of regions of single-crystal silicon separated by grain boundaries. They are easy to

figure 11.12



The CZ method for growing single-crystal silicon begins with polysilicon, which is melted in a heated crucible. A seed crystal drawn from the crucible forms an ingot, which is then sliced into wafers.

recognize when looking at multicrystalline PVs because light reflects slightly differently from each single-crystal region of the cell.

11.4.2 Thin-Film, Organic, and Nano-Solar Technologies

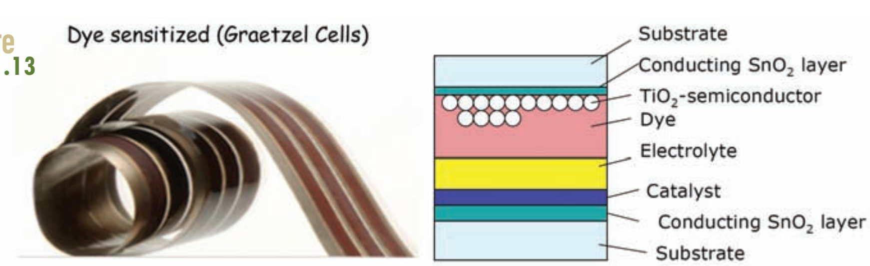
Although crystal-silicon cells dominate the current PV marketplace, a number of thin film technologies are beginning to receive considerable research and development funding and might one day shift the balance. At present these technologies tend to be less efficient, which means larger areas and area-related costs, but they hold the promise of ultimately being cheaper per watt generated.

Examples of thin-film cells and their maximum laboratory efficiencies as of 2006 include those made from amorphous silicon (a-Si, 13.1%), cadmium telluride (CdTe, 16.7%), and copper-indium-gallium diselinide (CIGS, 19.3%). Many of these thin-film technologies have their *n*-layers made from different materials than their *p*-layers and are thus referred to as *heterojunction* cells (as opposed to silicon *homojunction* cells). CIGS cells, for example, may have an *n*-layer made of cadmium and zinc sulfide (CdZn)S and their *p*-layer of copper-indium-gallium diselenide, $Cu(In,Ga)Se_2$.

Some of these emerging PV technologies offer the tantalizing promise of very low cost roll-to-roll production methods, similar to the way newspapers are printed and photographic films are manufactured. In one process, CIGS semiconductors are vacuum coated onto a film; another process applies CIGS materials using an ink printing method.

New organic and nano cells are being developed that could be printed or sprayed as an ultra-thin layer of semiconductor onto a roll of plastic. One of the most promising of these new devices is known as the Dye-Sensitized Solar Cell (DSSC), or Graetzel cell, after its Swiss inventor Michael Graetzel (Figure 11.13). The Graetzel cell uses an organic dye injected into nanocrystalline titanium-dioxide (TiO_2), a white pigment commonly used in sunscreen, toothpaste, and paint. The dyes absorb sunlight and create pairs of charged hole-electron pairs using a principle similar to photosynthesis. These photoreactive materials

figure 11.13



Organic and nano PVs can be printed onto flexible plastic rolls. Cross section is for a dye-sensitized, or Graetzel, solar cell.

Source: from Konarka Web site

can be printed onto flexible plastic materials using a continuous roll-to-roll manufacturing process similar to the way newspapers are printed. Different colors of dye can be used to absorb different wavelengths of light allowing a range of colored, semitransparent flexible films to be incorporated into windows, roofing materials, and a variety of portable electronic devices. They can even be invisible when tuned to collect just the near-infrared portion of the spectrum. Someday, the tent you take backpacking may generate its own electricity.

11.5 From Laboratory Cells to Commercial Modules

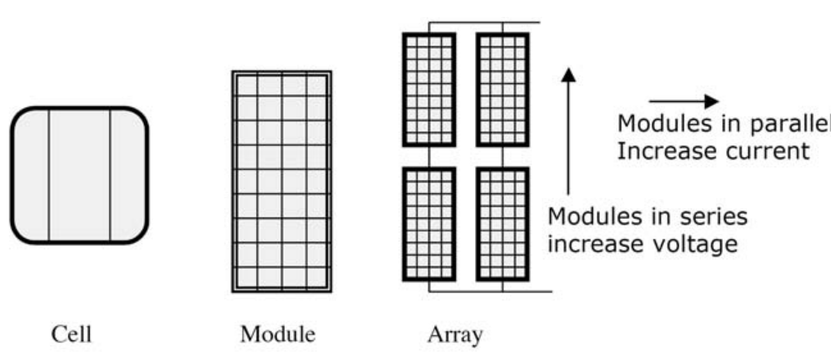
Because individual solar cells produce only about 0.5 V, it is a rare application for which just a single cell is of much use. Instead, the basic building block for PV applications is a *module* consisting of a number of preconnected cells in series, all encased in tough, weather-resistant packages. Multiple modules, in turn, can be wired together in series to increase voltages even more and in parallel to increase current. Recall power is the product of voltage and current. A simple figure illustrating the cell-to-module-to-array concept is shown in Figure 11.14.

As Figure 11.15 indicates, the overall efficiency of actual commercially available modules is never quite as good as the best cells being developed in laboratories. Some of that difference is related to packaging and some is just the difference between something someone can build in the lab versus a commercial product that can be warranted to perform as advertised for twenty years or more in the field.

11.6 Grid-Connected Photovoltaic Systems

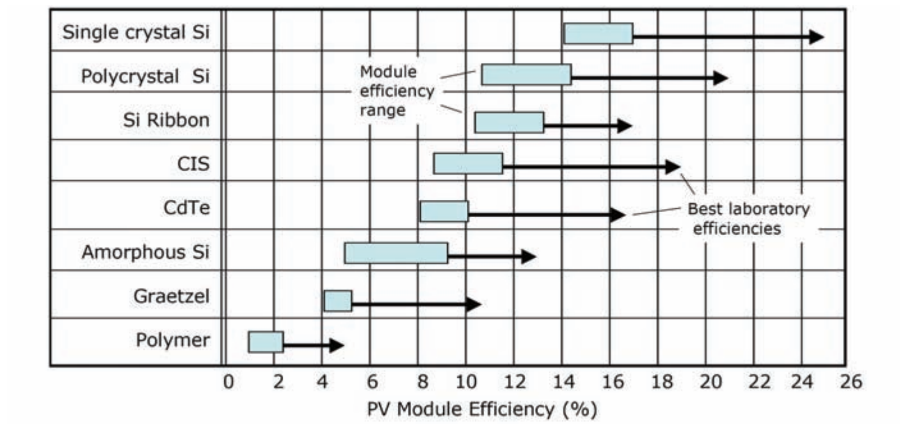
Whereas much of the early attention was directed toward remote, off-grid systems, the vast majority of current and future PV sales are projected to be for residential and commercial

figure 11.14 **Photovoltaic Cells, Modules, and an Array**



Modules can be connected in series to increase voltage and in parallel to increase current, the product of which is power.

figure 11.15 **Efficiencies of Various Photovoltaic Technologies**



The rectangles show the range of large-module efficiencies. The arrows indicate laboratory cells.

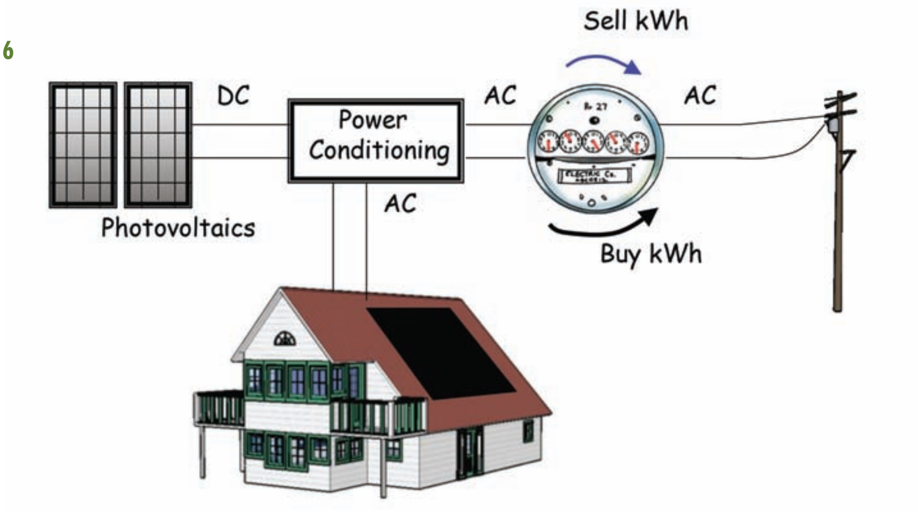
rooftop systems connected to the local utility grid. The primary advantage to being able to hook up to the grid is the ability to use it as your energy storage system. As suggested in Figure 11.16, a grid-connected system offers the opportunity to sell to the local utility any excess electricity your PVs might generate during the day, running your meter in one direction, and then buying electricity back from the grid at night or at other times when your load exceeds your solar supply, running your meter in the other direction. With time-of-use (TOU) rates, it is even possible to sell your electricity for a higher price during those hot, clear summer days when it is more valuable, and then buy it back at night at a cheaper rate (see, for example, Section 10.5.2). Most states now allow net metering, but with the usual proviso that at the end of the year, when the books are tallied, you cannot sell more kWh to the utility than you purchased back again, and you cannot make a net dollar profit on your sales either.

The power conditioning unit (PCU) shown in Figure 11.16 serves several purposes. Because PVs generate direct-current (dc) power and your house needs ac, the main function of the PCU is to convert dc into ac using an electronic device called an *inverter*. The PCU also will include a *maximum power point tracker* (MPPT), which helps optimize the electrical output of the PVs, a set of protective circuit breakers and fuses, and circuitry to disconnect the PV system from the grid if the utility loses power. The latter serves an extremely important safety function by ensuring that your PVs don't inadvertently send power to the grid during a power outage when utility workers may be working on the lines. Grid-connected PV systems can be designed with some battery storage to cover those power outages, but most customers elect not to include that added level of system complexity.

11.6.1 Various DC and AC Power Ratings

PV modules are rated under standard laboratory test conditions (STC) that include a solar irradiance of 1 kW/m^2 (called "1-sun"), a cell temperature of 25°C, and an air mass ratio

figure 11.16



Grid-connected systems allow you to spin your electric meter backward when your PVs generate more power than you need, in essence using the grid for energy storage.

of 1.5 (AM1.5). Under laboratory conditions, module outputs are thus often referred to as "watts (STC)" or "peak-watts." Up on your rooftop, modules are subject to very different conditions and their outputs will vary significantly from the STC rated power that the manufacturer specifies. You don't always have 1-sun of insolation, modules get dirty, and most importantly, modules are very temperature sensitive, with most losing about 0.5% of their power for each degree Celsius of increased cell temperature. Because cells are typically 20°–30°C hotter than the surrounding air, unless it is very cold outside, or it is not a very sunny day, they will usually be much hotter than the 25°C at which they are rated.

Based on extensive data collected in the field under a program called PVUSA, another rating system has emerged that attempts to more accurately specify dc output of PV modules. The PVUSA rating system is based on exposure to 0.8 kW/m^2 of solar irradiation, an ambient temperature of 20°C, and a wind speed of 1 m/s. Module dc output under these PVUSA test conditions is referred to as DC,PTC. When the DC,PTC power is multiplied by the efficiency of the dc-to-ac inverter, the result is an ac power rating based on PVUSA conditions referred to as AC,PTC. In some states, financial incentives are based somewhat on these PVUSA assumptions.

Finally, when all system losses are lumped together, including temperature effects, dirt, electrical mismatch of modules, and dc-to-ac inverter inefficiencies, the actual ac power delivered at 1-sun, call it P_{AC}, can be represented as the following product:

Eq. 11.3
$$P_{AC} = P_{DC,STC} \times (\text{de-rating factor})$$

where $P_{DC,STC}$ = the dc power of the array under standard test conditions

The de-rating factor is based on the sum of all of the system losses just mentioned.

SIDEBAR

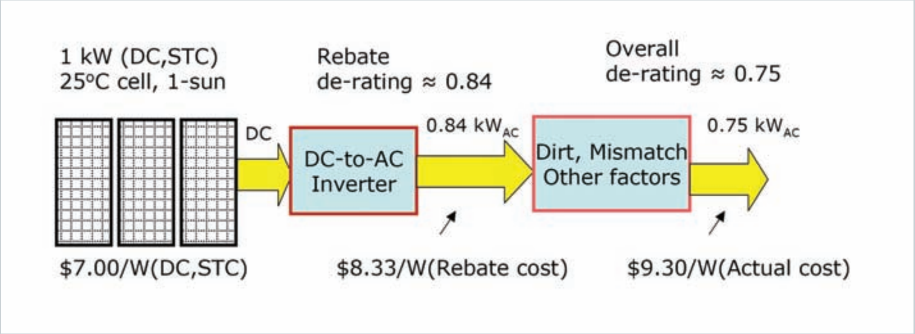
SIDEBAR 11.1

How Many Watts Do You Have?

The need to be quite clear about whether a system is specified in terms of its dc rated power, its actual ac output, or its output under some government- or utility-defined rebate program is absolutely essential, and is unfortunately, all too often overlooked. For example, system costs and rebates are often stated in \$/W terms. But are those DC,STC watts, expected ac watts for real systems, or ac watts defined by the rebate program?

Figure 11.17 shows three ways of quoting the cost of a 1 kW (DC,STC) system with an installed cost of \$7000, which is roughly the 2006 average cost of PV systems in California before rebates and tax credits (Wiser, 2006). For systems defined under California's rebate programs, the de-rating factor is based on the buyer's choice of modules and inverter and is typically about 0.84. In actual field conditions, however, including dirt, mismatch, and other factors, a more likely de-rating factor to predict actual performance is about 0.75. As shown, this system could be described as costing \$7/W, \$8.33/W, or \$9.20/W depending on the definition of what kind of watts are being quoted.

figure 11.17



Three different power outputs for a PV system with representative values based on 1 kW dc at standard test conditions. Also shown are corresponding ways to express the \$/watt cost of system having a pre-rebate cost of \$7/watt (DC,STC).

A typical PV system de-rating factor system is about 75%, which means an array typically delivers only about three-fourths of the manufacturer's DC,STC rated power. Sidebar 11.1 points out the importance of keeping clear the distinction between various dc and ac power ratings.

11.6.2 Annual Insolation is What Matters for Grid-Connected Photovoltaics

Predicting PV performance is a matter of combining the dc (STC) rated power of the array, an estimate of the overall de-rating factor, and the local insolation at the site. The National

Renewable Energy Labs has produced a wonderful publication called the *Solar Radiation Data Manual for Flat-Plate and Concentrating Collectors,* which provides solar insolation data for a number of cities across the United States. The full report can be downloaded from the Internet at http://rredc.nrel.gov/solar/pubs/redbook/.

For illustrative purposes, Table 11.1 provides some of NREL's insolation data. For fixed-orientation south-facing collectors, the tilt angles are designated as L +15°, L, and L –15°, where L is your local latitude. The table also includes data for the following tracking arrays: single-axis, north-south oriented, horizontal trackers; single-axis trackers for arrays with fixed tilt equal to the local latitude (called a polar axis since the axis points toward the north star *polaris*); and double-axis trackers that always face directly into the sun. The improvement of single-axis trackers over the best, fixed arrays is significant—often more than 30% better. It is interesting to note, however, that two-axis trackers, which always point the PVs directly into the sun, are not much better than single-axis trackers with tilt equal to the local latitude.

Sample monthly insolation data for Boulder, Colorado, for various fixed collector orientations, are plotted in Figure 11.18. If we were designing a stand-alone system with battery storage, those month-to-month variations would be very important and we would probably pick a collector tilt angle that provides relatively uniform insolation throughout the year. A tilt equal to your local latitude plus about 15° would be pretty ideal for that application because it evens out monthly variations, which reduces the amount of battery storage required.

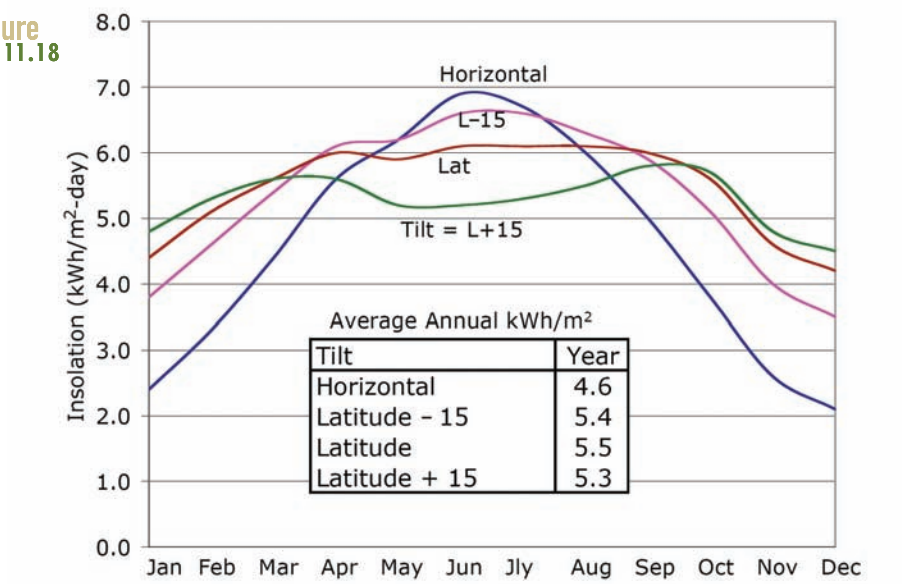
For grid-connected systems, however, it is the average annual insolation that matters the most. If you generate more than you need in the summer, you just sell the excess to the utility and buy it back again in the winter. In fact, designing your system to emphasize generation in the summer can be a good economic strategy because that is when grid electricity prices are usually the highest.

table 11.1 **Annual Average Insolation in kWh/m²-day for South-Facing Surfaces and Various Tracking Collectors**

Tilt Angle	Tucson, AZ	Los Angeles, CA	Sacramento, CA	San Francisco, CA	Boulder, CO	Miami, FL	Atlanta, GA	Honolulu, HI	Chicago, IL	Boston, MA	Minneapolis, MN	Raleigh, NC	Albuquerque, NM	Cleveland, OH	Medford, OR	Austin, TX	Roanoke, VA	Seattle, WA
Horizontal	5.7	4.9	4.9	4.7	4.6	4.8	4.6	5.4	3.9	3.9	3.9	4.4	5.6	3.8	4.4	4.9	4.2	3.3
L - 15	6.3	5.5	5.5	5.3	5.4	5.1	5.0	5.5	4.4	4.5	4.6	4.9	6.3	4.2	4.9	5.2	4.8	3.8
Lat	6.5	5.6	5.5	5.4	5.5	5.2	5.1	5.7	4.4	4.6	4.6	5.0	6.4	4.1	4.9	5.3	4.8	3.7
L + 15	6.3	5.4	5.2	5.1	5.3	5.1	4.9	5.5	4.1	4.4	4.4	4.8	6.2	3.9	4.5	5.1	4.6	3.5
90	3.9	3.5	3.4	3.4	3.8	3.0	3.1	2.9	3.0	3.2	3.3	3.2	4.1	2.7	3.1	3.1	3.2	2.6
1-Axis (Horiz) N,S	8.1	6.4	6.8	6.3	6.4	6.2	6.0	7.2	5.1	5.2	5.3	5.7	7.8	4.8	6.0	6.4	5.6	4.3
1-Axis (Latitude)	8.7	7.0	7.4	6.9	7.2	6.5	6.4	7.4	5.5	5.7	6.0	6.2	8.5	5.1	6.5	6.7	6.1	4.7
2-Axis	9.0	7.2	7.6	7.1	7.4	6.7	6.6	7.7	5.7	5.9	6.2	6.4	8.8	5.3	6.7	7.0	6.3	4.9

Source: data from NREL, 1994

figure 11.18



Monthly and annual average insolation for Denver for various south-facing collector tilt angles. On an annual basis, insolation varies only a few percent for a wide range of tilt angles.

Source: based on NREL, 1994

As shown in Figure 11.18, for quite a range of south-facing collector tilt angles—all the way from an L –15° to an L +15° tilt—the Denver total average daily insolation hardly changes at all (5.3-to-5.5 kWh/m^2-day). Indeed, even a collector lying flat on a horizontal roof loses only about 16% compared to the ideal tilt angle (tilt = latitude). Although these conclusions were noted for Denver, they are reasonably true for most locations in the United States.

11.6.3 The "Peak-Hours" Approach to Sizing a Grid-Connected PV System

Because the grid provides the backup source of electricity, how large a PV system you choose is mostly a matter of how much you can afford and the available area of appropriately oriented roof having good solar exposure.

The "peak-hours" approach makes a very simple, and reasonable translation between average daily insolation expressed in kWh/m^2-day and the number of equivalent hours of full sun. Because 1-sun of insolation is defined as 1 kW-m^2, we can think of an insolation of say 5.4 kWh/m^2-day as being the same as 5.4 hours per day of 1 kW/m^2 sun, or 5.4 hours of "peak sun." So, we can write

Eq. 11.4 $$\textbf{Energy (kWh/yr)} = P_{AC}\textbf{(kW)} \times \textbf{(hr/day of 1-sun)} \times \textbf{365 day/yr}$$

where P_{AC} = the ac power produced by the array when exposed to 1-sun of insolation

SOLUTION BOX 11.2

Sizing a PV Array for San Francisco

How many kW (DC,STC) would be needed to deliver 3600 kWh/yr (300 kWh/mo) to a home in San Francisco? Assume south-facing collectors tipped up at an L –15° angle (23° for San Francisco at latitude 38°) and use a de-rating factor of 0.75. At 17% efficiency, how big would the PV array be?

Solution:

Table 11.1 indicates an L –15° tilt exposes the array to 5.3 kWh/m²-day of insolation (5.3 hours of 1-sun). Equation 11.5 suggests we will need

$$P_{DC,STC}\,(\text{kW}) = \frac{3600\ \text{kWh/yr}}{0.75 \times 5.3\ \text{hr/day} \times 365\ \text{day/yr}} = 2.48\ \text{kW}$$

Using Equation 11.6 with 17% collector efficiency, we can find the area needed for this array:

$$A\,(\text{m}^2) = \frac{P_{DC,STC}\,(\text{kW})}{1\ \text{kW/m}^2 \cdot \eta} = \frac{2.48}{0.17} = 14.6\ \text{m}^2\ (157\ \text{ft}^2)$$

SOLUTION

Modules are rated according to their dc output under standard test conditions (DC,STC), so we can insert Equation 11.3 into Equation 11.4 and get the following simple sizing equation:

Eq. 11.5 $$\text{Energy (kWh/yr)} = P_{DC,STC}(\text{kW}) \times (\text{de-rating}) \times (\text{hr/day of 1-sun}) \times 365\ \text{day/yr}$$

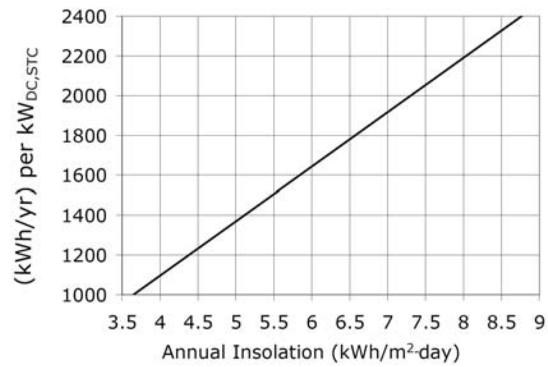
We would also like to know how big an array must be to deliver the energy found in Equation 11.5. To do that, we need to know the PV efficiency under standard test conditions, η, which is easy to obtain from manufacturer specifications. The area required can then be calculated as follows:

Eq. 11.6 $$P_{DC,STC}(\text{kW}) = 1\ \text{kW/m}^2\ \text{insolation} \times A\ (\text{m}^2) \times \eta$$

The area, A, found in Equation 11.6 is in square meters. The conversion to square feet is 1 m² = 10.76 ft². Solution Box 11.2 illustrates the use of these sizing relationships.

One simple way to make quick estimates of annual energy production from a PV array as a function of the average insolation at the site is to use the sizing estimator provided in Figure 11.19. For example, a good site with 6 kWh/m²-day of insolation can provide about 1600 kWh/yr of delivered ac electricity per kilowatt of rated DC,STC power.

figure 11.19



Simple sizing estimator from annual insolation to energy generated (kWh/yr) per kW of DC,STC rated power. Assumes a de-rating factor of 0.75.

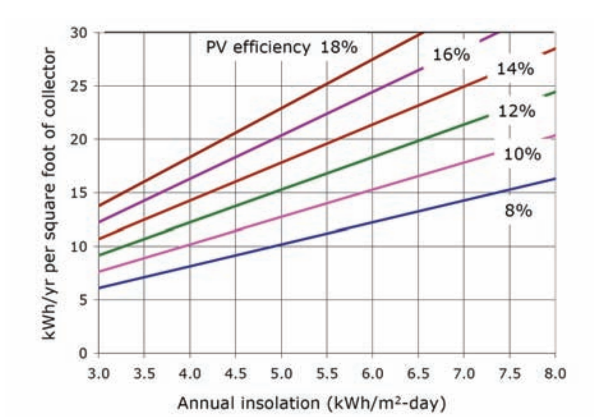
Using PV efficiency and local insolation as parameters, we can use the graph shown in Figure 11.20 to help estimate array area requirements. For example, with 14%-efficient collectors in a site with 5.5 hours of full sun, one square foot of collector could deliver about 20 kWh/yr of ac electricity.

Solution Box 11.3 provides an intriguing estimate that suggests the total potential for rooftop PV systems is sufficient to supply over one-third of all of U.S. electricity demand.

11.7 Economics of Photovoltaics

The manufacturer's price of PV modules has followed a fairly steady and consistent decrease over time. As shown in Figure 11.21, when plotted on a log-log scale versus cumulative production, a nearly straight line results. Projecting that line into the future suggests that

figure 11.20



Annual energy production from a PV array per square foot of collector using efficiency as a parameter. Assumes a de-rating factor of 0.75.

SOLUTION BOX 11.3

The Total Potential for Rooftop PV in the United States

A study of the roof area in the United States potentially available for PVs estimates 3.5 billion square meters of residential rooftop area and 2.9 billion square meters of commercial roof area (Chaudhari, 2004). These estimates account for roof orientation, shading, and structural issues. Assuming 17%-efficient collectors, an average annual solar exposure of 5 kWh/m^2-day, and a de-rating factor of 0.75, find the annual energy that could be delivered if that entire available space is utilized.

Solution:

The total area of 6.4 billion square meters would allow an installed capacity of

$$P_{DC,STC} = 6.4 \times 10^9 \text{ m}^2 \times 1 \text{ kW/m}^2 \times 0.17 = 1088 \times 10^6 \text{ kW}$$

With 5 kWh/m^2-day of insolation (equivalent to 5 hrs of 1 kW/m^2 sun), and using the 0.75 de-rating factor, the energy that could be delivered would be

$$\text{Annual energy} = 1088 \times 10^6 \text{ kW} \times 0.75 \times 5 \text{ hr/day} \times 365 \text{ day/yr} = 1490 \text{ billion kWh/yr}$$

The total net output of all U.S. power plants in 2005 was 4340 billion kWh, so PVs could supply just over one-third of the entire demand. In fact, if we include transmission losses from traditional power plants to end users, which are avoided by on-site generation, this full build-out of PVs would be sufficient to supply half of the total electricity demand of all U.S. buildings.

SOLUTION

when cumulative production reaches about 100,000 MW, modules might cost as little as \$1/Watt (dc). At that price, subsidies would not be necessary. Integrating the subsidy using the projected experience curve shown leads to a conclusion that the total subsidy needed before PV systems would be cost-effective is on the order of \$25 billion (Swanson, 2004).

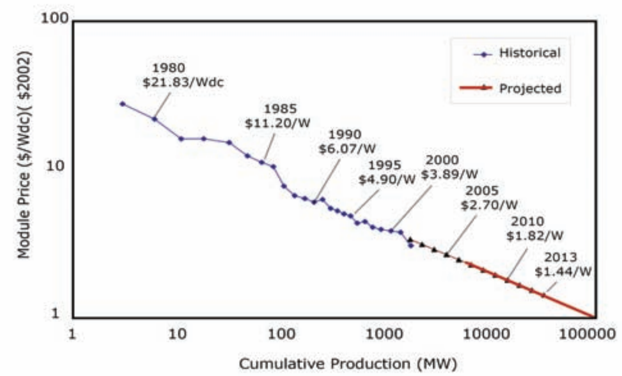
But, modules are only one part of the cost of PV systems. Inverters, installation fees, and other *balance of systems* (BOS) costs add to the total. In one study of these costs, modules were 62% of the total installed cost of residential PV systems (Figure 11.22).

11.7.1 Amortizing Costs

Because the capital cost of a PV system pretty much covers the cost of the next several decades of electricity delivered, we need some way to amortize that cost into something that can be

figure 11.21

Historical and projected manufacturer's price of PV modules suggests with cumulative production of 100,000 MW, costs might drop to $1/watt(dc).



Source: based on Swanson, 2004

compared to the usual cents/kWh found on your electric bill. A convenient way to do so is based on imagining that you take out a loan to pay for the system, which results in annual loan payments that can be divided by the annual kWh generated.

Recall the Capital Recovery Factor, CRF(i,n) introduced in Chapter 4. If I take out a loan of P dollars at interest rate i with a loan term of n years, my annual payments will be

Eq. 11.7

$$A = P \cdot \text{CRF}(i,n) \text{ where } \text{CRF}(i,n) = \frac{i(1+i)^n}{(1+i)^n - 1}$$

A short set of capital recovery factors is given in Table 11.2.

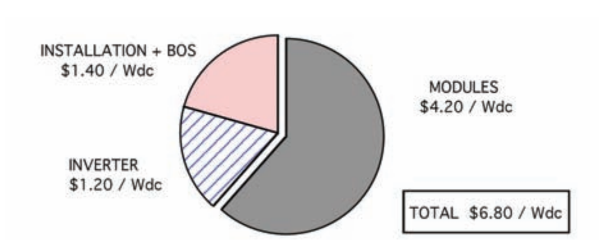
If Equation 11.7 is combined with the annual electricity delivered in Equation 11.5 we can find the cost of PV-generated electricity. Solution Box 11.4 illustrates the approach.

Eq. 11.8

$$\$/\text{kWh} = \frac{\$/\text{yr}}{\text{kWh/yr}} = \frac{P \cdot \text{CRF}(i,n)}{P_{DC,STC}(\text{kW}) \cdot (\text{de-rating}) \cdot (\text{hr/day of 1 - sun}) \cdot 365 \text{ day/yr}}$$

Figure 11.23 shows the impact of PV capital cost on annual cost of electricity produced, using the same assumptions that were incorporated in the example in Solution Box 11.4.

figure 11.22



Average installed cost for 625 residential PV systems installed between 1994 and 2000.

Source: Chang, 2000

table 11.2 Capital Recovery Factors, CRF (*i,n*)

Term (yr)	Interest rate (% yr)*				
	5.0%	5.5%	6.0%	6.5%	7.0%
15	0.09634	0.09963	0.10296	0.10635	0.10979
20	0.08024	0.08368	0.08718	0.09076	0.09439
30	0.06505	0.06881	0.07265	0.07658	0.08059

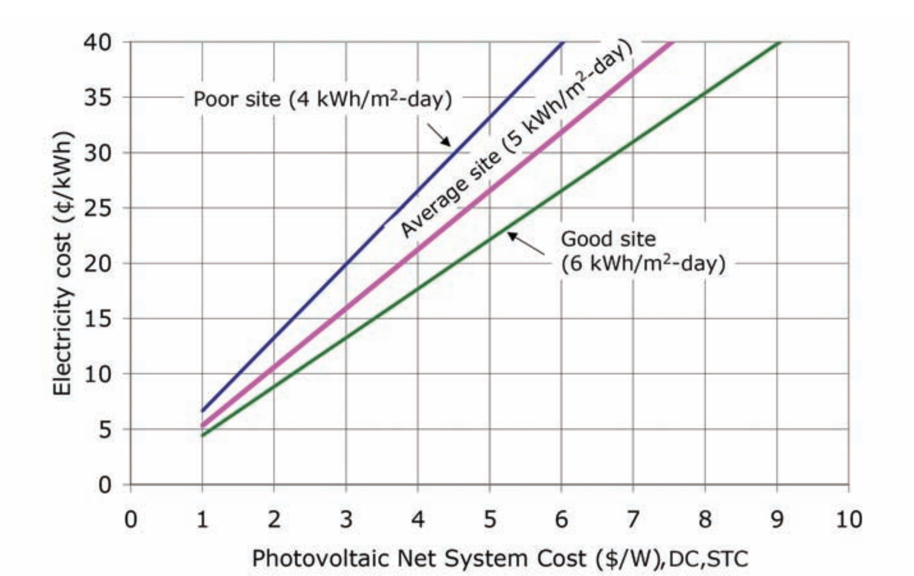
* Units are per year.

11.7.2 Rebates and Tax Credits

The 34¢/kWh found in Solution Box 11.4 doesn't make a very good case for investing in a PV system. There are, however, two other factors that can help close the deal. One is government and utility incentive programs. The other is tax-deductible interest on home loans.

As of 2007, there is a federal tax credit of 30% for residential and commercial PV systems (unlimited on commercial, but a maximum of $2000 on residential). There are also many state and utility incentive programs. These rebates and tax credits can work together to help close the cost gap between utility electricity and your PV electricity (Solution Box 11.5).

figure 11.23



Showing the impact of net system cost $/W(DC,STC) (after tax credits and rebates) on annualized electricity cost. Assumptions: de-rating = 0.75, 6%, 30-year loan, no deduction for mortgage interest.

SOLUTION

SOLUTION BOX 11.4

Cost of Electricity from PVs

Suppose you install a 2 kW(DC,STC) array (also referred to as 2 kW peak, or 2kWp) in Los Angeles that costs \$7/W(DC,STC). If you borrow the money at 6% interest on a 30-year loan, find the cost of electricity generated if it is installed on a south-facing roof with tilt = L –15° and we assume a de-rating factor of 0.75.

Solution:

From Table 11.1, the average annual insolation is 5.5 kWh/m^2-day (5.5 hr/day @ 1-sun), so the system generates 2 kW × 0.75 × 5.5 hr/day × 365 day/yr = 3011 kWh/yr.

The system costs \$14,000. From Table 11.2, CRF(6%,30yr) = 0.07265/yr, so the annual cost of the loan is \$14,000 × 0.07265/yr = \$1017/yr. Combining the \$/yr and kWh/yr, or just using Equation 11.8, we find the cost of electricity to be

$$\$/\text{kWh} = \frac{\$1017/\text{yr}}{3011\ \text{kWh/yr}} = \$0.338/\text{kWh}$$

11.7.3 Closing the Deal with Tax-Deductible Home-Loan Interest

If the cost of a PV system is part of a home-equity loan, or part of your home mortgage, the interest on your loan is tax deductible. The value to you of a tax deduction depends on your marginal tax bracket (MTB). For instance, if you are in a 28% tax bracket, every dollar of deductions (e.g., charity, interest on home loans) saves you \$0.28 on your taxes.

Eq. 11.7 **Tax savings on interest = Unpaid balance × Interest rate × MTB**

In the first years of your mortgage, almost all of the loan payment you make is paying for interest on the original balance of the loan. A good approximation, then, is that in those early years, the value of tax-deductible interest is just the original principal times the interest rate times your marginal tax bracket. The example in Solution Box 11.6 shows how this tax deduction on loan interest helps the overall economics of PVs.

In some states with relatively high utility rates, such as California, the 17.6¢/kWh cost of PV electricity is potentially attractive. This is especially true for customers who use a lot of kilowatt-hours, for whom the marginal cost of electricity can be extremely high. Table 11.3 shows the 2007 residential rate structure for a major California utility in which high-demand customers may be paying as much as 37¢/kWh.

SOLUTION

SOLUTION BOX 11.5

PV Economics with a Rebate, Tax Credit, and Tax Deduction

Suppose we continue the example in Solution Box 11.5, in which a 2 kWp, $14,000 system without incentives generates electricity costing $0.34/kWh. Let's assume we are eligible for the 30% (max $2000) federal tax credit and a state rebate of $2.80/W based on a de-rating factor of 0.84. Find the cost of electricity.

Solution:

The system cost after applying the state rebate is therefore

$$\textbf{System cost} = \$14{,}000 - 2000\text{W} \times 0.84 \times \$2.80/\text{W} = \$9296$$

The federal tax credit is 30% of the price you pay after other rebates, so it is

$$\textbf{Tax credit} = \textbf{Minimum}\ (0.30 \times \$9296 = \$2789, \text{ or } \$2000) = \$2000$$

As a credit, this actually reduces your taxes by $2000 making the system cost now

$$\textbf{After-tax-credit and rebate system cost} = \$9296 - \$2000 = \$7296$$

Borrowing that on a loan with CRF(6%,30) = 0.07265 gives you annual loan payments of

$$A = \$7296 \times 0.07265 = \$530.05/\text{yr}$$

The system still generates 2 kW × 0.75 × 5.5 hr/day × 365 day/yr = 3011 kWh/yr. So our cost per kWh is now

$$\$/\text{kWh} = \frac{\$530.05/\text{yr}}{3011\ \text{kWh/yr}} = \$0.176/\text{kWh}$$

That's better but still more than most people pay for their utility-generated electricity.

11.8 Stand-Alone Photovoltaic Systems

Stand-alone PV systems are much harder to design than those connected to the grid. Without the grid to provide energy storage, stand-alone systems are much more dependent on month-by-month load estimates, collector tilt angles, and solar availability. They are also more complicated since they involve battery storage and (usually) backup generators,

SOLUTION

SOLUTION BOX 11.6

Including Tax-Deductible Interest

Continuing the previous two examples, we have a system that costs $7296 after tax credits and rebates. Now let's add the impact of that 6% loan interest. Let's assume you are doing well and are in the 28% marginal tax bracket (MTB). Now find the cost of PV electricity.

Solution:

Using Equation 11.9, in the first year your loan balance is the full amount you borrowed; that is, $7296.

$$\textbf{Tax reduction for interest (year 1)} = \$7296 \times 0.06 \times 0.28 = \$122.57$$

The cost of your loan in the first year is now the loan payment of $530.05 minus the tax savings on interest of $122.57, which is a net cost for the PV system of $407.48. The cost of PV electricity to generate those 3011 kWh/yr is therefore

$$\$/\text{kWh} = \frac{\$407.48/\text{yr}}{3011\ \text{kWh/yr}} = \$0.135/\text{kWh}$$

which means they cost more, require more maintenance, and are considerably less reliable. On the other hand, stand-alone systems don't have to compete economically with relatively cheap utility power. When your site is miles from the nearest power lines, it can cost more to bring power to the site than to buy a PV system. And, those who live with these systems have a personal stake in their operation and maintenance and are much more likely to value the electricity produced. After all, compared to no electricity at all—the situation faced by a couple of billion people on this planet—having even a small amount of PV electricity, maybe just enough to power a light for a few hours in the evening, can dramatically change lives.

table 11.3 **Residential Rate Structures in California, 2007**

Customers who use large amounts of electricity have added motivation to use PV Power. Compare these prices with the $0.135/kWh cost of PV electricity derived in Solution Box 11.6.

Baseline Rate	$0.11430 per kWh
101–130% of Baseline	$0.12989
131–200% of Baseline	$0.22986
201–300% of Baseline	$0.32227
Over 300% of Baseline	$0.37070

A complete stand-alone system has a number of components, including the PV array, some batteries for energy storage, and an ac fuel-fired generator for backup power (Figure 11.24). Other components include a charge controller to keep from overcharging the batteries; a charger, which converts ac to dc to let the generator charge up the batteries when necessary; and an inverter, which converts dc from the batteries into ac for ac loads. Depending on the design, some loads may take dc directly from the batteries, thereby eliminating inverter losses, whereas others may be normal ac loads served by either the battery/inverter or directly from the ac generator.

Although the complete design of these systems is beyond the scope of this book (for such an analysis see, for example, Masters, 2004), we can illustrate the most important considerations.

Because every kilowatt-hour supplied by these systems is costly, the starting point for any design is a careful analysis of the loads that need to be supplied. Table 11.4 presents some examples of the power requirements for a variety of such loads. For most of these devices, energy is just the product of power and the number of hours the device is in use. For thermostatically controlled devices, such as refrigerators and freezers, the table provides daily energy estimates. An emerging concern is devices, such as TVs and satellite receivers, that use standby power even when they appear to be turned off, along with an array of other devices, such as portable phones, battery chargers, and so on, that are also constantly sucking up small amounts of power (look around the room and see how many little green and red lights you spot). For many entertainment systems, as much as two-thirds of their energy consumption occurs when they are not even being used.

Solution Box 11.7 shows an example estimate of a modest household demand and a first pass at sizing a PV array.

The example PV sizing for a stand-alone system for the cabin in Solution Box 11.7 is merely a first-cut at the design. To do a more careful job, we would have to trade off the number of days of battery storage we might want to provide with the number of hours of backup generator use that we could tolerate.

figure 11.24 **A Versatile Stand-Alone PV System Capable of Providing DC or AC Power**

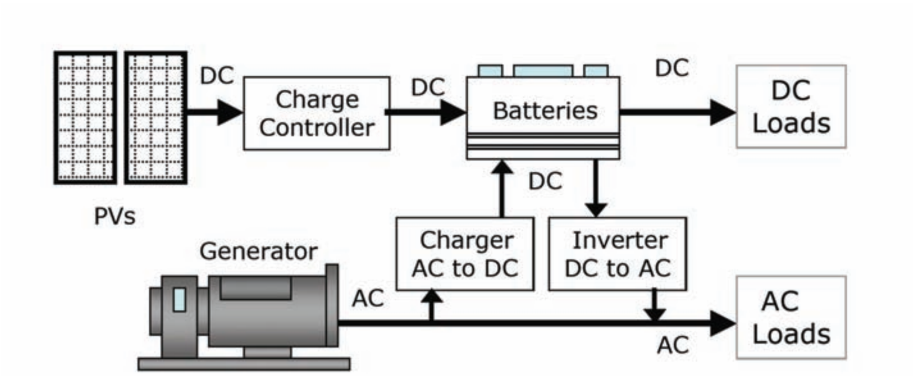


table 11.4 Approximate Power Requirements of Typical Loads*

Kitchen Appliances	DEMAND
Refrigerator: AC ENERGY STAR, 14 cu. ft.	1080 Wh/day
Refrigerator: AC ENERGY STAR, 22 cu. ft.	1250 Wh/day
Refrigerator: DC Sun Frost, 12 cu. ft.	560 Wh/day
Freezer: AC 7.5 cu. ft.	540 Wh/day
Electric range (small burner)	1250 W
Microwave oven	750–1100 W
Toaster	800–1400 W
General Houshold	
Clothes washer: vertical axis	500 W
Clothes washer: horizontal axis	250 W
Dryer (gas)	500 W
Vacuum cleaner	1000–1400 W
Furnace fan: 1/3 hp	700 W
Ceiling fan	65–175 W
Whole house fan	240–750 W
Air conditioner: window, 10,000 Btu/hr	1200 W
Heater (portable)	1000–1500 W
Compact fluorescent lamp (60 W equivalent)	16 W
Electric clock	4 W
Consumer Electronics	
TV: Conventional CRT (active/standby)	4.5 W/in. / 4 W
TV: LCD per inch (active/standby)	3.6 W/in. / 10 W
TV: Plasma per inch (active/standby)	7.6 W/in. / 20 W
TV: Rear projector microdisplay per inch (active/standby)	3.7 W/in. / 16 W
Analog cable box (active/standby)	12/11 W
Satellite receiver (active/standby)	17/16 W
VCR (active/standby)	17/5.9 W
Component stereo (active/standby)	44/3 W
Compact stereo (active/standby)	22/9.8 W
Clock radio (active/standby)	2.0/1.7 W
Computer, desktop (active/idle/standby)	125/80/2.2 W
Laptop computer	20 W
Ink-jet printer	35 W
Laser printer	900 W
Xbox 360	160 W

(*continued*)

Shop	
Circular saw, 7 1/4"	900 W
Table saw, 10-inch	1800 W
Hand drill, 1/4"	250 W
Water Pumping	
Centrifugal pump: 36 VDC, 50-ft @ 10 gpm	450 W
Submersible pump: 48 VDC, 300-ft @ 1.5 gpm	180 W
DC pump (house pressure system)	100 Wh/day

* Some include estimates of standby power as well as power when in use.

SOLUTION

SOLUTION BOX 11.7

PVs for a Modest Cabin

Find the monthly energy demand for a cabin with a 22 cu. ft refrigerator, five 16 W compact fluorescent lamps used 6 hr/day, a 20 in. LCD TV used 4 hr/day, a 1000 W microwave used 6 min/day, and a 300-ft well that supplies 150 gallons of water per day (1.5 gpm, 180 W). If the average sun available is 5 kWh/m^2-day (5 hr of full sun), use a de-rating factor of 0.75 and a PV efficiency of 14% to size a PV system to meet this load.

Solution:

From Table 11.4, we can figure out the daily energy demand:

refrigerator:		= 1250 Wh/day
CFLs:	5 × 16 W × 6 hr/day	= 480 Wh/day
LCD TV:	3.6 W/in × 20 in × 4 hr/day	= 288 Wh/day
LCD TV standby:	10 W × 20 hr/day	= 200 Wh/day
microwave:	1000 W × 6 min/60 min/hr	= 100 Wh/day
well:	150 gal/day /1.5 gal/min/60 min/hr × 180 W	= 300 Wh/day
		Total: 2618 Wh/day

Notice the energy required by this TV when it isn't turned on is almost as much as when it is. This user might consider a power strip to really turn that thing off when not in use. From Equation 11.5, a first-cut at the rated power needed for this PV array would be

$$P_{DC,STC} = \frac{2618 \text{ Wh/day}}{(5 \text{ hr/day @ 1-sun}) \times 0.75} = 698 \text{ W} \approx 0.7 \text{ kW}$$

A 14%-efficient 0.7 $kW_{DC,STC}$ PV array would have an area of

$$\frac{0.7 \text{ kW}}{0.14 \text{ kW/m}^2} = 5 \text{ m}^2$$

11.9 Summary

This chapter has presented quite a range of PV topics, from the basic physics that describes how they work, to the influence of collector orientation, to array sizing and evaluation of system economics. The emphasis has been on PV systems located on the customer's side of the meter, in which case they compete against the retail price of electricity. In sunny locations, with existing tax credits, utility rebates, and tax-deductible interest on loans, PV systems are cost-effective, especially for customers who use lots of power and for whom the marginal cost of utility electricity is high.

Sales of PV modules have been increasing at roughly 40% each year, which is a phenomenal rate of growth. But, they are starting from a very small base and total installed capacity is still just a few gigawatts. In the next chapter we will look at bigger renewable energy systems located on the utility side of the meter, including the very rapid growth of large wind-turbine power plants around the globe.