8 Photovoltaic (PV) Applications

8.1 INTRODUCTION

PV systems can be used for a wide variety of applications, from small stand-alone systems to large utility grid-tied installations of a few megaWatts. Due to its modular and small-scale nature, PV is ideal for decentralized applications. At the start of the twenty-first century, over one-quarter of the world's population did not have access to electricity, and this is where PV can have its greatest impact. PV power is already beginning to help fill this gap in remote regions, with literally millions of small residential PV systems installed on homes around the world, most commonly as small stand-alone PV systems, but also increasingly as larger on-grid systems in some industrialized regions (notably Japan, Germany, and California). Ironically, the wealthy, who want to demonstrate that they are "green," or often impoverished remote power users, who need electricity and have limited options, form the majority of PV users.

8.2 GRID-TIED PV

Decentralized PV power production promises to be a widely applicable renewable energy source for future clean energy production. Because most of the electric power supply in industrialized countries is via a centralized electric grid, the widespread use of PV in industrialized countries will be in the form of distributed power generation interconnected with the grid. Indeed, since 2000, the fastest growing market segment for PV has been in the grid-tied sector. Utility-interactive PV power systems mounted on homes and buildings are becoming an accepted source of electric generation. This tremendous growth has been due to government incentives and policies encouraging clean energy out of concern for the environmental impacts, especially global warming, of conventional electric generation technologies (especially coal). Growth has been particularly phenomenal in Europe, Japan, and California.

Grid-tied PV represents a change from large-scale central generation to small-scale distributed generation. The on-grid PV system is really the simplest PV system. No energy storage is required and the system merely back-feeds into the existing electrical grid. This growth has also had unintended consequences for the off-grid market, in that many module manufacturers have ceased production of their smaller, battery-charging PV modules in favor of larger, higher voltage modules made for on-grid inverters.

Utility-interactive PV systems are simple yet elegant, consisting of a PV array (which provides DC power), an inverter, other balance of systems (such as wiring, fuses, and mounting structure), and a means of connecting to the electric grid (by back-feeding through the main electric service distribution panel). During the daytime, DC electricity from the PV modules is converted to AC by the inverter and fed into the building power distribution system, where it supplies building loads. Any excess solar power is exported back to the utility power grid. When there is no solar power, building loads are supplied through the conventional utility grid. Grid-tied PV systems have some advantages over off-grid systems:

- *Lower costs.* Grid-tied PV systems are fairly simple and connect to the standard AC wiring. Only two components are required: the PV modules and the inverter (with associated wiring and overcurrent protection).

- *No energy storage.* Because the utility grid provides power when the PV system is off-line, no energy storage is required. The grid effectively is the energy-storage bank, receiving energy when a surplus is generated and delivering energy when the load exceeds on-site generation.
- *Peak shaving.* Typically, sunlight and thus PV peak power production coincide with utility afternoon peak loading periods; the utility gains from solar peak shaving. Even better, during the summer cooling season when the sun is out and hottest, this is exactly when the PV system will be producing maximum power. With grid-tied PV systems, daytime peaking utilities gain a reduction in peak load while not impacting off-peak energy sales. The customer benefits by having lower utility bills while helping the utility reduce peaking loads.

Utility-interactive PV systems cost about \$6–\$8/watt peak (W_p) when installed. Existing rooftops are the lowest cost siting option because both the real-estate and mounting structures are provided at no cost. The system cost includes about \$3–\$4/W_p for the PV modules, about \$0.60/W_p for power conditioning, and from \$2 to \$3/W_p for mounting and labor. Thus, a turn-key 2 kW_p PV residential system will cost about \$12,000–\$16,000.

For a location receiving an average of 5 sun-hours/day (for example, Atlanta, Oklahoma City, or Orlando), a 2 kW_p system after system losses will produce about 2,700 kWh/year. At a value of \$0.10/kWh, this energy is worth a little over \$270/year. Assuming that the system cost about \$12,000 to install, simple payback for a grid-tied PV system is over 40 years. Grid-tie PV life-cycle costs are typically over \$0.20/kWh, assuming a relatively good solar resource and amortizing over a couple of decades. Although PV system prices can be expected gradually to decrease, it will still be a couple of decades before they are competitive with the grid in the United States. However, in places like Japan or Germany, where grid power is already more than double the cost in the United States, PV has achieved basic parity with grid-tied power on a life-cycle cost basis, as discussed in Chapter 9.

There are also no real issues with PV systems endangering line workers; indeed, many knowledgeable utilities no longer require an outside disconnect. A PV inverter behaves very differently than a conventional rotating-type generator that powers the grid. A rotating generator acts as a voltage source that can generate independently of the grid and is synchronized with it. A PV inverter acts as a sinusoidal current source that is only capable of feeding the utility line by synching up with it when voltage and frequency are within standard limits. Thus, islanding (independent operation of the PV inverter) is for all practical purposes impossible because line voltage is not maintained by PV inverters. Also, under fault conditions, a rotating generator can deliver most of its spinning energy into the fault. A PV inverter, which is a controlled-current device, will naturally limit the current into a fault to little more than normal operating current. The PV cells themselves act as current-limited devices (because output current is proportional to sunlight).

Modern PV inverters use pulse-width modulation (PWM) to generate high-quality sinusoidal currents, so harmonic distortion is not a problem. Modern PWM inverters also generate power at unity power factor (i.e., the output current is exactly in phase with the utility voltage). Grid-tied PV inverters are designed with internal current-limiting circuitry, so output circuit conductors are inherently protected against overcurrent from the PV system. The overcurrent protection between the inverter and the grid is designed to protect the AC and DC wiring from currents from the grid during faults in the PV system wiring. PV inverters are available in a range of sizes, typically 1–6 kW with a variety of single phase voltage outputs including 120, 208, 240, and 277 V. The interconnection from the inverter to the grid is typically made by back-feeding an appropriately sized circuit breaker on the distribution panel. Larger inverters, typically above 20 kW, usually are designed to feed a 480 V three-phase supply.

Typically, PV power producers enter into an interconnection agreement with the local utility for buying and selling power and the necessary metering scheme to support this arrangement. The basic options include:

- for net metering, a single bidirectional meter;
- for separate buy and sell rates, two individual ratcheted meters to determine the energy consumed and generated; and
- other arrangements that take advantage of time-of-use rates. These may require additional meters capable of time-of-use recording, which is particularly advantageous for PV power producers because PV power production normally coincides with peak rate periods.

Grid-tied PV power systems have proven to be a reliable method of generating electricity. Some of the largest grid-tied PV power installations and highest concentrations of PV residences in the world can be found in Japan (Figure 8.1). A closer look at what the Japanese have accomplished will give a good idea as to where the rest of the world will be going over the next couple of decades.

8.3 JAPANESE PV DEVELOPMENT AND APPLICATIONS

Japan has one of the most advanced and successful PV industries in the world, which warrants a closer look. Japan became the first country to install a cumulative gigawatt of PV back in 2004. Through aggressive government policies beginning with the SunShine Program launched in 1974 and then more recent subsidies promoting deployments, Japan has become a global PV production and industry leader. PV-powered homes are now a common site throughout Japan. Japan used to provide half of global production, but now provides one-fifth of global PV production as the rest of the world ramps up. Japan's Sharp was the second largest global producer in 2007 with 370 MW (but it has produced more than that in the past and was supply constrained) and Kyocera ranked fourth with 200 MW. Other key producers in 2007 included the world's largest producer in Germany (QCells with 400 MW) and China's Suntech, which is ranked third with 300 MW in 2007 (Renewable Energy World 2008).

The Japanese government is making solar energy an important part of its overall energy mix, with a goal of 10% electricity production from PV by 2030. It seeks to reduce PV costs to be on par with conventionally generated electricity. Likewise, Japan is a signatory to the Kyoto Protocol and sees solar power as a viable part of the solution to meeting CO_2 reduction targets. Japan became a global PV leader for three key reasons:

FIGURE 8.1 Ohta City has the highest concentration of grid-tie PV homes, with over 500 homes installed in this neighborhood.

- aggressive government policies promoting PV to help meet Kyoto Protocol goals;
- tight research and development (R&D) collaboration among industry, government, and academia; and
- majority overseas exports helping to drive down PV in-country manufacturing costs.

Individual homeowners are the most common PV buyers in Japan, comprising nearly 90% of the market. In Japan, there is a twofold reason for buying PV. First, the Japanese consider it "good to be green" and have ties to nature that are culturally embedded. Second, the retail price of residential electricity in Japan is the highest in the world, at ~¥23/kWh (~US$0.21/kWh). Thus, over a 20-year lifetime, grid-tied PV power is actually cost effective. Initially, the government offered substantial rebates on PV installations (50% in the mid-1990s), but these rebates were dramatically reduced and phased out as PV prices dropped. Japan's budget for development and promotion of PV systems has more than halved since its peak in 2002. This has been possible as PV prices have decreased, and homeowners without rebates today are paying approximately the same price they paid a decade ago with rebates. Some local city and county governments do continue to offer incentives for PV installations.

The costs of PV systems in Japan are among the lowest in the world and were down about ¥670/W_p (or about US$6/$W_p$) installed for residential installations by 2004. Japan is able to achieve lower costs through simplified balance of systems, including transformerless inverters. All equipment used is manufactured in country. Japan also has a customized mass production technique and some housing manufacturers offer PV options on homes. Likewise, regulations are simple and nonprescriptive for PV installations. There are no special PV installers; rather, electricians are trained by industry to install PV systems. Installations are self-inspected. The Japanese electric code for PV is simple (one page) and not prescriptive. The Japanese rely on the industry to self-police and do a good job out of a cultural honor tradition. If there is a problem, the homeowner can make claims against the warranty and company. Most Japanese companies are very responsive if there is a problem because it is a matter of honor and pride for them to do a good job. Indeed, Japan has among the best installed PV systems anywhere.

PV systems are also made easy for homeowners to use and understand. Simple graphical displays are used so that homeowners can easily see how their PV systems are doing on a real-time and cumulative basis. This generates interest and participation from the homeowner, who in turns shows off his system to his friends and learns to conserve electricity. Systems are metered and the homeowner sees a reduction in his monthly electric bill by using a PV system.

Overall, PV technology deployment in Japan is mature and there are few reported failures. The government has put most of its funding into deployment and determining how to maximize power from clustered PV systems. Basic research is shifting toward thin film technologies and the Japanese are leading the world on how to recycle PV modules.

Japan is a global PV manufacturing leader and also has the most mature PV market in the world. The Japanese market represents about one-twentieth of global PV sales, and the country exports over 60% of its PV module production overseas. The rapidly changing Japanese market and experience hold a number of lessons learned that are pertinent for other countries interested in large-scale PV deployment. Numerous technology and policy insights can be gained from the Japanese experience.

The Japanese government has been developing a self-sustaining residential PV market free of incentives. There has been a successive annual decline in government subsidies that were phased out by 2006. The reason for this is that PV prices have declined over 30% in the last decade, and PV is now competitive in Japan, especially because domestic grid power costs about US$0.21/kWh. PV is now an attractive and economically competitive electricity option for many homeowners.

Few nondomestic companies operate in the Japanese market. Although there are no particular trade barriers for other companies to sell product in Japan, the national Japanese market is so competitive that most foreign manufacturers find it difficult to enter. The Japanese PV manufacturers should continue to lead global PV production in the future. They have learned how to make it cheaper and better through mass commercialization.

The Japanese culture has always had strong ties to nature, exemplified through the country's famous gardens, poetry, etc. Likewise, the Japanese culture has always had a unique relationship with the sun, reflected on its national flag as the "Land of the Rising Sun." Thus, many Japanese view the use of solar energy as in keeping with their cultural traditions. With the signing of the Kyoto Protocol on Global Warming, the Japanese also see it as a matter of national pride for Japan to meet its share of the protocol's objectives on limiting CO_2 emissions. Thus, again, solar energy is seen as an important part of the solution to achieving these objectives. This attitude permeates all levels of the society, from homeowners to schools, government, and industry. Most want to use solar energy on their buildings and help the country become "solarized."

Countering the effects of global warming is a mainstay of Japanese government policy. Economics for PV plays a secondary role as compared to national goals of meeting the Kyoto Protocol. The prime minister's residence, as well as the Japanese Parliament and many key government buildings, all have 30- to 50-kW PV arrays mounted on their rooftops (Figure 8.2). There is nearly a megaWatt installed on key government buildings in downtown Tokyo. A total commitment to making Japan a solar nation exists from the government officials and planners, industry leaders, and the public. Japan has an integrated solar development approach. Also, there is a sense of need for energy independence. Because grid electric costs are the highest in the world in Japan, there is also an economic return for residential PV.

The Japanese also feel that the expansion of PV power generation systems in Japan will greatly contribute to creating new jobs and industries in the coming decades. This meets the goals of energy and industrial policies that the Japanese government is pursuing.

Most of the Japanese PV systems are installed on single-family residences belonging to average homeowners. These are typically middle-aged Japanese parents with a couple of children. The typical household income in Japan is ¥6.02 million per year (MHLW 2002). Most of the Japanese PV systems (about three-quarters) are installed as retrofits on existing homes. Typical household electricity consumption in Japan is 290 kWh/month (JAERO 2004); this is more than half that of the United States. In Japan, a 1 kW_p PV system annually generates about 1,050 kWh/kW_p on average.

FIGURE 8.2 Installed grid-tied PV array on Japanese prime minister's official residence (Sishokante) signals to the country the government's deep commitment to solar energy.

Although the majority of PV systems are installed as retrofits on existing homes, some prefabricated homes also offer PV as part of a package deal. There is no standardized specification, and manufacturers are free to partner with the PV companies that offer them the best deals. More and more of the prefabricated homes will offer a PV option in the future.

Close cooperation among government, industry, and academia has made Japan a leading producer of solar cells in the world, with about 16% of global production (previously Japan had over 40% of global production as did the U.S. before that, but other countries like China and Germany have greatly increased production). Of the installed systems in Japan, about 92% are for grid-connected distributed applications such as residences and public buildings. Total PV production in Japan for 2006 was 927 MW. Sharp is the largest PV module producer, with about 370 MW of production in 2007 (Renewable Energy World 2008).

Japan sets the global standard for residential PV installation programs in terms of size and cost. The country currently installs 50,000–60,000 PV homes per year in cooperation with the large cell manufacturers and the home builders. Japan has more PV homes than any other country; total number of residential PV systems will surpass a half million by 2010. Given the large PV manufacturing base in Japan, PV systems are more inexpensive there than in the rest of the world. The balance of systems (BOS) is also cheaper due to simplified electrical code requirements. The average residential PV system cost is about ¥650/W_p (<US$6/$W_p$) (Kaizuma, 2005/2007).

8.3.1 Japanese Government's Approach

The Japanese government supports PV development at every step, from the prime minister and Parliament down to the different implementing agencies. The Ministry of Economy, Trade and Industry (METI) began a subsidy program for residential PV systems (PV modules, BOS, and installation) in 1994. At first, the subsidy covered 50% of the cost. The program was open to participants from residential homes, housing complexes, and collective applications. By 1997, METI grew the program to encourage mass production of PV systems (Figures 8.3 and 8.4). After achieving their price goals, the Japanese government rolled back the subsidy program in 2003 and had largely phased it out by 2006. The Japanese government has now shifted focus to larger commercial- and utility-scale systems (e.g., water plants for backup power; see Figure 8.5).

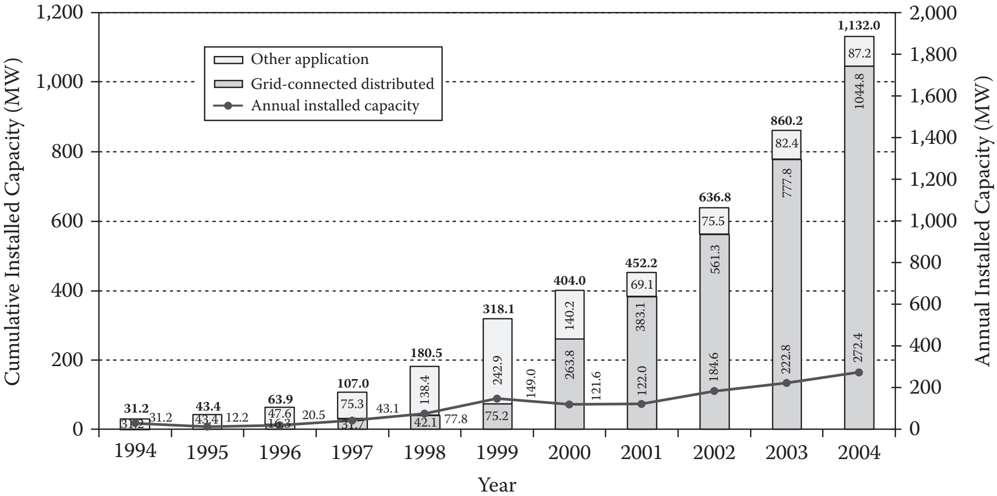

FIGURE 8.3 Growth of Japanese PV installations from 1994 to 2004 (IKKI, 2005).

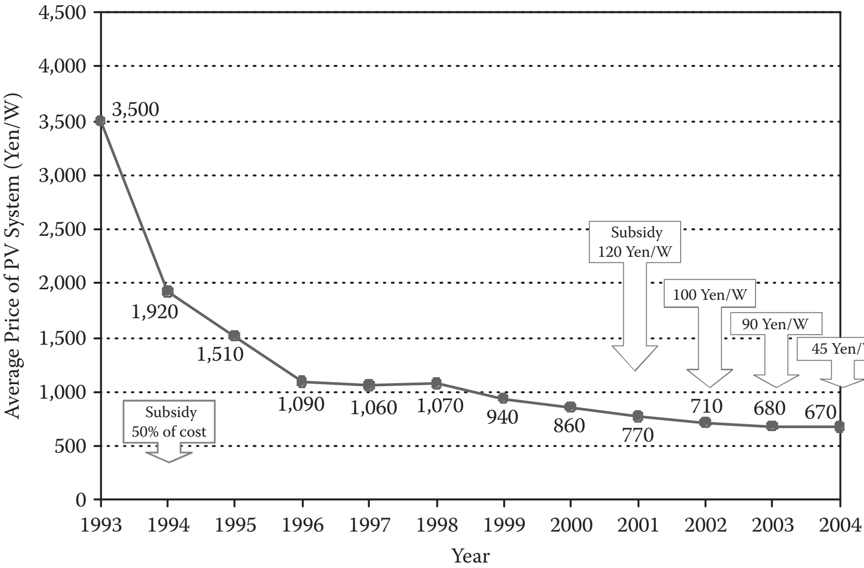

FIGURE 8.4 Average PV system price in Japan from 1994 to 2004 and corresponding national government subsidy, which was phased out by 2006 (Ikki, 2005).

FIGURE 8.5 Project designer Mr. Ohashi and Osaka Waterworks Kunijima Treatment Plant with a 150 kW_p PV plant (Kyocera), one of over a dozen such PV water plants in Japan.

8.3.2 Japanese PV Utilities

The electrical sector in Japan is deregulated. There are five electric utilities in Japan, all of which are investor owned. Generation, transmission, and distribution are vertically integrated. Some independent power producers also generate electricity. The electric generation industry is regulated by the Agency for Natural Resources and Energy (ANRE) of METI.

The distribution network for electricity in Japan is single-phase, three-line, 100/200 V AC. The western part (e.g., Osaka) of the country uses 60 Hz, while eastern (e.g., Tokyo) Japan uses 50 Hz power. This fact also is an advantage for the Japanese inverter industry, which designs inverters for both 50 and 60 Hz for its own market and thus has ready-made products for the European and U.S. markets.

Typical metering arrangements and tariff structures for electricity consumers are 30-minute interval readings. A time-of-use tariff is available. Utilities are responsible for their side of the grid. The PV installation is done by the PV and contractors' industry. There are some big utility PV installations, but over 90% of PV is installed on residences. Normally, a separate meter monitors PV system performance. Japan has about a half million PV-powered homes (Figure 8.6).

8.3.3 Japanese Marketing

PV plays an important role within Japan's overall energy strategy. The government has raised public awareness on climate and energy matters and on how solar PV can bring global and personal benefits. Ongoing government publicity campaigns from both national and local governments discuss the benefits of PV related to environmental issues. PV technology is promoted through a range of media from newspaper to television.

The Japanese PV industry conducts marketing activities for its own PV products. In Japan, solar energy is a popular idea with the public, so industry sales need to differentiate themselves from their competitors rather than selling the public on the solar energy system concept. Most are systems sold to homeowners who have a profound understanding of the ecological impacts of their purchases and are not as concerned about the decades' long payback for the system.

PV commercials are aired on television. One classic solar commercial in Japan by Kyocera shows a young Japanese woman homeowner proudly viewing the energy production of her Kyocera PV system with the Kyocera graphical display meter inside her home. Then there is a clap of thunder and rain, and she is sad that her system is not producing power. The shot cuts away to the PV system and explanation. Soon, the sun comes out again and the birds are singing and the PV system owner is once again pleased about producing energy. Likewise, Sharp has a commercial promoting the ecological aspects of solar energy and exhorts viewers to "change all the roofs in Japan into PV plants."

The Japanese PV industry has also made it easy for consumers to understand the performance of their PV systems, which also figures prominently in advertisements. Instrumentation on installations comes from industry. Graphical meters are simple to read so that homeowners can easily follow their system's performance (Figure 8.7).

FIGURE 8.6 PV system grid inter-tie (note 2 meters) in Ohta City. Inverter and battery bank are housed in the large boxes on the right.

FIGURE 8.7 Consumer-friendly Kyocera residential PV meter display

Overall, Japanese PV systems are professionally installed and exhibit excellent workmanship with dedication to detail. The image of PV in Japan is a positive one that the technology works. Overall, the industry is not highly regulated and the Japanese companies are entrusted to design and install PV systems. Some general guidelines for grid-tied installations have been recommended by JET; although these are not law, they are generally followed by the industry (Jet, 2002).

8.3.4 Japanese PV Electrical Code

The Japanese Industrial Standards (JIS) specify the standards used for industrial activities in Japan. The standardization process is coordinated by the Japanese Industrial Standards Committee (JISC) and published by the Japanese Standards Association (JSA). The objective of the JSA is "to educate the public regarding the standardization and unification of industrial standards, and thereby to contribute to the improvement of technology and the enhancement of production efficiency (JSA, 2007)." The Japanese have a well established electric code developed after 1945, known as the Technical Standard for Electric Facilities. This simple, technical approach has proved to be very effective and safe in Japan for installing high-quality PV systems. Engineers do not get lost over detailed nonsensical discussions about "how many angels can fit on the head of a pin"—unlike some other industrialized countries with prescriptive electric codes that inhibit growth and innovation of PV systems design.

Japan has among the highest quality PV installations in the world, while maintaining some of the simplest regulations. The equivalent to the U.S. NEC Article 690 for PV in Japan is Section 50 in the Japanese code. It is essentially a simple one-page checklist. Unlike the U.S. NEC, the Japanese code is not prescriptive, but rather more of a handbook. Individual manufacturers are responsible for following the code on their installations. In Japan, the work ethic is such that companies take pride in their work and want to do quality installations. The code does not require use of listed modules, inverters, etc.; however, the manufacturers take pride in getting their equipment listed with JET, and installers will want to use listed equipment. The main points of the Japanese electric code related to PV installations are simple and straightforward (Kadenko, 2004):

- Charging parts should not be exposed.
- PV modules should have a disconnect located near the array.
- Overcurrent protection should be installed for PV modules.
- The minimum size wire used for module installations should be 1.6 mm^2 and follow existing wiring codes.
- Interior installations should follow all other codes (Sections 177, 178, 180, 187, and 189).

- Outside installations should follow all other wiring codes (Sections 177, 178, 180, 188, 189, and 211).
- Wires should be connected using terminal connectors and the connections should have appropriate strain relief.

Japanese PV systems are installed in compliance with the Japanese electrical code. In eastern Japan, systems use a European standard of 50 Hz AC, while western Japan uses a U.S. standard of 60 Hz. Japanese electrical codes are somewhat similar to European electrical codes, with PV systems ungrounded on the DC side and grounded on the AC side. A chassis ground is always used (AC and DC sides; Tepco, 2004).

8.3.5 Japanese PV Design

PV companies and electrical contractors design PV systems in Japan. Utilities sometimes may get involved in the design of a few large-scale systems, but typically not for the smaller residential systems. Residential PV systems generally range from about 3–4 kW_p and average about 3.6 kW_p (Kaizuma, 2005/2007).

PV arrays are often mounted directly onto reinforced corrugated metal roofs (no roof penetrations). Most roofs in Japan are metal or a traditional style ceramic for high-end roofs. There is a great deal of concern in Japan that PV systems be able to withstand typhoon (hurricane)-force winds, which are common during the late summer months. Often, commercial PV installations in Japan are not optimally tilted for solar energy production but are tilted in favor of better wind survivability (typhoons). System profiles are installed low to the roof to reduce wind loading (Figure 8.8). Local codes typically call for PV systems to withstand winds of 36 m/s in Tokyo, 46 m/s in Okinawa, and even 60 m/s in some places, such a Kanazawa City.

One unique aspect for some Japanese PV installations is that many systems are installed with PV arrays facing south, east, and west on the same roof. This is due to the limited roof space of smaller Japanese homes. The west and east arrays typically produce about 80% of the energy of a south-facing array. Some inverters (e.g., Sharp) are designed to max power point track three different subarrays independently for this reason.

Japanese PV systems are not grounded on the DC side (although they all have a chassis ground). Only the AC side is grounded. Operating voltage is 200/100 V AC. The distribution network for electricity in Japan is single-phase 100/200 V AC. The western part of the country uses 60 Hz (e.g., Osaka), while eastern Japan uses 50 Hz power (e.g., Tokyo).

Crystalline PV modules are by far the most popular in Japan, representing over 80% of PV modules produced and installed in the country. Modules normally carry a guarantee on performance

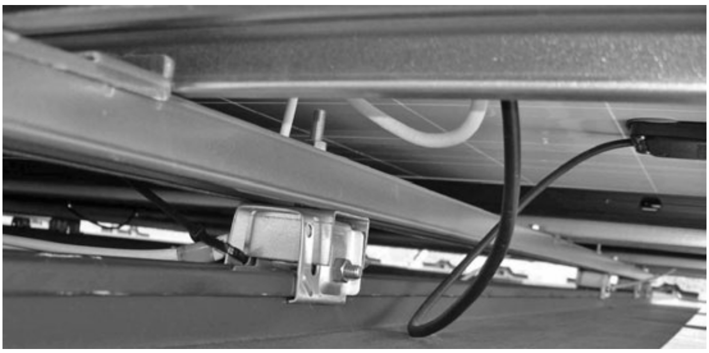

FIGURE 8.8 Underside of typical Japanese PV array clamp mounting on metal corrugated roof (no roof penetration) designed to withstand typhoon force winds.

from 10 to 25 years, depending on the manufacturer (those active in U.S. markets will have a superior warranty). Thin film modules are slowly gaining in popularity, but still greatly lag sales of crystalline modules. Cadmium telluride (CdTe) modules will never be found in Japan due to the society's disdain for using toxic materials. In Japan, a lot of thought has been given to how to recycle a PV module; thus, toxic materials are quickly eliminated from consideration of use in PV modules.

In Japan, there are about two dozen residential PV inverter manufacturers. Most Japanese inverters do not use transformers. There are over 100 listed residential PV inverters in Japan. Inverters are single phase and three wire (100 and 200 V). Inverter warranties vary by manufacturer (typically 1–3 years).

Several Japanese PV producers also make their own inverters, such as Kyocera, Sanyo, and Sharp. Sharp and Daihen are developing inverters jointly for large-scale PV systems installed by commercial users and electric utilities. Daihen is responsible for manufacturing the solar inverters, and Sharp focuses on PV modules targeting electric utilities. In the future, it can be expected that Japanese inverters will become as prevalent as Japanese PV modules around the globe. Some of the major inverter manufacturers include Sharp/Daihen, Omron, Toshiba, Mitsubishi, Sanyo, GS, Matsushita, and Kyocera (Figure 8.9). Inverters in Japan are a mature technology. One very interesting application in Japan is that the industry is looking at how large clusters of inverters work together and how to improve performance, such as the Ohta City project with over 500 PV homes (Figure 8.10).

PV installations in Japan exhibit excellent workmanship and are done by certified electricians. There are no independent certified installers (e.g., no North American Board of Certified Energy Practioners (NABCEP) equivalent). Industry is responsible for training its installers and maintaining quality standards. Some module manufacturers, like Kyocera, will also install PV systems; others rely on electrical contractors. In new homes, often the same electricians that install a home's wiring system also install the PV system.

Overall installation costs for PV systems in Japan are generally less than in the United States because systems have simpler BOS requirements and more streamlined installation procedures (e.g., no roof penetrations). Systems for 3 or 4 kW_p can be installed efficiently in only a couple of days. Electrical crews generally consist of two or three electricians/assistants. PV installations are normally completed within 2 or 3 days. No on-site QA records are maintained, and it is up to the installer to do a good job. If there is a failure, the installer will be held responsible. Generally, in Japanese culture, the installer and also manufacturers will want to fix any problems with their products. It is a matter of cultural honor for them to have satisfied customers.

FIGURE 8.9 Four-kiloWatt transformerless Omron inverter on AIST PV parking structure.

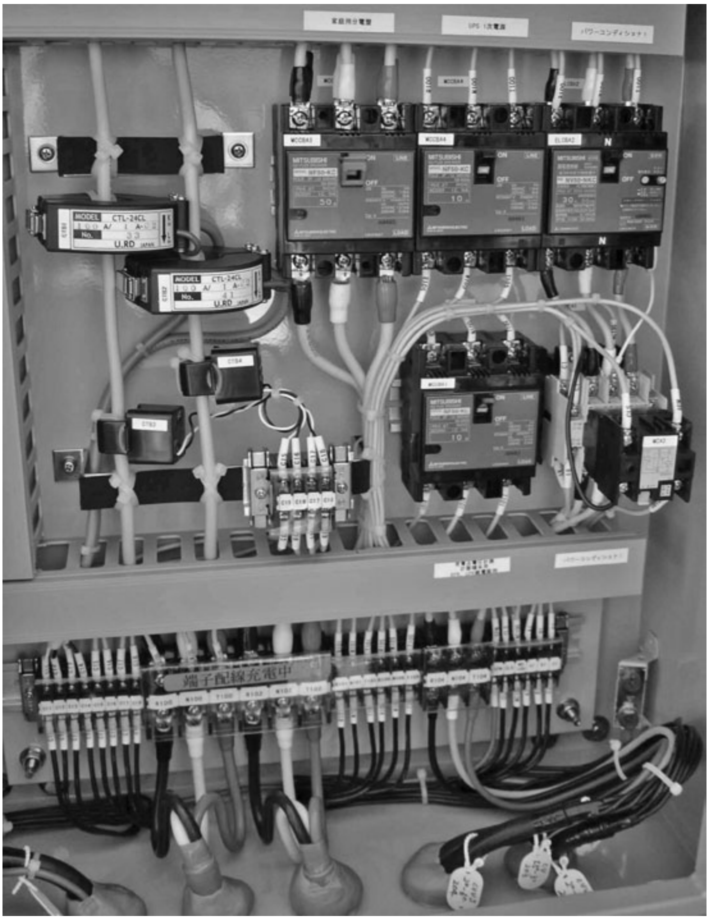

FIGURE 8.10 Excellent workmanship typifies Japanese installations, such as with this PV system breaker box with monitoring transducers at Ohta City clustered systems project.

8.3.6 Japanese PV System Guarantees

Japanese PV systems and components are warranted against defects in product or workmanship. A normal PV system installation warranty is for 3 years. Of course, additional module warranties vary by manufacturer (10–25 years). Some in the industry believe that a 10-year module warranty is sufficient (e.g., a car has only a 3-year warranty but everyone knows it will last longer).

There are no requirements for using listed equipment in Japan. It is strictly voluntary to have listed modules and inverters. However, most manufacturers will seek a voluntary listing from JET to be more competitive. Japanese installers are left on their own to do the right job (this is akin to how the Japanese automobile industry operates). It is a matter of cultural and professional pride for Japanese industry to install quality PV systems.

8.3.7 Japanese PV Development

Japan is a global leader when it comes to PV manufacturing and innovation. Residential system needs have helped promote higher cell efficiencies and smaller sizes. Larger commercial systems have led to innovation in PV for building integration that requires flexible, lightweight, light-transmitting, or bifacial products for facades and large-area installations. A number of office buildings now have see-through PV on their south-facing windows (Figure 8.11). Some prefab homes use PV,

FIGURE 8.11 Building integrated see-through PV modules (Sanyo) at the Ohta City government office complex.

but only 25% of installed residential systems are on new construction. Research and development on expanding the use of PV on prefab construction continues. The factory will offer a PV system packages for delivery. Most assembly is still done in the field.

Japan is also shifting home construction toward a "mass customization" approach. A future homeowner is given a wide menu of standardized options to customize his or her prefab home design (e.g., a dozen different stairway designs, windows, etc.). Customized modifications can be significant on homes and gets the homeowner involved with the home design. PV manufacturers do offer standardized systems, but these vary from manufacturer to manufacturer.

The Japanese industry forms the backbone of the global PV industry. The government research program has been tightly coordinated with Japanese industry and academia. There are 13 major PV module manufacturers in Japan; these include some of the world's leading PV companies, such as Sharp, Sanyo (Figure 8.14), Kyocera, Mitsubishi, and Kaneka. Japanese industry continues to strive for cost reductions in PV manufacturing while maintaining a healthy profit, especially for those companies well established in the sector. Residential PV installations are the driving application for the domestic PV market in Japan (Figure 8.12).

PV growth in Japan has also nurtured peripheral industries, such as production of silicon feedstock, ingots and wafers, inverters, and reinforced aluminum frames. Sharp is the number one PV manufacturer, followed by Kyocera and Sanyo. Japan overtook the United States in terms of manufacturing in 1999 and their current market share of overall worldwide PV production is about 15% (Figure 8.13).

8.3.8 Japanese PV Module Certification

As a METI-designated testing body and independent and impartial certification institution with a proven track record, Japan Electrical Safety and Environment Technologies (JET) provides product certifications by use of a symbol that represents "safety and authority" to manufacturers and importers as well as to consumers. JET receives a range of requests from government agencies, including requests to conduct tests on electrical products purchased in the market, to harmonize domestic standards with IEC standards, and to conduct research and development on technologies for assessing solar power electric generation systems.

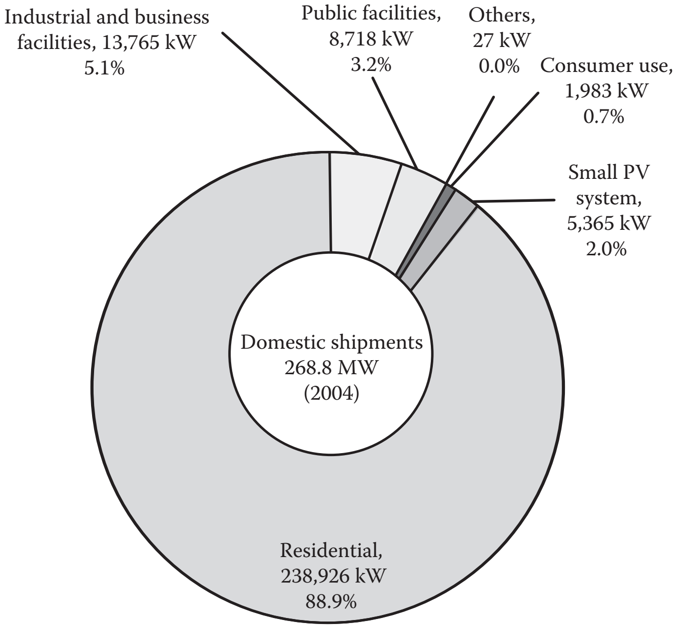

FIGURE 8.12 Japanese installations by sector type in 2004, dominated by residential (OITDA).

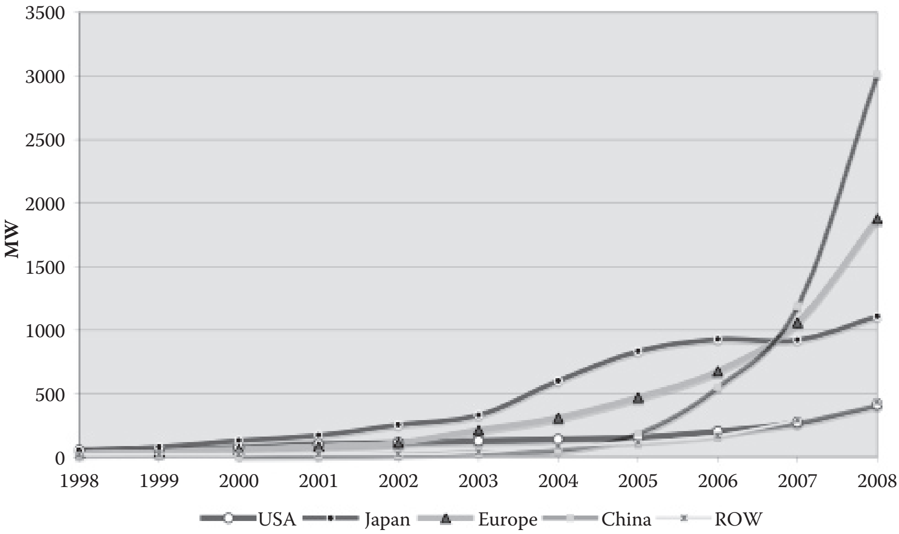

FIGURE 8.13 Japan led annual global PV production until 2007, when China became the global leader exporting 98% of its production (Approximated from sources: Worldwatch, Maycock, Kaizuka, Marketbuzz, and Wicht).

With regard to PV generation systems, in 1993, JET began registration of system interconnection devices linking PV modules installed on residential homes with electric power company systems. In addition, JET began calibration service for PV modules in April 2002 and began certification of PV modules in 2003. The JET PVM Certification Scheme is a voluntary program operated by JET and certified to IEC standards 61215 and 61646. The main objectives are to verify the safety and reliability of PV modules. Certificates are granted to modules after successful completion of applicable

FIGURE 8.14 Sanyo corporate headquarters in Tokyo with BIPV on the south, east, and west sides of this office complex.

tests based on IEC module test standards. In 2006, JET also began testing for PV module safety in accordance with IEC 61730 (JET, 1998, 2002).

Likewise, JET certifies inverters for PV systems. In Japan, there is no requirement to use JET-listed inverters and modules. However, most manufacturers want to participate in the JET program so that their modules are viewed as independently certified and thus be more competitive in the marketplace.

8.4 FUTURE JAPANESE TRENDS

In Japanese society, the use of PV is seen as important and necessary from a social, cultural, and ecological perspective. Likewise, Japanese leaders and industry see PV as a revolutionary technology that can make significant contributions to the electric power sector while making good business sense. A combination of R&D support and installation subsidies support has proven an effective strategy to promote PV technology development.

Government involvement has been important at the initial stage of technology introduction. Market subsidies help create initial markets. The Japanese PV system market will continue to benefit and expand even as government subsidies for the residential sector are eliminated. The leading market sector will continue to be residential installations for the near future. However, there will be greater emphasis on PV systems growth in the public, industrial, and business facilities sectors.

The Japanese government and industry view the next 25 years as a critical period for the creation of a full-scale PV market. A cumulative capacity of 83 GW of PVs in Japan is seen as achievable by 2030, by which time PV could meet 50% of residential power needs. This is equivalent to about 10% of Japan's entire electricity supply.

The PV price targets to be achieved by means of R&D, large-scale deployment, and export sales are ¥23/kWh by 2010, ¥14/kWh by 2020, and ¥7/kWh by 2030. Future PV cost goals were chosen based on making PV competitive with conventional energy rather than on any type of technology feasibility study. Thus, the goal of ¥23/kWh by 2010 corresponds to the current residential electric rate, 14¥/kWh by 2020 corresponds to the current commercial rate, and ¥7/kWh by 2030 corresponds to the current industrial rate. All price goals are defined in terms of 2002 yen.

As PV systems grow across the world, Japan has placed itself as a global leader to meet future PV demand. The Japanese industry model is outwardly focused toward export markets and the majority of Japanese-produced PV product is exported. Japanese industry has set up overseas manufacturing operations in Europe, the United States, Asia, and Mexico.

8.5 STAND-ALONE PV APPLICATIONS

Over the past quarter century, the developing world has adopted stand-alone PV technologies in earnest for social and economic development. PV is a viable alternative to traditional large-scale rural grid systems. With the advent of PV as a dependable modern technology alternative and more private participation and choices made available to the general public, PV systems have become attractive throughout the less developed parts of the world. The challenge is to develop financing strategies that are affordable to potential clients.

Off-grid markets represent the natural market for PV technology, which does not require any government subsidies to be competitive or successful. The technology fills a real-world niche and is especially useful for developing countries, where often the national electric grid is lacking coverage. The use of PV systems in rural regions of the developing world has increased dramatically from an initial concept pioneered by a few visionaries over 25 years ago to many thriving businesses throughout the developing world today.

PV is a viable alternative to traditional large-scale rural grid systems. With the advent of PV as a dependable modern technology alternative and more private participation and choices made available to the general public, PV systems have become attractive all over the globe, with literally millions of rural households electrified via PVs. Indeed, the most common PV system on the planet is the small ~50 W_p solar home system providing basic electricity for a few lights, radio, and maybe a small TV. Even smaller solar lanterns and flashlights incorporating LCDs are more popular. The challenge is to develop financing strategies that are affordable to potential rural clients, who often have incomes dependent on crop harvest cycles.

8.5.1 PV Solar Home Lighting Systems

PV first served space and remote communication needs, but quickly became popular for basic domestic electricity needs for residences in rural regions in the United States and then throughout Latin America, Africa, and Asia. During the mid-1980s, solar energy pioneers began to disseminate PV technologies in rural Latin America as a solution for providing basic electricity services for populations without electricity. Some of the first pilot projects in the world were undertaken by non-government organizations (NGOs), such Enersol Associates in the Dominican Republic beginning in 1984 (Figure 8.15). Gradually throughout the developing world, small solar companies began to form as key module manufacturers of the time, such as Solarex and Arco, sought out distributors for off-grid rural markets. By the mid-1990s, these activities were followed by large-scale solar electrification activities sponsored by government agencies in Mexico, Brazil, South Africa, etc.

Many of these early large-scale PV government electrification efforts faced sustainability issues as planners attempted to force large-scale rural solar electrification projects onto unknowledgeable rural users. Common problems included use of inappropriate battery technologies, substandard charge controllers, unscrupulous sales personnel, and poor-quality and unsupervised installations. Often these were giveaway programs, so there was no sense of ownership from the recipients, which can often lead to a lack of responsibility to care for systems. Despite these hurdles, only rarely did PV modules themselves ever fail; in fact, they continued to be the most reliable part of any installed system.

In response to early system failures, implementing agencies gradually began to adopt basic technical specifications that observed international standards that improved the quality and reliability of PV systems. Rural users mostly want a PV system that works to provide basic electric light and entertainment with radio and TV. PV users are not interested in the finer points of technical operation and maintenance. They want a simple and functional system that is easy to maintain.

FIGURE 8.15 Latin America's first PV training center established by Richard Hansen (far left) of Enersol Associates in the Dominican Republic, training both local technicians and Peace Corps volunteers (1985).

Think sustainability. All paths should lead to this and institutions applying solar energy systems must have a true commitment for long-term sustainability. Government agencies face particularly difficult challenges because the parties in power often change. The ultimate goal is to have a well designed and installed solar energy system that will provide many years of reliable and satisfactory service. The past quarter century has set the stage for future solar development, which is growing exponentially.

One good example of a PV lighting system (PVLS) for the home was deployed in Chihuahua, Mexico, by Sandia Labs/NMSU for the USAID/DOE Mexico Renewable Energy Program in the late 1990s with the state of Chihuahua. The program installed a Solisto PVLS designed by Sunwize Technologies to meet the Mexican electric code requirements (i.e., NEC). This is a prepackaged control unit specifically engineered for small-scale rural electrification and long life. Key characteristics of this system were that both the positive and negative legs were fused (an ungrounded 12 V system) and proper disconnects were used. The system employed a sealed maintenance-free lead-acid battery and a solid-state UL listed charge controller that uses fuzzy logic to help determine battery state of charge.

A total of 145 systems were installed in the municipality of Moris, located about 250 km west of Chihuahua City. The terrain consists of steep mountains and 1,000 m deep canyons in the midst of pine forests. The steep topography makes electric grid access difficult and indeed there is no interconnection with the national electric grid and no paved roads. Over three-fourths of Moris residents do not have access to electricity, and the few that do are mostly on diesel-powered minigrids.

The Moris PV systems consist of one 50 W Siemens SR50 module, which was the first deployment of these modules specifically developed for the rural lighting market. The PV modules are mounted on top of a 4 m galvanized steel pole capable of withstanding high winds. The module charges a nominal 12 V sealed gel VRLA battery (Concorde Sun-Xtender, 105 Ah at C/20 rate for 25°C; Figure 8.16). These are sealed, absorbed glass mat (AGM) and never require watering. The immobilized electrolyte wicks around in the absorbed glass mat, which helps the hydrogen and oxygen that form when the battery is charged to recombine within the sealed cells.

The thick calcium plates are compressed within a microfibrous silica glass mat envelope that provides good electrolyte absorption and retention with greater contact surface to plates than gel batteries. The Concorde batteries are in compliance with UL924 and UL1989 standards as a recognized system component. These batteries meet U.S. Navy specification MIL-B-8565J for limited hydrogen production below 3.5% during overcharging (less than 1% in Sun-Xtender's case), which

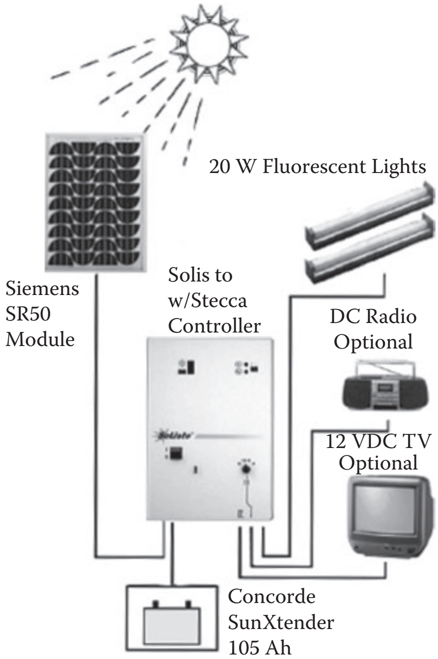

FIGURE 8.16 Residential Solisto PV system used in Chihuahua, Mexico.

means they are safe for use in living spaces. All batteries were installed inside a spill-proof, child-proof, heavy plastic battery case strapped shut.

Control is maintained through the Solisto power center via a UL-listed Stecca charge controller with a 10 A fuse. The system has a DC disconnect and six other DC fuses protecting different circuits. The Stecca controller uses fuzzy logic to monitor battery charging to avoid under- or over-charging the battery and is equipped with an LED lighted display to indicate state of charge. The Solisto power center is still available on the commercial market; Chihuahua marked the first use of these power centers in the world.

The PV system powers three compact fluorescent lamps with electronic ballasts (20 W each). It also has a SOLSUM DC–DC voltage converter (3, 4.5, 6, 7.5, and 9 V options) and plug to allow for use of different types of appliances, such as radio and TV. For an extra US$200, end-users could also elect to install a Tumbler Technologies Genius 200 W inverter; although few chose to do so, several users did install satellite TV service, which comfortably allowed them about 3 hours of color TV viewing in the evenings. The design of the Solisto SHS assumed that a household using the full set of three fluorescent lamps for an average of 2 hours a day would consume about 120 Wh/day on average. Given that Chihuahua averages about 6 sun-hours/day and assuming an overall PV system efficiency of 60% for this fairly well designed system (i.e., including battery efficiency losses, module temperature derate, line losses, etc.), the user could expect on average to have about 180 Wh/day of available power.

Of course, there are seasonal variations and double or more power could be extracted from the battery on any single day, but could not be sustained long term. As is typical for solar energy users, the Mexican users quickly learned to live within finite energy system bounds and to ration energy use during extended cloudy periods, which are relatively rare in Chihuahua.

Also of particular interest was an additional innovative financing component representing the first financing of PV systems anywhere in Mexico. The financing activities of this program were conducted by the State Trust Fund for Productive Activities in Chihuahua (FIDEAPECH). This state trust fund provides direct loans and guarantees, primarily based on direct lending (e.g., to

FIGURE 8.17 Solisto 50 W_p PV lighting system installed in Talayotes, Moris County, Chihuahua.

farmers for tractors). FIDEAPECH designed and implemented the revolving fund in which the municipality paid 33% of the total cost of PV home-lighting systems up front, end users provided a down payment of 33%, and the remaining 34% was financed for 1 year by FIDEAPECH. The municipal government provided the loan guarantee and eventual repayment to FIDEAPECH. The total installed cost of each quality-code-compliant PV home lighting system was about US$1,200. Other 50 W_p PV systems had been installed at the same cost in this region, at considerably worse quality and performance (e.g., with some failures reported in less than a month) (Figure 8.17).

Since October 1999, the performance of a Solisto PV lighting system has been continuously monitored at the Southwest Region Solar Experiment Station of New Mexico State University (NMSU) in Las Cruces, New Mexico, simulating usage of about 171 Wh/day. The long-term monitoring provides a reasonable base case with which to compare fielded systems. The monitored system was still functional in 2008. The Stecca charge controller successfully protected the battery from severe abuse from overcharging and deep discharging during prolonged cloudy periods. Charge regulation using pulse-width modulation charging and fuzzy logic to determine battery state of charge has performed very well for the sealed batteries, providing good lifetime. The nominally regulated voltage on the battery averaged 12.9 VDC each day, with the lowest battery voltages observed as 11.9 VDC after cloudy periods. The average daily depth of discharge (DOD) was about 13.5%. The Sun-Xtender battery manufacturer claims that the 105 Ah battery should have a cycle life of approximately 1,600 cycles for 40% DOD at 25°C and 5,200 cycles at 10% DOD.

NMSU also had the opportunity to monitor the systems in the field after 5 years. Performance was assessed through electrical measurements, visual inspection, and an end-user survey to determine user satisfaction. A total of 35 evaluations were performed. The results showed that over 80% of the installed systems were operating correctly and as designed, 11% were in fair condition (most commonly, one of three lamps was no longer working), 6% were nonoperational, and 3% of systems had been dismantled (e.g., user moved). The high percentage of working PV lighting systems after 5 years demonstrates the potential reliability for PV home lighting systems. In the household survey, NMSU found that 94% of users expressed complete satisfaction with their PV lighting systems, 86% thought that PV was better than their previous gas lighting source, and 62% believed that the PV systems were reasonably priced for the service provided (Foster, 2004). The sealed battery lifetimes were good. PV modules proved to be one of the most reliable components, all modules were functional, and no module problems had been reported. New and expanded evening activities, such as sewing, watching TV, reading, and studying, were also reported.

The PV lighting systems in Moris Chihuahua performed well after 5 years and met original system design and life criteria (Figure 8.18). The PV systems saved an average of US$300 over 5 years

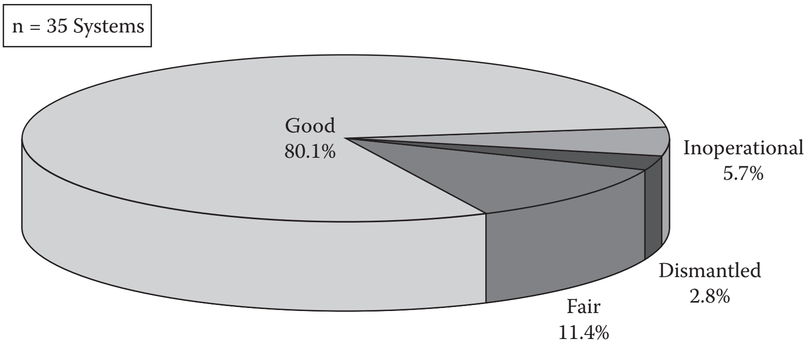

FIGURE 8.18 Over 90% of Solisto PV SHS were operational in Chihuahua after 5 years.

in lieu of previous gas and dry-cell battery options, while providing superior light and entertainment capabilities. The end-users have been very satisfied with the PV lighting systems. The Moris PV lighting systems demonstrate that, with proper diligence and detail to design and installation, PVLS can provide many years of useful service with little or no maintenance actions required.

8.5.2 PV Battery Charging Stations

The Nicaraguan National Energy Commission (CNE) with the World Bank implemented a large-scale solar rural energy initiative called the Renewable Energy for Rural Zones Program (PERZA—Proyecto de Electrificación Rural para Zonas Aisladas) during the mid- to late-2000s. Approximately 80% of Nicaragua's rural population does not have access to electricity. PV is a promising alternative for providing energy to rural areas there, either through individual PVLS for the home or centralized PV battery charging stations (PVBCSs). The project installed centralized PVBCSs in the Miskito region of northeast Nicaragua, which is one of the countries with the lowest electricity coverage in Latin America.

Both approaches charge batteries through charge controllers. Typical appliances powered by one battery per household are a few energy-efficient light bulbs, a radio, and perhaps a black-and-white TV. The main difference is that the batteries are charged centrally in the PVBCS (and then transported by the users). For PVLS, each household has its own small PV module, battery, and charge controller. The advantages of PVBCS are potential economies of scale in management and battery charging, as well as the potential to adapt payment schedules to local needs. The main advantages of PVLS are the increased convenience and the household charge controllers, which avoid deep discharging and increase battery lifetime over PVBCS.

These indigenous Miskito communities are located in the North Atlantic Autonomous Region (RAAN) of Nicaragua north of Puerto Cabezas in the Waspam area. The project financed seven PV battery charging stations that provide energy for approximately 300 homes that represent about three-quarters of the total population of the communities of Francia Sirpi, Butku, Sagnilaya, and Ilbara. These battery charging stations were installed in November 2005 in locations selected by the communities so as to facilitate access by the population. Each home has a complete "kit" that includes a battery, two fluorescent lamps, and a voltage regulator. All of the PV systems and kits have similar design and construction.

This project was subsidized entirely by the government of Nicaragua, due to the extreme poverty conditions of the Miskito indigenous communities. The users paid a small fee, calculated based on their payment capacity, to recharge their batteries. A typical PV battery charging station in the community of Francia Sirpi comprises a 2,400 W PV array with three subarrays that can charge up to 24 lead-acid batteries at the same time (Figure 8.19). Shell SQ80 80 W_p PV modules are used.

FIGURE 8.19 One of the three PV battery charging stations (NW system) at Francia Sirpi, Nicaragua.

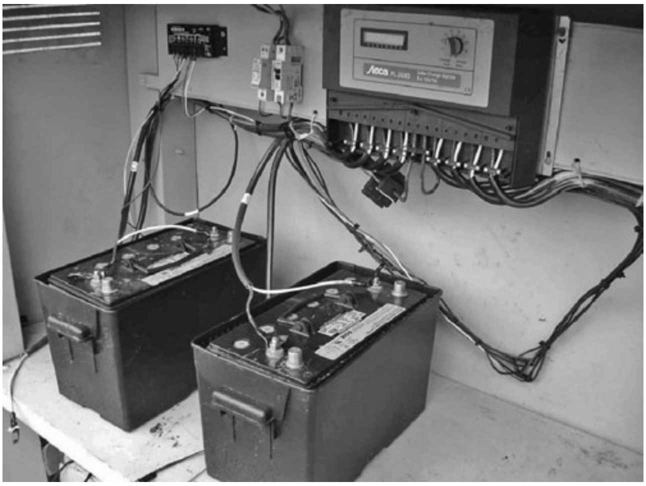

FIGURE 8.20 Battery charging at Francia Sirpi with Stecca controller capable of charging eight batteries simultaneously.

The complete system is composed of three PV 800 W_p substations with its own individual Stecca PL2085 controller capable of charging eight PV batteries per station simultaneously (Figure 8.20). The intelligent control unit in which the adjustment, operation, and display functions are carried out by a microprocessor serves as the brains of the battery charging station. The batteries are charged as quickly and efficiently as possible, in the order of priority according to when they are connected. In addition, an MPP-tracking system enables optimum use to be made of the energy available even if not all battery stations are fully utilized. No energy is wasted, even if all eight stations per subarray are not occupied (Ley 2006).

Approximately 150 residential household lighting packages were installed in the Francia Sirpi community. Residents were provided a PV lighting household kit with two or three 15 W fluorescent lamps. The lighting kit installed on each house had a small 6 A Morningstar SHS-6 charge controller used as a low-voltage disconnect for the 12 V, 105 Ah maintenance-free AGM battery

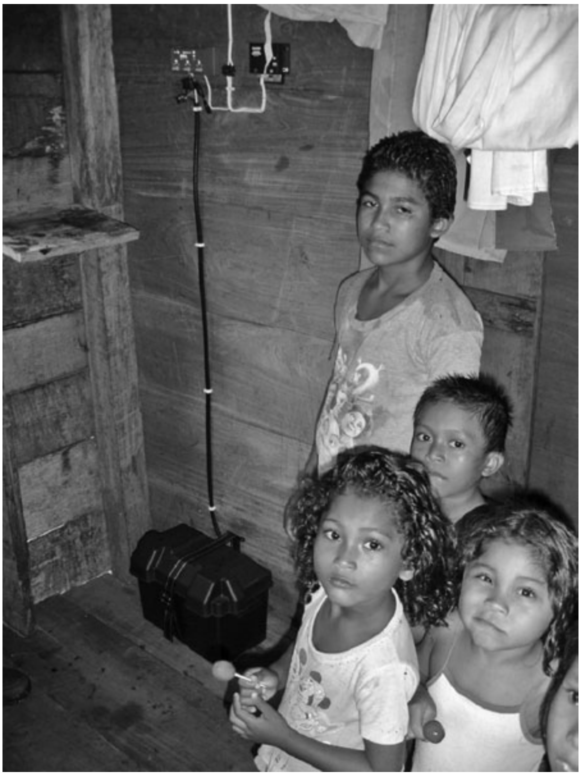

FIGURE 8.21 Nicaraguan home lighting kit with deep-cycle battery safeguarded in a battery box against the most curious PV system clients.

(Figure 8.21). No PV modules were installed on the individual homes. Instead, when the battery was low on energy, it was disconnected from the home lighting system and taken to the charging station site to be recharged. When fully charged, the battery was then brought back to the house and reconnected to the home lighting system.

The main concern for PVBCS is that, if the users overly deep-discharge their batteries (e.g., bypass the LVD), then battery lifetimes could be prematurely cut short. There were some early controller failures with the Stecca controller because, if the operator reversed polarity on the battery leads, the controller could fail because it was not polarity protected. These failed controllers were later replaced by Phocos controllers, which could only individually charge a battery. Some of the installed projects were also hit hard by a hurricane in October 2007, which hit the Miskito communities particularly hard.

The PERZA project essentially represents a “supply push” rather than a “demand pull” for off-grid PV applications. Off-grid rural energy services can be designed to be franchised and supplied through standardized distribution chains. The advantages of PVBCS are potential economies of scale in management and battery charging, as well as the potential to adopt payment schedules to local needs. The main advantages of PVLS are the increased convenience and the household charge controllers, which avoid deep discharging and increase battery lifetime over PVBCS. Typically, as seen by this project and others in Brazil and Bangladesh, PVLS is a more successful application.

8.5.3 PVLS Human Motivation: the Final Driver of System Success [Guest Authors Debora Ley, University of Oxford and H. J. Corsair, The Johns Hopkins University]

The community of Xenimajuyu is located in the highlands of Guatemala in the department of Chimaltenango. Although the electric grid ends fairly nearby, a confluence of factors including the mountainous terrain and the political fallout resulting from the division of this community from another larger community have made it very unlikely that the electric grid will be extended to Xenimajuyu in the foreseeable future.

One household in the community chooses to generate its own electricity. In addition to a small electric generator, the homeowner uses solar PV panels to meet his electricity demand for lighting and entertainment. The system has been in operation for over a decade, even though the panels are of poor quality, the system lacks a charge controller, and the automotive battery is inappropriate. This system uniquely illustrates the role of human motivation in the sustainability of rural solar PV systems: The individual decisions of the homeowner to keep the system operational have proved more powerful than the technical shortcomings of the system.

Guatemala has an overall electrification rate of 83.1% (CEPAL 2007a), although more than 40% of the rural population remains without electricity (Palma and Foster 2001). This is equivalent to approximately 2.2 million people or almost 440,000 homes (CEPAL 2007b) without access to the national electric grid. The so-called Franja Trasveral Norte, consisting of the Departments of Huehuetenango, Quiché, Alta Verapaz, Baja Verapaz, and Izabal, together with Petén, include the poorest departments with the most people without electricity in Guatemala. This population without electricity consists mainly of the 32% of the population that lives in extreme poverty, according to statistics from 2000 (Hammill 2007). The same statistics indicate that 56% of the population lived in poverty in 2000 (Hammill 2007). In addition to high rates of poverty and extreme poverty, these departments are characterized by communities with very difficult access and a high dispersion rate of houses (Arriaza 2005)—characteristics that make it economically infeasible for the grid to be extended. Because of this, renewable energy is often the best electrification option. This is especially true for Guatemala due to its solar resources.

According to various PV design guidebooks, the minimum solar resource that should exist before a project can be considered feasible is 300 W/m^2/day. The *Solar and Wind Energy Resource Assessment* (SWERA), cofinanced by the Global Environmental Facility (GEF) and the United Nations Environment Program (UNEP), indicates good to excellent solar resources (400–600 W/m^2) in areas of Guatemala coincident with the most marginalized population of the country. Rural Guatemalan communities have been using isolated PV systems since the early 1990s in applications that vary from household and community lighting to productive uses to community services (CEPAL 2007a; Arriaza 2005; Palma and Foster 2001).

Although there is not an exhaustive list of installed PV systems in the country, the government, through the Ministry of Energy and Mines, has installed PV panels in approximately 80 communities serving nearly 3,435 families with 50 W systems. Some of these systems have been uninstalled and a subset of these relocated. In the 8 years leading up to 2001, other institutions installed nearly 5,000 household systems. These systems typically consist of a 50 W PV module, a 12 V deep-cycle battery, a charge controller, and three CF light bulbs, providing about 3 hours of illumination per night. This means over 220 kW of residential PV have been installed, generating over 400,000 kWh per year (Palma and Foster 2001).

Numerous lessons have been learned over the years and some of them have shaped more recent installations. Early PV projects focused on technical aspects while ignoring human and social needs (Palma and Foster 2001). Although technical shortcomings may be a cause of failure of PV projects, the case study in the next section illustrates that, despite these technical shortcomings, human motivations and convictions can lead to long-term project sustainability.

8.5.4 PV in Xenimajuyu: the Xocoy Family [Guest Authors Debora Ley, University of Oxford and H. J. Corsair, The Johns Hopkins University]

The use of candles, kerosene, and ocote (a type of fuel wood) are common in rural unelectrified households in Guatemala. Richer families might be able to afford a car battery or a diesel generator to power light bulbs, radios, and televisions; however, most families do not have this option and burn three to five candles per night depending on the number of family members. With the cost of each candle at 1.5 quetzales, families can spend up to US$1 on lighting energy per day, representing a higher percentage of their income than lighting consumes in urban populations (UNDP 2005).

The Xocoy family lives in the community of Xenimajuyu. The terrain where the community is located is very mountainous, which can make the extension of the power grid prohibitively expensive even over short distances (Palma and Foster 2001; CEPAL 2007a). According to a local Peace Corps volunteer, the community of Xenimajuyu split off from Chuisac, a larger neighboring community, to form its own autonomous village. When the parent village got access to grid electricity in 2000, Xenimajuyu was not included in the plan. Because it is small and particularly difficult to access, the community does not anticipate grid extension in the foreseeable future. The Peace Corps proposed a community-wide photovoltaics electrical project, though it is in the very early stages and the timeframe for completion is not realistically known.

Estanislado Xocoy and his family currently meet their energy needs using three different sources: the traditional fuels often used in rural Guatemala, a gasoline-fired generator, and a small PV system. The family seems to prefer its small gas generator to more traditional lighting sources. Although the generator produces enough energy for the family's needs, it is not an ideal option because of the high and volatile price of fuel and the difficulty of transporting fuel from the gas station to the home.

The lighting energy source that the family claims to prefer is their solar PV system. The system is very simple and consists of solar panels, a battery, three compact fluorescent lamps, and a small black-and-white television.

The owner has two identical PV panels, neither of which has a module plate. The first one was purchased new almost 11 years ago, while the second was purchased used 3 years ago. The previous owner stopped using it when he got grid electricity. The first PV panel is mounted on the house's roof. It is a 50 W nominal amorphous thin-film silicon panel. The discoloration in the panel surface and the corrosion in the wires are evidence of significant degradation of the panel. The homeowner has had the panel for longer than the anticipated 10-year life of an amorphous panel, so this degradation is not unexpected. The degree of degradation could not be measured precisely because ambient conditions were not conducive to accurate measurement. It is installed on an eastward-facing roof slope, rather than facing south as recommended, and is mounted directly on the metal roof, rather than on a mounting structure that would allow air circulation to cool the panel and improve its performance. It is also installed with an inclination of less than 10°; an inclination approximately equal to the latitude of the location (about 15° in this case) will produce optimal annual power output. The dirt on the panel reduces the amount of sun that hits the panel and therefore its output.

The second panel, which is even more severely degraded than the first, had been connected in parallel to the first panel for approximately 6 months, but was removed from service because the owner believed it was no longer providing any benefit. Measurements of output of this second panel showed that it was capable of producing some electricity, though the small quantity may or may not merit its being reinstalled to supplement the currently installed panel.

A charge controller can significantly improve system performance by preventing overcharging or overdischarging of the battery. This household system lacks a charge controller; thus the frequency with which the battery must be replaced and therefore the cost of the system are increased.

A deep-cycle battery designed for PV or marine use is best suited for solar applications. This system made use of an automotive battery, which degrades quickly under the deep discharge cycles demanded of this type of system. However, the battery is well maintained, without evident corrosion, overheating, or loose connections that can be problematic with batteries in solar home applications. The owner replaces the car battery every 2–3 years when the terminals “get humid,” as he describes it. The system can only light one bulb for 1 hour instead the normal three bulbs for 3 hours, together with 3 hours of television or, alternatively, 5 hours of lighting with no television.

The Xocoy family’s system almost entirely fails to meet the norms and standards expected of a robustly designed quality system: The panel is inappropriately mounted and in poor condition; the wiring is in poor condition; the battery is inappropriate to the application; important system components such as the charge controller are missing; and the system is installed without basic safety considerations such as electrical grounding or a compartment to protect family members from accidents with the battery. However, this household has kept this system successfully operational for over a decade, and even wants to expand the system by replacing the second faulty panel with a new one. The owner’s conviction is that solar energy works: Photovoltaics represents a more attractive option to his family and his community than do fossil fuels or traditional energy sources, as well as a more realistic option than waiting for grid extension. Estanislado Xocoy may be an opinion leader and a technical resource who will be a powerful enabler of the project to electrify the community using solar energy.

8.6 PV FOR SCHOOLS

Thousands of rural schools in the developing world do not have access to electrical grid power. It is important to bridge this gap so that rural student populations living outside electricity grid services can also have the same opportunities as other students. An enhanced quality of education forms a foundation for increased productivity, leading to higher standards of living. Solar power offers a practical way to meet such power needs. Renewable energy technologies can be used to bring services, such as distance education and computer Internet access, to rural isolated communities, where the application of such technologies is appropriate and suitable. The high costs associated with fuel purchases, transportation of fuel, and engine maintenance, coupled with environmental costs that are difficult to quantify, make renewable energy an attractive alternative to conventional fuel-burning motor generators. PV systems are used to power televisions, DVDs, and computers to modernize the educational experience of rural schoolchildren (Figure 8.22).

Several programs in Mexico and Central America are using renewable energy to bring quality distance education programs to their rural populations. The Mexican Secretariat of Public Education is recognized for its distance learning programs that are based on satellite broadcast. Most of the schools in the programs are located on the electrical grid, but there is an increasing desire to extend the educational network to off-grid areas (Figure 8.23).

An ingredient often lacking in many programs is a clear understanding of what renewable energy technologies are, what equipment is available, and how they can best be used to meet energy needs. The technical expertise required to implement projects that incorporate the use of renewable energy is often overlooked and does not exist within implementing agencies. In-country partners need knowledge, experience, and engineering expertise to install and operate long-lived, quality systems.

PV systems are currently installed on more than 500 off-grid schools in Mexico and over 300 schools in Honduras and Guatemala. Some of the PV systems in use have been poorly designed and installed and thus are operating inefficiently. Most problematic PV systems have been identified to suffer from simple, resolvable problems such as

FIGURE 8.22 PV-powered COHCIT satellite telecenter with Internet connectivity using quality BOS components with master PV installer Ethel Enamorado in Sosoal, Lempira, Honduras.

FIGURE 8.23 A solar PV-powered one-room *Telesecundaria* school in Quintana Roo, Mexico.

- undersized battery cables, thus limiting battery recharge;
- improper orientation and location of the panels;
- incorrect types of batteries used for the application; and
- lack of end-user knowledge on proper operation and maintenance.

Public education agencies in Mexico and Central America had, in some measure, lost confidence in the use of renewable energy sources and technologies—thus diminishing the willingness to repair or replace existing systems and/or to purchase new systems for additional rural off-grid schools. However, with appropriate knowledge and institutional capacity, the majority of the problems are simple and resolvable. Around 2000, PV school installations in many parts of Latin America began to show great improvements as the industry matured and implementing agencies gained valuable training and experience. Successful large-scale rural school PV electrification programs have been implemented in Mexico, Guatemala, Cuba, Honduras, Peru, and Brazil. The PV systems are used to power televisions and computers to modernize the educational experience of rural schoolchildren.

8.7 PV FOR PROTECTED AREAS

Renewable energy technologies have been widely applied to support protected areas throughout Latin America, especially in Guatemala, Mexico, and Ecuador (Galapagos). Key environmental agencies such as the Nature Conservancy, World Wildlife Fund, and Conservation International have embraced PV technologies.

Use of solar energy in protected areas benefits the living conditions of researchers, technicians, and rangers, as well as providing energy for environmental training centers. The solar energy systems also have the advantage of providing power without the noise or pollution associated with conventional fossil-fueled generators, while reducing the risk of fuel spills in these sensitive biosphere reserves. As always, up-front design decisions, user operation, and long-term maintenance issues play an important role for overall system reliability.

Solar energy is an environmentally appropriate example to neighboring buffer communities (often without electricity) surrounding biosphere reserves, which can likewise benefit by replicating the protected areas' example. Solar energy systems also provide a useful example for visitors and tourists to take back home.

In addition, the remote protected-area facilities benefit economically from solar installations through reduced operation and maintenance costs associated with fossil fuel generators. Actual system life-cycle costs for any particular solar or wind energy system vary and are a function of design, usage, application, and maintenance. With proper system operation and maintenance, the expected solar energy system lifetime should exceed 25 or more years (with appropriate battery replacements, etc.).

One example of a PV-wind hybrid system application is found at Isla Contoy in Quintana Roo, Mexico (PNIC—Parque Nacional Isla Contoy) (Figure 8.24). It is informally known as Bird Island, due to the 151 bird species found on the island, surrounding which are over 5,000 frigates. It is also an important site for protecting marine turtles, crocodiles, 31 coral species, and 98 indigenous plant species.

The park was burning gasoline transported by boat from nearby Cancun for a 3.5 kW generator, with significant noise pollution that disturbed birds, as well as the constant threat of fuel spills. Eventually, $35,000 in funding was secured from USAID to support the installation of a hybrid renewable energy system. Of particular concern was the potential impact of wind turbines on the large bird sanctuary (i.e., threat of bird kills). Because small wind turbines spin very fast and are quite visible, it is unlikely that a bird would fly into the spinning blades. It was agreed that any wind turbines would not be installed on any of the key bird transit routes over the island (typically, right along the coastline) or in critical nesting areas (which are off limits to all visitors as well). Only two birds had been killed by the wind turbine after the first 5 years.

During the system design process, it was determined by Sandia Labs that a hybrid solar–wind energy system would be the best option for PNIC. The average annual wind speed was measured at 6.5 m/s. Loads were sized for an average daily usage of 5,000 Wh/day, mostly for lighting, communications, radio, fans, and TV/VCR, as well as an LCD projector (for workshops), shop equipment, kitchen appliances, and a water pump.

The architecture of the original hybrid system consisted of two 500 W wind turbines, a 256 W_p amorphous PV array, a 4,500 W Trace sine-wave inverter, and 19.2 kWh battery bank. The wind machines were originally installed on a tall dune on the east side of the small island. A 3-day training course was then conducted on renewable energy systems design, operation, and maintenance for 23 persons from area institutions, including PNIC. Also, individual training was provided to the three key PNIC maintenance personnel on appropriate RE system operation and maintenance (Romero-Paredes, 2003).

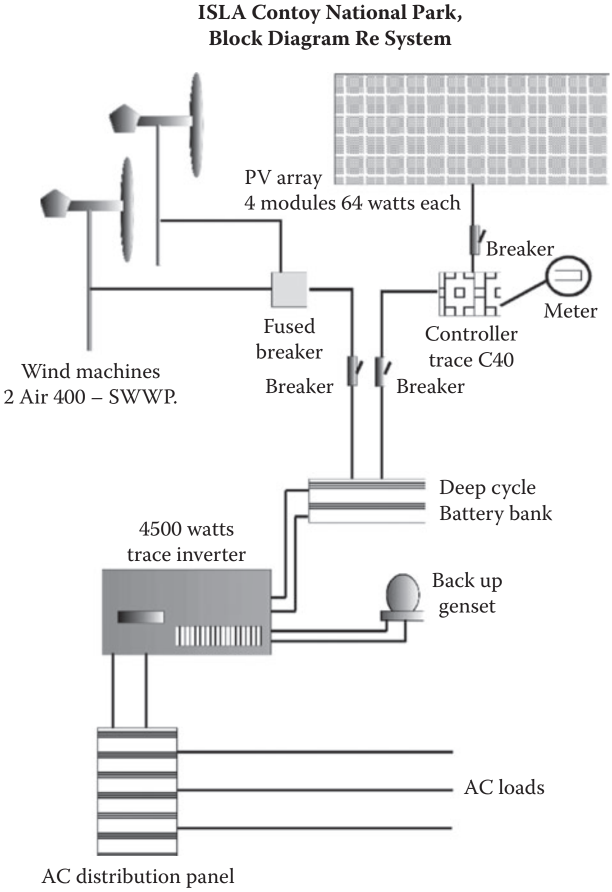

FIGURE 8.24 Isla Contoy National Park (Quintana Roo, Mexico) solar-wind hybrid system designed by Ecoturismo y Nuevas Technologias and funded by USAID with Sandia National Laboratories.

The hybrid system has evolved since installation, adjusting to expanding energy needs and operational conditions. After the first year of operation, the original wind machines had suffered from severe corrosion problems due to the salt spray environment and, under warranty, were replaced by the installer. Two Southwest WindPower (SWWP) Marine Air 400 W_p units (more corrosion tolerant) were installed at the top of the park's observation tower, and one H80 wind machine was left on the original dune site.

The PNIC station was completely remodeled in 2000 by SEMARNAT. A 40 kW diesel plant was installed to operate a reverse osmosis desalination unit, as well as vapor compression air-conditioning systems. However, the desalination plant was never operated and the diesel plant is used just a few hours per month. Subsequently, the battery bank and the PV array were further expanded thanks to a donation from the European Union (EU); the bank grew 300% in size (to 2,400 Ah) and an additional PV subarray was added for a total of 1.5 kW_p. This is one of the most complex renewable energy systems installed in Quntana Roo.

In September 2002, Hurricane Isidore caused substantial damage to the Isla Contoy hybrid system. The hurricane destroyed the dune-mounted H80 wind turbine due to a unique tower failure mode. The galvanized NRG tower had been guyed with stainless steel guys due to the severe corrosion of the area, so the guys and tower tubes did not fail; rather, the actual tower base failed. The base had corroded to the point that the high hurricane winds caused it to fail where the tower and base meet. The wind turbine itself did suffer some damage at its mounting base due to the fall. There was no damage to the actual rotor, but two of the three rotor blades were damaged when the tower collapsed. The smaller SWWP units had been lowered for the hurricane and did not suffer any damage.

The Trace inverter also failed during Hurricane Isidore due to rainwater entering the inverter through a conduit leak, which caused a circuit failure. It took about 4 weeks for the two technicians sent by the Ecovertice Company to repair the inverter failure. An additional floor fan is now necessary to provide cooling because the original inverter fans failed.

The battery bank is somewhat undersized given current loads and should be further expanded to about 4,000 Ah. This will reduce cycling and extend the battery lifetime. The expanded EU portion of the battery bank did not include spark arrestors, unlike the original USAID portion, and thus presents a safety hazard for such a large bank (Figure 8.25).

In addition to hurricanes, one problem the PNIC has had to contend with is the ever changing park technicians and maintenance personnel, who make various adaptations to the hybrid system configuration that are never documented. This complicates future maintenance actions by new personnel who have to spend a great deal of time trying to understand undocumented system changes; which exacerbates accident or failure potential if components are incorrectly connected due to poor system documentation.

In summary, the PNIC RE hybrid system has satisfactorily met park energy needs. Since the tower collapse of the H80 wind turbine, most of the energy is generated from the PV array. Despite system ups and downs, the PNIC staff have been able to maintain the solar/wind hybrid system successfully and it has survived several major storms and hurricanes over the past 5 years. The system clearly shows that an important component for successful application of RE technologies is the institutional aspects related to follow-up support and maintenance.

FIGURE 8.25 Isla Contoy solar and wind energy power center, inverter, controls, and batteries.

8.7.1 PV Ice-Making and Refrigeration

Another key market segment for PV technology is application for remote refrigeration or ice-making. This can be done with or without electrochemical battery storage. Battery-based PV refrigeration technology is relatively mature from the standpoint that DC compressors, batteries, and charge controllers have been in mass production for years, leading to lower cost manufacturing. The battery-free technology is newer and has a much lower level of production, so the manufacturing cost is still relatively high.

A PV direct–drive or "PV-direct" solar refrigerator uses thermal storage, and a direct connection is made between the vapor compression cooling system and the PV panel. This is accomplished by integrating a phase-change material into a well-insulated refrigerator cabinet and by developing a microprocessor-based control system that allows direct connection of a PV panel to a variable-speed DC compressor. This allows for peak power-point tracking and elimination of batteries. This new direct-drive approach with ice storage may revolutionize refrigeration in remote regions around the world.

Solar PV power system applications are increasing due to both technical and economic factors. Some of the most successful applications for solar energy, such as water heaters and PV water-pumping, benefit from built-in energy storage. This is now true for solar refrigerators that use ice thermal energy storage. Although past solar PV refrigerators used batteries to store electricity, the latest work focused on the "PV-direct" concept and thermal storage to eliminate electrical energy storage. PV-direct technology can be applied to freezers, air-conditioners, and larger scale refrigeration systems; however, initial efforts have focused on small-scale refrigerators, which are most appropriate for off-grid personal or small-scale commercial use.

The battery-free solar refrigerator stores thermal energy in a phase change material rather than storing electrical energy in a battery. To develop a practical thermal storage system that effectively replaces the batteries, a well insulated cabinet and a phase change material with a high latent heat of fusion is required. For the commercial application, a chest-style cabinet with standard insulation is used. For the phase change material, a nontoxic, low-cost, water-based solution that has good freezing properties is selected. Based on the heat-leak rate of the cabinet, a quantity of thermal storage material is calculated to provide 7 days of reserve cold storage for an assumed average ambient temperature of 29.5°C (85°F). This thermal storage reserve is intended to simulate approximately the electrical energy reserve of batteries used for solar refrigeration systems. For efficiency, it is also necessary to make good thermal contact between the thermal storage material and the refrigeration system evaporator. Poor contact reduces the refrigeration system efficiency as well as the cooling capacity of the compressor. The phase change material is stored in containers located against the cold inner wall of the refrigerator cabinet, behind a polyethylene liner that holds the containers in place and hides the thermal storage containers from view.

To drive the refrigeration system directly (and efficiently) from solar panels, a variable-speed DC compressor is used. The variable-speed feature allows the compressor to operate longer during the day and make better use of the variable solar resource. A fixed-speed compressor would not be able to begin cooling as early in the morning or as late in the afternoon and would waste power during solar noon (when the available power is more than the compressor needs to operate). A fixed-speed compressor can only utilize about 50% of the solar resource.

A variable-speed compressor uses about 75% of the available solar resource on a sunny day, because its speed can vary to match the available solar input. The speed is controlled by a microprocessor, which seeks to maximize the compressor speed for the available solar power. The control algorithm effectively maintains the PV array at its peak power point while the compressor is on. The microprocessor also performs load testing of the array before starting the compressor, temperature control of the cabinet, and additional speed control as required to keep the compressor power within the manufacturer's limits. Starting capacitors are also used to furnish the compressor with a short power burst during turn-on. A small DC cooling fan is used to improve condenser and compressor heat removal.

The SunDanzer direct-drive prototype refrigerator uses thermal storage, and a direct connection is made between the cooling system and the PV panel (Figure 8.26). This is accomplished by integrating a water–glycol mixture as a phase-change material into a well insulated refrigerator cabinet and by developing a microprocessor-based control system that allows direct connection of a PV panel to a variable-speed DC compressor. The refrigerator uses a more efficient variable-speed DC compressor.

The unit is designed to run on 90–150 W of PV power (needed for compressor start-up), but only draws about 55 W when cycling. During cloudy weather, internal thermal storage keeps products cold for a week, even in a tropical climate. The battery-free unit is designed to work optimally in locations with at least 4 sun-hours per day using a variable-speed compressor and peak power tracking. The unit offers the most economical method for on-site refrigeration for rural people. SunDanzer is an American success story and has now sold thousands of solar refrigerators (most using batteries) around the globe.

8.7.2 PV Ice-Making

PV ice-making has not been widely deployed yet, but there have been some attempts. The world's first automatic commercial PV ice-making system was installed in March 1999 to serve the inland fishing community of Chorreras in Chihuahua, Mexico (Figure 8.27). The system was designed and installed by SunWize and supported by the New York State Energy Research and Development Authority, which teamed with USAID, Sandia, the state of Chihuahua, and New Mexico State University.

The US$38,000 hybrid system produced an average of 8.9 kWh/day at 240 V to the ice maker. The system coefficient of performance (COP) was 0.65 and a total of 97% of the energy was supplied by the PV array; only 3% was supplied by the backup propane generator. Production of ice varied each month due to changes in insolation and ambient temperatures and averaged about 75 kg of ice/day (11.5 kg/sun-hour). About every 9 months, the ice-maker water lines would need to be cleaned to remove calcium deposits. With a fixed timer setting, the ice

FIGURE 8.26 SunDanzer PV-direct drive refrigerator piloted in the indigenous Mayan village in Quiché, Guatemala, by NASA and Fundación Solar.

FIGURE 8.27 World's first PV ice-maker developed by SunWize for fishermen in Chihuahua (1999).

maker operated daily for 3 hours with a dozen 15-minute cycles at night to make ice, except on Sundays when there is no fishing (Foster, 2001).

The ice maker performed well for the first few years of operation but eventually fell into disuse after about 4 years. Long-term commitment and follow-up by the Mexican project partners was necessary for continued project success. Unfortunately, there were state political changes and the area faced a severe drought. The lake receded over 2 km from the ice house by 2003 and the fishermen moved their catch out to the other end of the reservoir. The ice-making system was shut down and has not been operated for the past few years.

8.8 PV WATER-PUMPING

PV water-pumping is highly competitive compared to traditional energy technologies. PV power is often the least expensive alternative as compared to extending the power supply grid for applications in remote sites or where loads are small. PV is best suited for remote site applications that have small to moderate power requirements. Some typical cost-effective applications in addition to water-pumping include residential electrification, lighting, small-scale irrigation, refrigeration, and electric fences.

Pumping water is a universal need for agriculture and the use of PV power is a natural choice for this application. Agricultural watering needs are usually greatest during sunnier summer periods when more water can be pumped with a solar energy system. Arid regions, which have the greatest water needs, also have the greatest amount of sunlight available. PV-powered pumping systems can meet the range of needs between small hand pumps and large generator-driven irrigation pumps: drip/trickle, hose/basin, and some open channel irrigation, although flood or sprinkler irrigation are rarely used with photovoltaics. PV water-pumping systems are simple, reliable, and low maintenance. Tens of thousands of agricultural PV water-pumping systems are in the field today throughout the world. PV pumping systems' main advantages are that they are reliable and durable, no fuel is required, and little maintenance is needed. The principal disadvantage of a PV system is the relatively high initial capital cost.

A PV-powered water-pumping system is similar to any other pumping system, with the exception that the power source is solar energy. These systems have, as a minimum, a PV array, a motor, and a pump. PV water-pumping arrays are often mounted on passive trackers (which use no motors) to follow the sun throughout the day, which increases pumping time and water volume. AC and DC motors with centrifugal, displacement, or helical rotor pumps are commonly used with PV pumping systems. If absolutely needed, a battery bank can be used to store energy (e.g., some residential systems often use this approach), but water is typically much more cheaply and effectively stored in a tank.

The advantages of PV water-pumping are long-term lower costs when compared with other alternatives such as diesel- or gasoline-operated water pumps. PV pumping is never a least-cost option if a site is already on the existing conventional electric grid. PV water pumps do not require an on-site operator and have a low environmental impact (no water, air, or noise pollution). Another advantage is system modularity, which provides the owner with the ability to meet specific needs flexibly at any given moment and to increase system size as water-pumping needs grow. Well designed and installed systems are relatively simple to operate and maintain. In order to make a PV water-pumping project successful, it is best to understand basic concepts such as solar energy, PV, water hydraulics, pumps, motors, and other system requirements.

Solar water-pumping is one of the most simple yet elegant solar applications found today, often providing many years of reliable service.

8.8.1 Hydraulic Workloads

The volume of water required daily is not adequate to determine the size and cost of a water-pumping system. The total dynamic head (TDH) should also be considered (pumping depth plus discharge height plus drawdown plus friction losses throughout the length of pipe.). For example, more energy is required to extract a cubic meter of water with a TDH of 10 m than with a TDH of 5 m.

A useful formula for quickly determining whether a given project is a good candidate for solar power pumping is to determine the hydraulic burden or duty (Figure 8.28). Multiply the daily volume of water that will be required (expressed in cubic meters) by the total dynamic head estimated for the pumping system (expressed in meters of height). This product is the *hydraulic workload* and provides an excellent indication of the power that will be required to meet the project's needs. If the result is less than 1,500 m^4, then the project is most likely feasible using PV. If it is between 1,500 and 2,000 m^4, it may or may not be feasible for solar pumping. If it is over 2,000 m^4, a technology other than solar options should generally be considered.

For example, 5 m^3 to be pumped with a TDH of 15 m gives a hydraulic workload of 75 m^4. Similarly, 15 m^3 to be pumped with a TDH of 5 m gives a hydraulic workload of 75 m^4. In both cases, the energy required is approximately the same and the cost of these systems is similar. When is the demand considered to be too great for solar water-pumping? Experience shows that a project

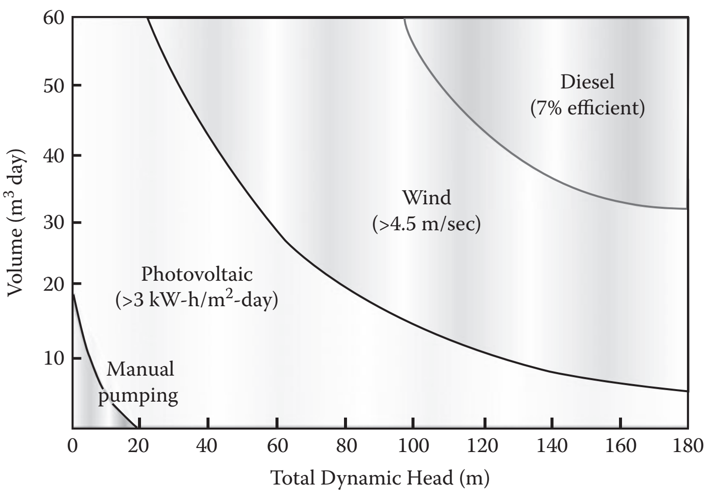

FIGURE 8.28 Water-pumping technology selection based on hydraulic workload.

is economically viable when the hydraulic workload is less than 1,500 m^4. Water-pumping systems powered by internal combustion engines or wind are more competitive when the hydraulic workload is greater than 2,000 m^4.

To obtain maximum benefit from a solar water-pumping system, the water pumped should be used for products of high value to the owner. The water should not be more expensive than the product. The hydraulic duty of any project is essential in determining the most appropriate technology. Figure 8.28 indicates the most appropriate technology, considering the daily volume and total dynamic head and assuming a minimal solar or wind energy resource. This assumes a daily solar insolation of greater than 3.0 kWh/m^2/day, an average annual wind resource greater than 4.5 m/s, and an average efficiency of 7% for diesel-powered systems (fuel at U.S. $1.50/gallon). Note that most diesel- and gasoline-powered pumps are often oversized and efficiencies are typically very poor, especially in the range competitive for PV.

8.8.2 Other Considerations

Other factors of significant importance are not easily quantifiable:

- *Experienced installers.* Ideally, PV water-pumping systems should be installed by professionals from the region, although this is not always easy for remote areas. In addition, it is important that the installer be easily located in case service should be required in the future (especially for the pump). The provider and installer should be able to demonstrate their experience, technical expertise, and integrity.
- *User acceptance.* Users should understand the abilities of solar energy systems, including their limitations, advantages, expected maintenance requirements, and principles of operation. Designers should involve users with general project design. This will allow them to grasp the technology better as well as feel a sense of buy-in to the project and its realistic outcome.
- *Security.* The nature and portability of solar water-pumping systems make them ideal for remote and isolated applications, but they also become vulnerable to theft and vandalism. They are best protected from theft if they are placed in areas that are not likely to be transited and seen by the general public.
- *Environmental benefits.* Solar energy technology helps maintain clean air and water quality. An added plus is that it pumps with little noise, unlike noisy diesel- or gasoline-powered pumps.
- *Batteries.* Batteries are a key part of PV systems in most applications, but are rarely used in stand-alone solar pumping systems. Batteries add cost and complexity to the system. It is far better to design a system where energy is stored in the form of additional pumped water available at the distribution tank instead of in electrochemical form with batteries. The only time batteries are commonly employed is for a household water pump with an existing battery bank supplying energy to other household loads as well.
- *Water needs.* In communities where water is easily available from traditional sources and the perceived benefit that the potential PV pumping project brings is mostly about an improvement in convenience, the attitudes regarding the real value of water and water conservation may be too cavalier to make a PV project feasible. This is a notable issue in some countries where many communities have multiple sources of spring water. The issue should be honestly examined with the community from two interrelated reference points. First, because PV is more expensive than other solutions, there should be some reflection of the higher cost in the tariff set. Communities unwilling to pay a higher price for water than the very low fees used in gravity flow systems are questionable prospects for PV. Second, in communities where water (even bad water) is relatively easily available from a traditional source, it can be extraordinarily difficult to inculcate the attitudes of

water conservation and careful use that are absolutely essential to making a PV project practical.

In defining a water program strategy with a PV focus, it is important to realize that PV occupies a niche, and that this niche is confined to a certain community size, well depth, and service level. It is far better to include PV in a mix of implementation options as one of the tools for meeting a rural need than to stipulate PV for a determined number of projects. PV can be a good option in some very difficult circumstances where other solutions are impossible, but it may not be suited to broad application within a region.

The flow chart in Figure 8.29 summarizes the key technical points for considering when PV is a likely feasible method for a water-pumping system. The selection process considers such parameters as distance to the grid, hydraulic workload, and the solar energy resource available at the site. As is often the case with water-pumping, no matter what the technology is, every project requires a somewhat customized and individualized approach.

For PV power systems, the energy needed to power the pump is provided by the Sun. Solar energy is captured and transformed into electrical energy by solar cells, which are the building blocks of a PV module. The solar energy is typically coupled directly to power a pump motor.

8.8.3 Pressure

A column of water enclosed in a pipe or tank exerts a force due to the weight of the water. This force is described as *water pressure,* also known as *head.* Water pressure is expressed in terms of pounds per square inch (*psi*) or in kilograms per square centimeter (kg/cm^2). Head is a useful indicator of water pressure that refers simply to the height of the column of water. For example, a column of water 20 m high would be said to have 20 m of head. Knowing the head, one can calculate the pressure and vice versa.

8.8.4 Static Head

A system where the water is not in movement is static. Regardless of whether or not water in a pipe or tank is actually flowing, the water pressure always exists and is referred to as the static head. In a static system, the water pressure is dependent exclusively on the height of the water "column" in the system. That is, a narrow column of water will have the same static head as a wide column, provided that both are at the same height. Two tanks of water filled to the same height will have the

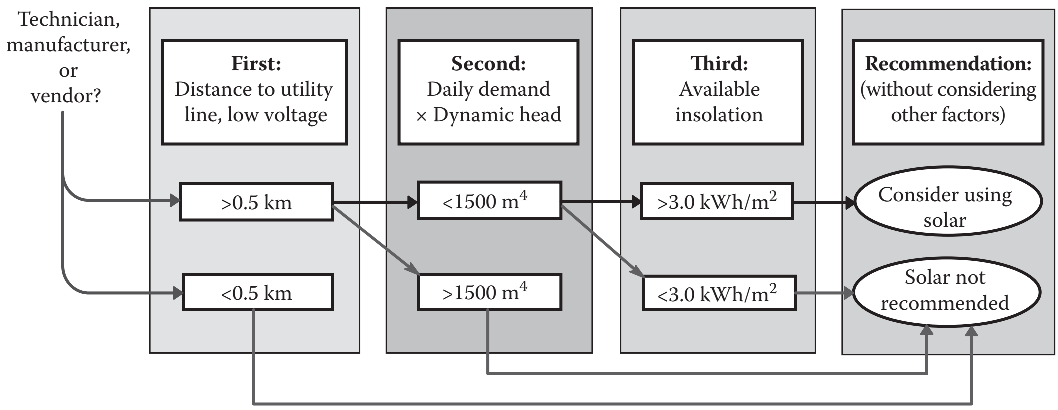

FIGURE 8.29 Basic decision-making flow chart for PV water-pumping use.

same pressure at an outlet on the bottom, even if one tank is narrower and has a smaller volume of water. The rule of thumb for calculating pressure and head is as follows:

$$1 \text{ psi} = 2.3 \text{ ft of vertical height (head)}$$

$$1 \text{ ft} = 0.43 \text{ psi}$$

or, in the metric system, as

$$1 \text{ kg/cm}^2 = 10 \text{ m}$$

$$1 \text{ m} = 0.1 \text{ kg/cm}^2$$

Example 8.1

A static column of water in a pipe indicates on a gauge a pressure of 37 psi. What is the vertical height of the column of water (i.e., head)?
Solution:

$$37 \text{ psi} * 2.3 \text{ ft/psi} = 85 \text{ ft}$$

Example 8.2

A column of water in a pipe runs to a point 25 m above its starting point. If the pipe is closed and full of water, what is the pressure at the starting point?

Solution:

$$25 \text{ m} * 0.1 \text{ kg/cm}^2\text{/m} = 2.5 \text{ kg/cm}^2$$

The column exerts a pressure of 2.5 kg/cm^2.

8.8.5 Pumping Requirements

For solar water-pumping systems, it is important to think in terms of how much water is required each day. Many water users, such as ranchers, are accustomed to pumping all of their water in a relatively short timeframe with an oversized gasoline- or diesel-powered pump. Solar pumping gradually pumps the same quantity of water during the course of the daylight hours. The pumping requirement is QH (meters to the fourth power/day), where Q is flow (cubic meters/day) and H is the dynamic head (m) (1 m^3 = 1,000 L). For surface water resources (rivers, streams, reservoirs), the water capacity needs to be determined by season or month. For wells, it is very important to determine the capacity and drawdown for different pumping rates. In both cases, the dynamic head needs to be determined correctly in order to select the right pump and the total solar energy power system required.

8.8.6 Dynamic Systems

When there is movement of water in a system, it is a *dynamic system*. The water pressure in a dynamic system is dependent not only on the water "column" height, but also on the friction from the movement of water in a pipe, as well as any drop in the static water level due to pumping. In the dynamic system it is necessary to take the following into account:

- *Length* of the pipe. The longer the pipe is, the greater is the pressure drop due to friction.
- *Diameter* of the pipe. The smaller the pipe is, the greater is the pressure drop.

- *Flow* of water. The greater the flow is, the greater is the pressure drop.
- *Roughness* of the inside of the pipe. The rougher the interior surface is, the greater is the pressure drop. PVC pipe is smoother than galvanized iron pipe.
- *Fittings and joints.* Each union or elbow has an additional associated pressure drop.
- *Change in static water level.* As water is pumped, the water level may drop.

The length of the pipe, the speed of the water, drop in static water level, etc. increase resistance and cause an increased pressure drop and higher pumping power requirements.

The *static head* (*SH*) refers to the height from the static water level in the well up to the discharge level. This is often divided into two components, as expressed in the formula that follows this paragraph. The *total dynamic head* (*TDH*) is the sum of all the components that contribute to the total pumping height, expressed in feet or meters. Dynamic head includes drawdown and all frictional and pressure losses. Frictional losses depend on size of pipe, flow (volume/time), number of elbows, etc. (Figure 8.30).

$$\text{TDH} = \text{SH} + \text{well drawdown} + \text{friction} \tag{8.1}$$

The friction factor can be handled in two ways: with pipe friction tables or with an estimated value. To use the friction table, the length of pipe used (vertical and horizontal distance), the type of pipe (PVC, GI), the flow rate, and diameter of the pipe must be known. The tables in Appendix B will provide the total friction loss. Because the friction losses are usually not a significant portion of the total, their value can also be reasonably approximated for the TDH equation. A standard default is to consider 2–5% friction loss for a well designed distribution system. If there are long pipe runs, this number may have to increase.

To use the friction tables found in Appendix B, first find the pumping flow rate (in liters per second) for the system by dividing the total daily water pumped by the number of seconds in the solar pumping cycle. A typical solar pumping cycle is around 6 h, between 9 a.m. and 3 p.m. In that period there are 21,600 s (6 h × 60 min × 60 s). If, for example, the daily water pumped is 25,000 l, then the average flow rate will be 25,000 L/21,600 s = 1.16 l/s.

This flow rate is applied to the tables along with the type of pipe material and pipe size (see Appendix B). In the case of a 2 in. PVC pipe, the friction factor for a flow of 1.16 l/s is 0.71, or more precisely, 0.71 m of friction for every 100 m of pipe distance (horizontal or vertical). If the pipe is 300 m long, the total friction factor would be about 2 m (0.71 × 3 = 2.13 m).

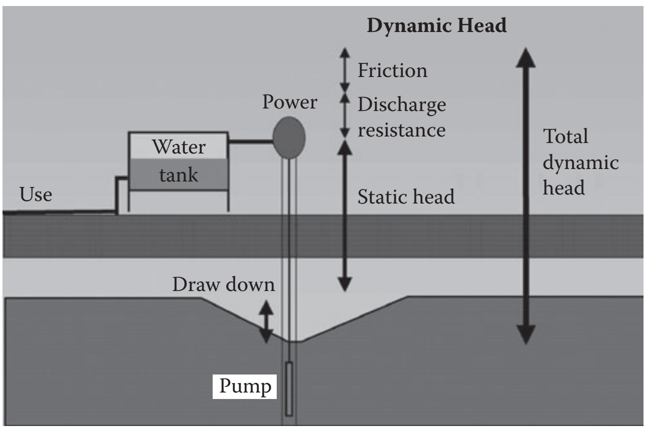

FIGURE 8.30 Total dynamic head includes all components.

Example 8.3

A small community has the following characteristics:

Static level of water in well	**31 m**
Drawdown	5 m
Height from well head to discharge at tank	16 m
Pipe run from well to tank	80 m
Daily water need (for 360 persons)	18,000 L
Pipe material and size	1.5 in. PVC
Average solar insolation	6 sun-hours/day

Determine the TDH.

Solution:

First, the height components are added (do not include the horizontal measurement):

$$31 \text{ m} + 5 \text{ m} + 16 \text{ m} = 52 \text{ m}$$

Then 2% is added for friction (using the default method):

$$52 \text{ m} * 0.02 = 1.04 \text{ m}$$

Round to the nearest meter.
The TDH is found to be

$$\text{TDH} = 31 \text{ m} + 5 \text{ m} + 16 \text{ m} + 1 \text{ m}$$

$$\text{TDH} = 53 \text{ m}$$

Alternatively, determine the friction factor from the friction tables:
Divide 18,000 l/day water need by the number of seconds for the average sun-hours: 6 sun-hours = 21,600 s

$$18{,}000 \text{ L}/21{,}600 \text{ s} = 0.83 \text{ l/s}$$

By the table for a flow 0.83 l/s, 1.5 in. pipe, PVC material: 1.70 m of friction for every 100 m of distance. For the 80 m pipe run in the example:

$$1.70 * 0.80 = 1.36 \text{ m}$$

Round to nearest meter.
The TDH is then likewise found to be

$$\text{TDH} = 31 \text{ m} + 5 \text{ m} + 16 \text{ m} + 1 \text{ m}$$

$$\text{TDH} = 53 \text{ m}$$

8.8.7 Water Demand

The average daily demand (cubic meters/day) is estimated for the month of high demand and/or the solar design month (month with lowest average solar insolation). Also, the demand must take into account any growth during the design period, which should be at least 10 years.

The water demand for livestock can be up to 90 l/day (Table 8.1). Evaporation, especially in windy and dry areas, will require even more water. Also, animals will only travel a limited distance from the water source, so the water sources need to be spaced around one source per 250 ha of rangeland. If the water supply and grassland are communal, then there is the distinct possibility that the growth in the size of the herds will result in overgrazing, especially close to the water supply.

The domestic water demand depends on number of people, usage, and type of service (Table 8.2). What is considered necessary in some countries or regions would be considered a luxury in other locations. In addition, people will consume more water during hot, dry periods. Local water consumption is the best guide; however, remember that usage per person will probably increase if water availability improves.

Village water supply includes clinics, stores, schools, and other institutions. Growth in demand will depend primarily on water availability, growth in size of herds or flocks, and growth in population for villages. Again, the growth in population should be estimated from present local trends (i.e., not from national trends).

Water demand for irrigation (low or high volume) will depend on local conditions, season, crops, and evapotranspiration. These data are generally available from regional or national government agricultural agencies.

8.8.7.1 Water Resources

For surface water resources (rivers, streams, reservoirs, etc.), the capacity needs to be determined by season or month. For wells, it is very important to determine the capacity and drawdown for different pumping rates. In both cases, the dynamic head needs to be determined. Dynamic head includes drawdown and all frictional and pressure losses. Frictional losses depend on size of pipe,

TABLE 8.1
Livestock Water Requirements

Animal	Liters/day
Cattle, beef	40–50
Cattle, dairy	60–75
Camels	40–90
Sheep and goats	8–10
Swine	10–20
Horses	40–50
Chickens (100)	8–15
Turkeys (100)	15–25

TABLE 8.2
Typical Water Consumption per Person

Service	Liters/day
Standpost	40
Yard tap	75
Home connection	100
World Health Organization recommendation	45

flow (volume/time), number of elbows, etc. If drawdown is not known and frictional losses are not calculated, these can be estimated but should be verified, especially for larger pumping projects. Smaller capacity sources may need a bigger storage tank for domestic, livestock, or village use, or even multiple wells.

Thousands of solar pumping systems are in operation throughout the world. They provide for a wide range of needs, including water for cattle and small-scale irrigation as well as for human needs, aquaculture, and industrial applications. They are reliable and low in maintenance when properly engineered and installed. Since the 1990s, the quality of solar pumps has increased significantly and the costs have dropped. Sometimes a solar pump costs no more to install than an engine-driven pump system.

A typical solar pumping system is shown in Figure 8.31. The main components consist of an array of PV modules, a controller, a motor, and a pump. The array can be mounted on a solar tracker to lengthen the daily pumping period and increase the daily water volume. The motor may be either a traditional type (with brushes) or an electronic "brushless" motor. The pump may use either a centrifugal or a positive displacement (volumetric) mechanism. Most often, water is stored in a tank instead of energy being stored in batteries. A nonbattery system is called "PV-direct" or "solar array direct." In this section, the pump, motor, and controller are briefly explained.

8.8.8 Storage of Water versus Storage of Energy in Batteries

To make water available at all times, some form of storage is required. Storing water in a tank is more economical than storing energy in batteries. Batteries are expensive and must be replaced every few years, while the useful life of a storage tank can be many decades. A battery system

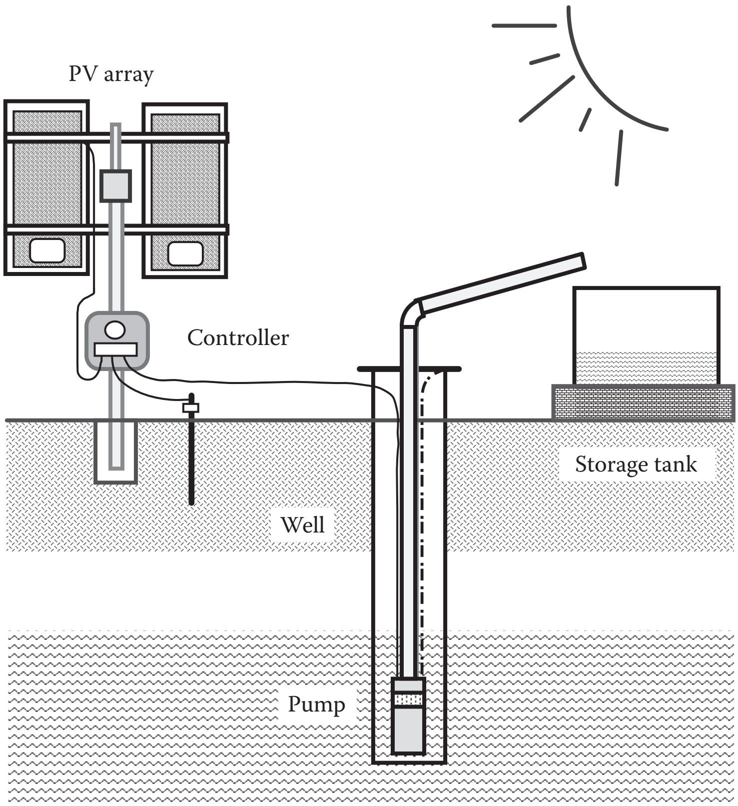

FIGURE 8.31 A typical PV water pumping system.

requires shelter from temperature extremes and controls to prevent overcharge and overdischarge of the batteries. Battery round-trip efficiencies are typically only about 70%, so they lose much of the energy that cycles through them. The introduction of batteries into a PV pumping system will reduce its reliability and increase cost and maintenance requirements. In general, it is best to size a solar pumping system to supply the required water volume without batteries, even if it necessitates installing two pumps in the same well or constructing an additional well and pump. A battery system might be used in cases where a water tank is not practical or the water must be pressurized beyond what is available from natural elevation of a tank.

8.8.9 Pumping Mechanisms Used for Solar Pumps

Conventional water well pumps are designed to run at a constant speed from a stable power source. However, the power from a solar array varies with the intensity of solar radiation and with the angle of the sunshine on the array. The speed of a solar pump varies accordingly. For this reason, some manufacturers have designed pumps for solar power. From a mechanical point of view, these pumps fall under two categories: *centrifugal* and *positive displacement* (*volumetric*).

8.8.9.1 Centrifugal Pumps

These pumps have one or more impellers that spin the water to subject it to centrifugal force. To attain high lift, a centrifugal pump may have a multitude of stages, each consisting of an impeller. Each stage adds to the pump's lift capacity. Conventional electric well pumps are built this way (Figure 8.32).

Centrifugal pumps may use over 20 stages to attain high lifts. Each stage adds pressure but also imposes friction, resulting in an efficiency loss of about 5% per stage. Centrifugal pumps with many stages can have poor energy efficiency and are not always optimum for solar pumping.

Centrifugal pumps are most efficient for flow in excess of about 40 l/m and for lifts less than 40 m. At lower flow rates and higher lifts, the efficiency is poor. At reduced speeds such as those that occur during low-sun conditions, centrifugal pumps lose efficiency in a disproportionate manner. For these reasons, positive displacement pumps are used for most systems that require high lift, especially at modest volumes.

8.8.9.2 Positive Displacement Pumps

A positive displacement pump draws water into a sealed chamber and then forces it out mechanically. A piston pump is a classic example. A solar pump may use a diaphragm, instead, or a helical rotor that traps water in cavities that progress upward as it turns. These pumps have high lift capacity and high energy efficiency. They are optimum for lower flow rates (e.g., 50 l/m), especially when the lift exceeds 15 m.

FIGURE 8.32 Surface centrifugal pump.

Positive displacement pumps are used for most solar pumps in the power range of 500 W (0.5 hp) or less. The efficiency and lift capacity of these pumps remain high even at low rotational speeds, such as those that occur in a solar-direct pump during low-light conditions. This is not true for centrifugal pumps.

8.8.9.3 Surface Pumps versus Submersible Pumps

A *surface pump* is one that cannot be submerged in water (see Figure 8.33). It can be installed above the water source, but nature imposes a strict limit on the height to which water can be drawn by suction. The pump must not be more than 3–6 vertical meters above the water source level. Otherwise, it will extract bubbles from the water and will fail to pump. A surface pump can draw from a river, irrigation ditch, pond, or water tank, but not from a deep well. It may be less expensive than a submersible pump and more efficient for high-volume pumping. However, a submersible pump is often simpler to install, better protected from the environment, and less likely to be damaged from running dry (Figure 8.35).

Some solar *submersible pumps* use the same centrifugal mechanism as a surface pump. Others use a positive displacement mechanism.

Centrifugal submersible pumps are the dominant technology for deep well pumping (see Figure 8.34). Solar pumps of this type are similar, except for the use of a specialized motor and controller.

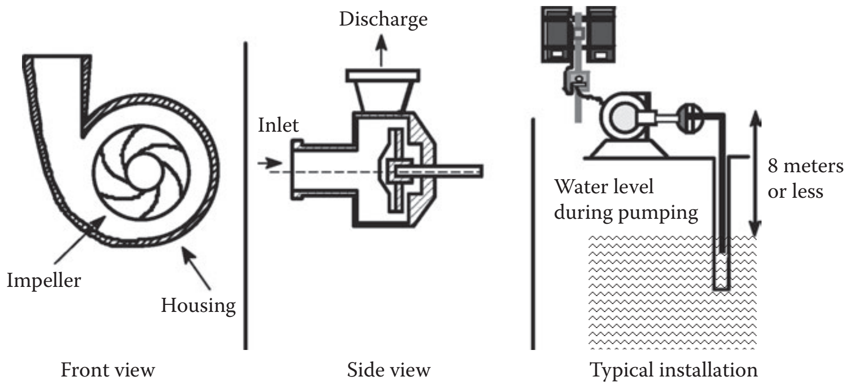

FIGURE 8.33 Diagram of a surface centrifugal pump.

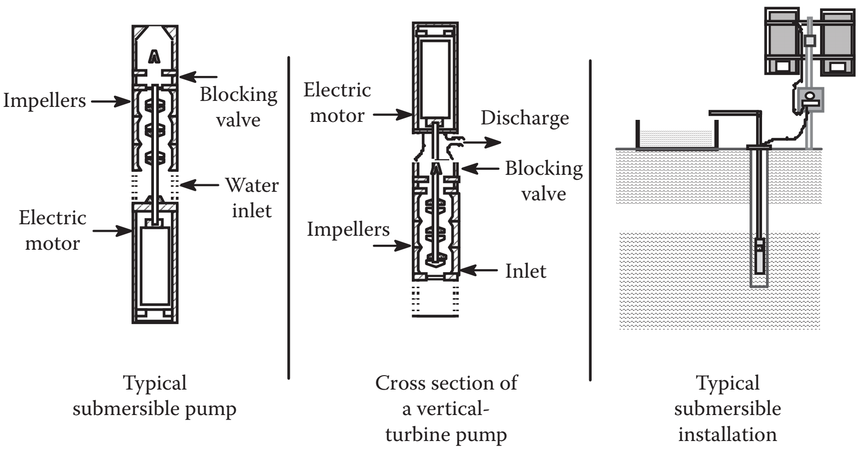

FIGURE 8.34 Diagram of a submersible centrifugal pump.

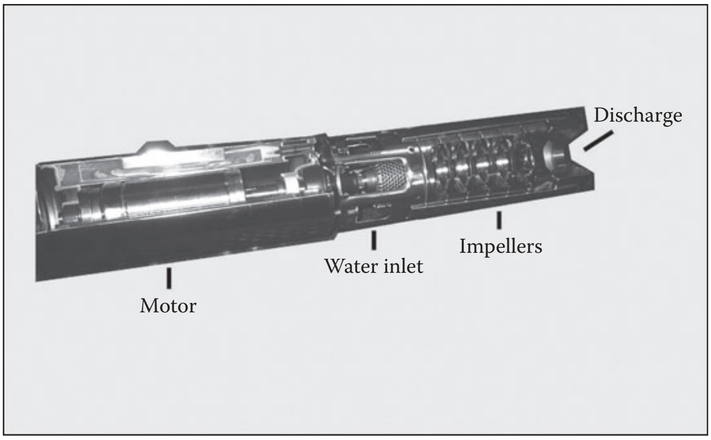

FIGURE 8.35 Grundfos submersible pump.

FIGURE 8.36 Submersible ETA helical rotor pump with controller.

The *helical rotor submersible pump* is a positive displacement pump mechanism that is mounted to a submersible motor. The motor is similar to that used for centrifugal submersibles. Like the centrifugal submersible, the helical rotor can last for many years with no regular maintenance. Many of the newer solar pumps use this type of design (Figures 8.36 and 8.37)

Diaphragm submersible pumps (Figure 8.38) displace water by means of a diaphragm made of flexible synthetic material. Diaphragms fail after about 2 or 3 years of continuous use. Manufacturers of these pumps provide diaphragm replacement kits. If the diaphragm fails in use, water floods the motor and destroys it. Therefore, preventive maintenance should be scheduled to replace the diaphragm before it fails. These pumps also use a brush-type motor that requires brush replacement at intervals of 3–5 years.

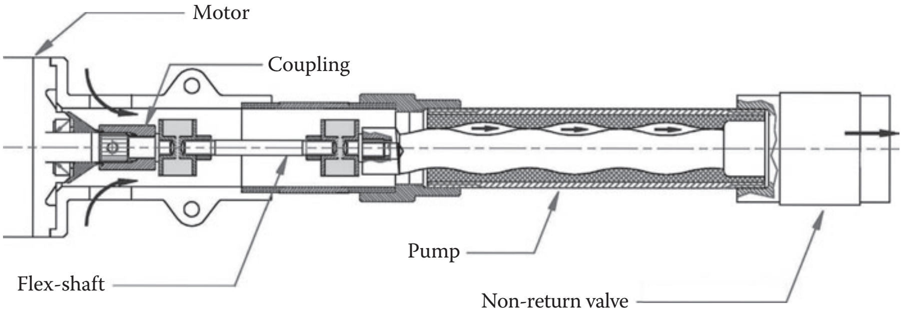

FIGURE 8.37 Diagram of a helical rotor pump.

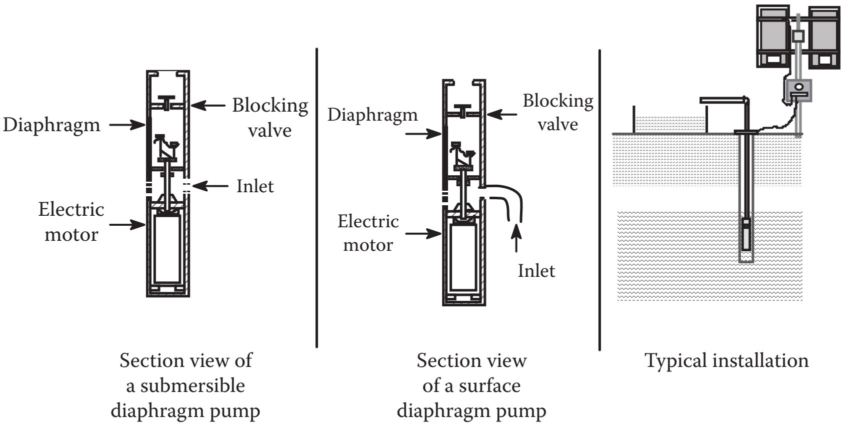

FIGURE 8.38 Submersible diaphragm pumps.

A diaphragm pump may be used when the initial cost must be minimal, when the water volume requirement is very low, and when the future cost of pump maintenance or replacement is acceptable.

8.8.10 Types of Motors Used with Solar Pumps

A PV array generates DC power at a power level that varies with the intensity of the sunshine that falls upon it. To run a pump directly from this unique source of energy requires a special kind of motor or motor/control system. There are two major types of solar pump motors: brush-type motors and brushless motors.

The *brush-type motor* is the traditional DC motor technology that has been used in battery-powered applications for many decades. The "brushes" are small blocks of electrically conductive carbon-graphite. They rub against the spinning part of the motor (commutator) and conduct current into it. This causes the current to alternate (to become AC) within the motor. This simple technology has two major disadvantages: (1) The brushes wear out and must be replaced periodically, and (2) the motor must be filled with air (not liquid) and must be 100% sealed against water leakage. These are major disadvantages for submersible pumps. Brush-type motors are often used for surface pumps where they are kept dry and access is easy.

The term *brushless DC motor* refers to a special type of AC motor driven by an electronic controller that converts DC power into variable AC power. The controller does the job of the brushes and commutator in a brush-type motor. The brushless motor has two major advantages: (1) There are no brushes to wear, and (2) the motor can be filled with oil or water. The safest solar submersible pumps use water inside as a lubricant, eliminating potential oil contamination.

8.8.11 Solar Pump Controllers

There are two types of solar pump controllers for both motor types:

Controllers (linear current boosters) for brush-type motors. A positive displacement pump requires a surge of current for start-up and must come up to speed against the constant pressure imposed by the water in the pipe. A PV array may not be sized large enough to produce the required starting surge, especially in low-light conditions, when it produces reduced current. A linear current booster (LCB) can be used to reduce the voltage from the PV array while it boosts the current. This starts the pump motor and prevents it from stalling during low-light conditions. A brush-type centrifugal pump is often supplied without an LCB because it starts easily and its current draw diminishes with speed. An LCB controller will increase its efficiency during low-sun periods, but the performance gain is relatively small.

Controllers for brushless solar pump motors. A brushless motor controller contains a special type of inverter (a device that converts DC to AC). It performs the LCB function and matches the motor speed to the available power. The three-phase AC power is optimum for starting and running the motor at high efficiency. The controller varies the motor speed by varying the frequency of the AC power. A brushless pump is normally sold with a controller that is engineered specifically for it.

8.8.11.1 Additional Features of Pump Controllers

Solar pump controllers incorporate other control functions to make solar pumping practical and efficient. A typical controller has connections for a *float switch* to prevent the storage tank from overflowing. When the tank fills, the switch signals the controller to turn the pump off. When the water level drops, the float switch resets. This prevents flooding, unnecessary pump wear, and waste of water.

Most solar pumps can be damaged if they run dry, so most pump controllers have a *dry-run prevention* system. This may use a sensor mounted above the pump's intake. If the water level drops below the probe, an electric current is opened and the controller will stop the pump. When the water level recovers, the controller will wait for the level to rise (typically a 20-min delay) and will then restart the pump. Other pumps use a thermal switch so that if the temperature begins to rise due to dry running, the pump automatically shuts off.

A controller also has *overload protection* to prevent damage if the pump is stopped by dirt, ice, crushed pipe, or a closed valve. A controller should also be installed with appropriate overload and surge protection (Figure 8.39). See Section 8.9.

The controller should also have *indicator lights* so that an observer can easily determine when the pump is running, when the tank is full, and when there is a fault in the system.

A function called *maximum power point tracking* (MPPT) is commonly used on most solar pump controllers. This is an improvement on the basic linear current booster. It helps the pump to draw the maximum power from the solar array even as solar cell characteristics vary with temperature and sun intensity.

Location of the pump controller. A brushless submersible solar pump may have its controller built into the motor (Grundfos SQFlex), mounted aboveground (ETA pump), or partly above and partly inside the motor (Sun Pumps). A submerged controller is isolated from the weather and from

FIGURE 8.39 Typical pump controller with overcurrent protection for PV water-pumping system in Chihuahua, Mexico.

human interference. However, if there is a problem with the electronics in the motor, the entire pump and pipe assembly must be removed from the well and the entire motor assembly replaced.

8.8.12 Pump Selection

The process of selecting a pump is critical to the success of a project. A solar pump must use energy efficiently because the PV array that powers it is the most expensive part of the system. Centrifugal and volumetric pumps offer different characteristics for different ranges of application. The pump-selection process can appear complicated due to the multitude of technologies available and the many models available. For help in selecting the best type of pump for a given application, refer to Figure 8.40 and Table 8.3. Manufacturers who produce both helical rotor and centrifugal submersibles (Grundfos SQFlex, ETA) have combined these into a single product line. The manufacturer's selection guide, often computerized, will indicate the best pump for a particular application.

8.8.13 Installation, Operation, and Maintenance

Good operation and maintenance practices are important to ensure the long-term reliability of a PV water-pumping system. Although a well designed and installed PV pumping system is safe, reliable, and requires little attention, there may be times when basic maintenance is required, especially for the pump. The operator should know how to run the system and perform routine maintenance and operation procedures, such as system shut-off/start-up procedures. All of this information should be included in an operation and maintenance manual from the original system provider. The operator

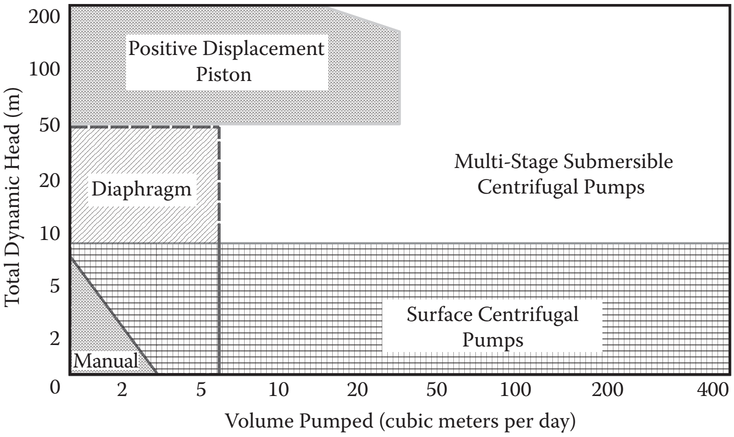

FIGURE 8.40 Approximate pump selection based on lift and volume requirements.

TABLE 8.3
Pump Characteristics

Type of solar pump	Advantages	Disadvantages
Submersible centrifugal	Simple, one moving part Regular maintenance not required Efficient at high flow rates Good tolerance for moderate amounts of sand and silt	Poor efficiency at low volumes (<30 L/m) Lift capacity is greatly reduced at slow speeds (during low-sun conditions)
Submersible helical rotor	Simple, one moving part Regular maintenance not required Highly efficient at low to medium flow rates (4–50 L/m) Maintains full lift capacity even at low speed Good tolerance for moderate amounts of sand and silt	
Diaphragm submersible	Low initial cost Efficient at very low flow rates (4–20 L/m) Maintains full lift capacity even at low speed	Requires regular preventive maintenance Poor tolerance for sand and silt
Surface centrifugal	Low cost Efficient for low lift and very high flow rates Easy to inspect and maintain due to surface location Good tolerance for moderate amounts of sand and silt	Suction limit is about 6 m May be damaged by running dry if it loses prime May be damaged by freezing in cold climates

should understand the expected system output in cubic meters per day, the flow rate on a sunny day, and the significance of indicator lights, as well as basic array, wiring, and pump features.

8.8.14 System Installation

Any water-pumping system component can fail if it is not properly installed and maintained. Because solar pumping systems are assembled in the field, qualified personnel are essential for a safe and professional installation. The installer should follow local electrical safety codes and is responsible to ensure that all materials and tools are available during installation. The pump manufacturer's installation recommendations should be followed. Additional special measures may be required, depending on location and local conditions (freezing, flooding, lightning, vandalism, theft, etc.) For a successful installation:

- verify the water source (seasonal production);
- check civil works (foundations, piping, and storage system);
- test mechanical and electrical field connections;
- run through system operational modes;
- quantify component and system performance (acceptance test);
- conduct basic system training for the system owner/operator; and
- provide an operation and maintenance manual to the system owner/operator.

Experience has shown that it is important to pay attention to detail during installation to avoid later unexpected system malfunctions that are often caused by poor initial electrical or mechanical connections. For example, thermal cycling of poor electrical connections over the years can cause a system to decrease in performance or fail. The system controller box may not be properly sealed, which allows moisture to enter and corrode circuit boards or connections eventually. These original simple problems can cause a halt in operation and later high repair costs.

The designer should correctly specify the gauge and type of conductor to be used for the current, voltage, and operation conditions of components and the system. All exposed cables should be approved for outdoor use (e.g., USE or SE wire) or installed in electrical conduit. Cables should be protected and adequately secured. In some cases, it may be necessary to bury conductors; underground cable or conductor approved for direct burial should be used (e.g., USE or SE). All connections should be made in accessible junction boxes where they can be inspected, repaired, and mechanically secured. All electronic equipment and electrical connections should be protected against water, dust, and insect intrusion. It is important to protect cables against physical abuse, especially where a pump cable enters a well. Excessively long wire runs should be minimized to avoid increased voltage losses. All connections should use strain relief. Any cable ties used should be sunlight (UV) resistant (i.e., black nylon).

Extra caution needs to be used for the installation of submersible pump cables. This cable may remain submerged in water for decades; consequently, it should be perfectly waterproof and have adequate strain relief to avoid failure. For pump cable splices, cylindrical butt connectors, sized for the wire, are normally used. If the wire gauge of the submersible cable is greater than that of the original manufacturer's pump cable, a connector sized for the submersible cable should be used and the pump cable doubled up in order to make a secure connection. Ratcheted crimping tools should be used for maximum force. Insulation of the pump splice connections should be done with epoxy and rubber-sealed thermal shrink tubing. Each splice connection should be separately insulated to avoid short circuits. The manufacturer's installation instructions should be followed carefully. The weight of the pump should never be supported on the electrical pump cable and a separate inorganic rope, corrosion proof cable, or rigid pipe should always be used to support the pump and to haul it into or out of a well.

8.8.14.1 Civil Works

Array support foundations are critical. The array support should be able to withstand a wind loading of at least 160 km/h (category 2 hurricane). Concrete must be allowed to cure adequately. For a well, the combined weights of the pump, motor, pipe, and water column must be considered for well supports.

8.8.14.2 Piping

The piping and fittings used for the system should be corrosion resistant. The piping that is used from ground level down to the well should be able to withstand the pressure caused by the column of water. The fittings should be able to withstand these forces without developing leakage over time. Leaks reduce productivity and, in the case of surface pumps, they cause loss of suction. Friction losses contribute significantly to the overall head and as a result decrease system productivity. To cut down on friction losses, long piping runs and small diameters of pipe should be avoided. The use of elbows and valves should also be minimized whenever possible. Corrosion-resistant mounting structures and fasteners should always be used.

It is advisable to protect the PV array against physical abuse from animals. A fence may be constructed around the array. Care should be taken not to shade the array (from trees, fences, buildings, etc.) between the hours of 9:00 a.m. and 4:00 p.m.

8.8.14.3 Surface-Pump Installation

Ground-level pumps should be mounted to a structure (typically concrete) placed over the surface of the water source (Figure 8.41). The structure and mounting fasteners should be sufficiently firm to withstand pump vibration and the weight of the water column in the piping that runs from ground level down to the well. Surface-mounted centrifugal pumps have a maximum suction capacity of about 7 or 8 m. Surface-mounted piston and diaphragm pumps also have suction limitations. For this reason, the vertical distance from the pump to the water level in the well should be minimized. To reduce friction losses, wide diameter pipes should be installed with valves and a discharge water flow meter.

A check valve is recommended for positive displacement pumps. Water must be present in the suction pipe in order for the pump to operate. After priming the pump, the check valve should keep the suction pipe full of water, including when the pump is off for a period of time. If a check valve is not installed, the system will require manual priming (filling the suction pipe with water) each time the pump is started. If the water-distribution line is long, it is important to install a check valve on the discharge side of the pump to avoid damage due to "ram" (water hammer). Any pump intake should be installed far enough away from the well bottom and sides to avoid pumping mud, sand, and debris, which can all cause damage to pump seals and components. If it is probable that the water level will fall below the intake, it will be necessary to install a switch (a float or electrode) to avoid pumping dry.

FIGURE 8.41 PV-powered surface jack pump in Chihuahua, Mexico, for a 170-meter deep well.

Sand is one of the main causes of pump failure because it destroys seals, fills impellers, etc. If the well is located where sand or dirt can penetrate into the pump, a sand filter should be installed. Most pump manufacturers who sell this kind of filter can recommend ways to reduce the risk of damage.

8.8.14.4 Surface Water Pumps: Preventing Cavitation and Noise

Excessive suction causes cavitation, which is the formation and collapse of bubbles. When water pressure is reduced beyond a critical point, water vapor and/or dissolved gasses are released similarly to when a carbonated beverage is opened. When a bubble reaches the pressure side of the pump, gas returns to the liquid state. Bubbles collapse in sudden implosion. This causes water to strike violently, like tiny hammer blows, against the working surfaces of the pump. Cavitation causes loud noise and excessive pump wear. It is not the fault of the pump, but rather of the installation. To prevent cavitation, follow these precautions:

- Refer to the pump's specification sheet and instructions and observe the limits of vertical suction lift.
- Water should flow easily for intake lines. Use large intake pipe (larger than the pump's intake port). This is especially critical in cases of long intake piping (see pipe sizing chart.)
- Avoid 90° elbows. Use pairs of 45° elbows to reduce friction losses.
- Carefully choose intake screens or intake filters for low friction and make sure that they will be easy to clean.
- Work carefully to minimize the possibility of air leaks.
- Avoid high spots in the intake pipe. They can trap bubbles that will restrict the flow (like in a siphon). If a high spot is unavoidable, install a pipe tee at the highest point, with a cap or a ball valve above it. When water is poured in at the high point, it will displace all of the air to prime the intake line fully.

8.8.14.5 Installation of Submersible Pumps

Good submersible pump installation requires experience. For example, submersible centrifugal pumps utilize components that must be installed within the well. Manual installation can be difficult without the use of mechanized equipment. The structure to which the equipment is connected should be robust in order to support the combined weight of the water column, the metal piping from the surface to the well, and the well point. Each manufacturer provides installation instructions.

It is important to install a safety cable on submersible pumps (Figure 8.42). It is best if the casing (but never the power cable) supports the weight of the pump and the water column. For centrifugal pumps, it is recommended that the piping from ground level to the well be sized to reduce friction losses.

8.9 GROUNDING AND LIGHTNING PROTECTION FOR SOLAR WATER PUMPS

Surges induced by lightning are one of the most common causes of electronic controller failures in solar water pumps. Damaging surges can be induced from lightning that strikes a long distance from the system. The risk of damage can be greatly reduced by taking the following steps:

- *PV array wiring.* Array wiring should use minimum lengths of wire, tucked into the metal framework and then run through metal conduit. Positive and negative wires should be of equal length and be run together when possible. This will minimize induction of excessive voltage between the conductors. Long outdoor wire runs should be buried instead of run overhead and placed in grounded metal conduit if maximum protection is required. The negative conductor should be grounded to meet electrical code specifications.
- *Location of pump controller.* In general, the input circuit of a pump controller is more sensitive than the output circuit. Therefore, in cases where a long wire run is required between

FIGURE 8.42 Installation of a PV submersible pump in Sonora, Mexico.

the PV array and the water source, it is usually best to locate the controller near the array to minimize the length of the input wires.

- *Construct a discharge path to ground.* A properly made discharge path to ground (earth) will discharge static electricity that accumulates in the aboveground structure. This helps prevent the attraction of lightning. When there is a nearby lightning strike, it is hoped that a well grounded structure will divert the surge around the power circuitry, greatly reducing the probability or the intensity of damage. Most solar pump controllers have built-in surge protectors that function only if they are effectively grounded.

8.9.1 Bond (Interconnect) All Metal Structural Components and Electrical Enclosures

The PV module (solar panel) frames, mounting rack, and ground terminals of the disconnect switch and the controller should be interconnected using wire of minimum size AWG#8 (6 mm^2) and the wire run to an earth connection. When connecting dissimilar metals, connectors approved for the materials involved should be used. For example, at the aluminum framework of the solar array, connectors labeled "AL/CU" and stainless steel fasteners should be used. This will reduce the potential for corrosion.

8.9.2 Ground

One or more 8 ft (2.5 m) copper-plated ground rods should be installed, preferably in moist earth. Where the ground gets very dry (poor conductance), more than one rod, spaced at least 10 ft (3 m) apart, should be installed. One can also bury AWG#6 (16 mm^2) or double AWG #8 (10 mm^2) or larger bare copper wire in a trench at least 100 ft (30 m) long. One end should be connected to the array structure and controller. If a trench is to be dug for burial of water pipes, ground wire can be run along the bottom of the trench. A steel well casing near the array can be used as a ground rod. A hole should be drilled and tapped to make a strong bolted connection to the casing. Concrete footers with rebar of a ground-mounted array will not provide adequate grounding alone.

8.9.3 Float Switch Cable

A long run of control cable to a float switch can pick up damaging surges from nearby lightning strikes. The best protection is to use shielded, twisted-pair cable. Shielded cable has a metallic foil or braid surrounding the two wires. The cable shield should be grounded at the controller end rather than at the float switch.

8.9.4 Additional Lightning Protection

Lightning protection devices (surge arrestors) are intended to bypass excessive voltage such as that from a lightning strike. Most pump controllers have built-in surge protection devices metal oxide varistors (MOVs) that are useful but limited in their capacity. Additional grounding measures or surge protection devices are recommended under any of the following conditions:

- isolated location on high ground in a severe lightning area;
- dry, rocky, or otherwise poorly conductive soil; and
- long wire run (more than 100 ft/30 m) from the controller to the wellhead or to the float switch.

Solar pump wiring should be kept away from electric fence systems and the pump system should not be connected to the same ground rod as an electric fence system. A float switch cable should not be run near an electric fence.

8.10 SOLAR TRACKING FOR SOLAR WATER PUMPS

A solar tracker is a PV rack that rotates on an axis to face the sun as it crosses the sky. Two-axes tracking can increase energy yield by about 25% annually, depending on latitude. For solar pumping, tracking can improve performance while reducing overall system costs. Tracking offers more water out of smaller, less expensive PV array by increasing performance.

Some solar pumps (particularly centrifugal pumps) experience a disproportionate drop in performance when the sun is at a low angle (early morning and late afternoon). When the PV array output is less than 50%, a centrifugal pump may produce insufficient centrifugal force to achieve the required lift. By causing the pump to run at full speed through a whole sunny day, tracking can greatly increase the daily water yield (30% or more). In the case of positive displacement pumps, the gain from tracking is more closely proportional to the actual energy capture.

The tracking decision is a variable in the design process. Often a proposed system produces a little bit less than is needed, but the next larger system costs much more. A tracker is a low-cost means to increase the yield of the smaller system sufficiently to meet the demand. Tracking is least effective during shorter winter days and during cloudy weather. If the need for water is constant during the year or greatest in the winter or if the climate is substantially cloudy, then it may be more economical to design the system with more solar Watts and no tracker.

8.10.1 Passive Trackers

Passive trackers have been in regular production since 1983. The tracking process uses no moving parts and no electrical parts, but rather only a fluid/vapor flow that tips a balance. An automotive type shock absorber may need replacement every 5–10 years. Passive trackers rarely fail, even after many years. In a case of failure, the tracker can be made to hold at mid-day position and the pump will still function, or it can be tracked by hand. New Mexico's Zomeworks Corporation invented the first widely used passive trackers.

8.10.2 Active Trackers versus Passive Trackers

An active tracker uses one or more electric motors powered by solar electricity. This is a more precise method of tracking the sun. High accuracy is necessary for a solar device that uses optical concentration and must be aimed accurately. However, with conventional flat-plate PV modules, a tracking error of as much as 10% will have no significant effect on the power. Therefore, either type of tracker may be considered. Most active trackers have a nighttime or early morning return mechanism that will deliver power earlier in the morning than a passive tracker, which may take a half-hour to wake up. Active trackers are much more complex and generally require more maintenance than passive techniques and may need to be replaced every 4 or 5 years as motors and gears wear out.

8.11 OPERATION AND MAINTENANCE OF THE SYSTEMS

Well designed and installed PV water-pumping systems are relatively simple to operate and maintain. Typically, the system has to start and stop depending on the demand and availability of water and sunshine. With the use of switches (float or electrode), the majority of the systems can be automated at a relatively low additional cost. Manual shutoff is necessary for repair or modification of the water distribution system and the electrical system, as well as when the pump is extracted from the well for inspection, maintenance, and repair.

Personnel responsible for operation and maintenance of the PV water-pumping system should be trained by the installer. The system installer should provide an operation and maintenance manual, which establishes the operational principles of the system, a routine maintenance program, and service requirements. The manual should also include information related to safety and common problems that might surface.

The most effective means of maximizing the benefits of PV water-pumping systems is through preventive maintenance. A preventive maintenance program should be designed to maximize the useful life of the system. Clearly, each type of system has different maintenance requirements; some pumps may operate 10–20 years without any maintenance actions, while others require maintenance in the first year. Specific operational and water conditions will determine frequency.

In general, maintenance of a PV water-pumping system requires the following:

- *Routine maintenance and minor repairs.* Included is monitoring of system performance, water level, and water quality. On-site inspections can detect small problems before they become big ones. It is necessary to look for unusual noises, vibrations, corrosion, loose electrical connections, water leaks, algae, etc. The system operator (typically the owner) should be able to perform routine maintenance and minor repairs. Routine maintenance will help detect and correct the majority of small problems that crop up from time to time before they become major problems (Figures 8.43 and 8.44).
- *Preventive and corrective repairs.* This may require the replacement or repair of components such as diaphragms and impellers as well as defective parts. This type of maintenance may require special tools and knowledge beyond that possessed by the system owner. In the majority of cases, it is necessary for trained personnel to perform the repairs. Pump failures are typically the most common problem found with PV water-pumping systems; PV modules rarely fail (Richards, 1999).

FIGURE 8.43 PV pump damaged cable splice where conductors have worn through from hauling the pump up and down on the pump cable rather than the security rope (Roatan, Honduras).

FIGURE 8.44 FIRCO engineers in Mexico learning how to inspect PV water-pumping systems with NMSU and Sandia Labs.

8.12 THE PV ARRAY

One of the most important points with regard to the PV array is the prevention of shade. Nearby weeds and trees can grow up over time and cause shade over the pump, so they must be controlled. It is not necessary to clean PV modules; heavy buildup of dust will reduce efficiency only 2–4% and will wash off with the next good rainstorm. If the mounting structure permits, the array inclination can be adjusted twice a year to ensure better productivity between summer and winter pumping seasons. Field maintenance of controllers consists of assuring a good seal to avoid the infiltration of dust, water, and insects.

8.12.1 Pumps and Motors

From an operational point of view, it is very important to avoid dry pumping, which will cause a motor to overheat and fail. Water in the pump is necessary for lubrication and heat dissipation. In the case of surface-mounted centrifugal pumps, if priming is frequently required, inspection should be made to ensure that there are no leaks in the suction pipe or the check valve. The operator should never allow pumping against an obstructed discharge, which could cause the motor to overheat.

Both surface-mounted and submersible centrifugal pumps require little maintenance. The majority of problems that arise are due to excessive sand and corrosive water with high mineral content. These agents can degrade impellers and pump seals. In some cases, the pump may not fail completely, but its productivity may diminish significantly as impellers fill with mud. All that may be required is a good cleaning of the impellers to bring a pump back to 100% capacity. Some pumps can be reconstructed with new impellers and water seals. Algae and other organic material can obstruct the entrance to the pump, which can be reduced with the use of intake screens. Submersible pumps are made of corrosion-resistant stainless steel.

Positive displacement pumps use more components that are subject to wear. Under normal operating conditions, diaphragms should be replaced every 2 or 3 years (more frequently for sandy water). The seals on piston pumps typically last 3–5 years, but can be damaged sooner due to freezing. Diaphragms and seals all fail prematurely in the presence of sand, which wears the components more rapidly. Many positive displacement pumps can be rebuilt several times in the field by replacing diaphragms.

Brushless AC and DC motors do not require field maintenance and can last 10–25 years under ideal operating conditions. The brushes on brush-type motors must be replaced periodically. This is a simple task in most designs. The brushes should be replaced with components supplied by the manufacturer to guarantee good equipment performance. Small motors with brushes can last 4–8 years, depending on use.

8.12.2 Water Supply Systems

Finally, it does no good to install a PV water-pumping system to provide water if the rest of the water supply system is not well designed and maintained. Poorly made wells can collapse and destroy hardware. Community water supply systems should be designed with health in mind and there must be drainage to avoid creating a swamp (breeding insects) through which people have to walk to obtain their water.

8.13 PV WATER-PUMPING RESULTS

PV systems have proven to be an excellent option in meeting water-pumping needs when electrical grid service does not exist. Between 1994 and 2005, over 1,700 PV water-pumping systems were installed throughout Mexico, initially as part of the USAID/DOE MREP–Fideicomiso de Riesgo Compartido (FIRCO) program and later with the GEF/World Bank renewable energy for agriculture program. PV water pumping was largely unknown in Mexico prior to 1994, and MREP paved the way for widespread adoption there; the country now leads Latin America in this application.

FIRCO, NMSU, and Sandia conducted a review in 2004 on 46 of the initially installed PV-pumping systems. Typical system configurations included a PV array (~500 W_p on average), pump, controller, inverter, and overcurrent protection. Over three-fifths of the surveyed systems were

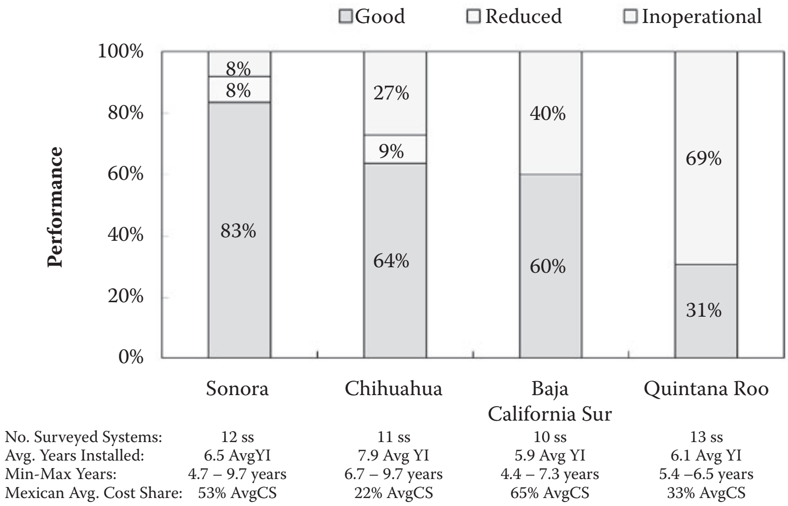

FIGURE 8.45 Performance of Mexican PV water-pumping systems.

operating appropriately after as much as 10 years. The surveys were conducted in Baja California Sur, Chihuahua, Quintana Roo, and Sonora. A total of 85% of users thought that PV systems had excellent to good reliability (Figure 8.45; Cota et al. 2004).

Fully 94% of users classified water production as excellent or good, with only 2% unsatisfied. The survey found that over four-fifths of the rural Mexican users were satisfied with the reliability and performance of their PV water-pumping systems. When system failures occurred, they were typically specific to pump technology and installer.

When problems have occurred, they have been mostly due to failure of pump controllers and inverters, well collapses, or drying out due to drought. There were no PV module failures. Investment payback for the PV water-pumping systems has averaged about 5 or 6 years, with some systems reporting paybacks in half that time (Cota et al. 2004).

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