chapter 2

System Design Considerations

EACH PHOTOVOLTAIC (PV) SYSTEM must be customized for the intended site. Site considerations include the amount of energy needed, obstructions, and the times when the PV system will be in use. This chapter discusses considerations necessary when designing a quality PV system. Recognizing effective and ineffective PV system design is also covered.

Topics & Concepts

This chapter covers the following topics and concepts:

- Effective and ineffective PV design
- The path of the sun
- Basic principles of high-quality PV system design
- Common PV system designs and options
- Design requirements

Goals

When you complete this chapter, you will be able to:

- List basic principles to consider when designing a PV system
- Recognize typical system designs and options
- Describe how the path of the sun can affect a PV system

Effective and Ineffective PV Design

The foundation of quality design work begins with following basic principles of PV system design. The qualitative and performance result of PV design begins with two questions:

- What kind of PV system is being designed?
- To what level of quality and performance will the system be designed?

A PV system is designed to generate electricity. Effective design targets the production of a substantial number of kilowatt-hours (kWh) for decades with low operations and maintenance costs. PV systems should not be designed strictly on the basis of first cost. The goal is to make the life of the system cost-effective. An effective PV system returns more energy at a lower cost than an ineffective system.

A well-designed system using premium quality components has a higher up-front cost than a poorly designed system using low-quality components. The difference is that the more expensive system will yield more energy, cost less to maintain, and last longer. This equals a net positive for the customer over the life of the system.

You must always balance quality and performance to make the PV system cost effective. Using the lowest-priced parts is not always the best solution. Consider the type of PV system and the performance expectations. What is necessary and where can you compromise? Effective PV design uses components and methods that generate the best price per kWh. This means you get the most energy possible for the best possible price.

The Path of the Sun

Understanding the sun, Earth, and the array surface relationships is critical to understanding how to design a PV system. The sun emits radiant energy. This energy reaches Earth's surface.

Insolation is a measure of this energy that reaches a specified area of Earth during a specified period of time. Most insolation occurs in a spectral region having a wavelength between .25 and 4.0 μm. Forty percent of insolation exists in the visible spectral region between .4 and .7 μm. Only 10 percent of insolation occurs in wavelengths that are shorter than the visible spectrum. Oxygen, nitrogen, and ozone high in the atmosphere absorb energy of wavelengths shorter than .29 μm.

Insolation is dependent on four main factors. The first factor is solar constant. The solar constant is the amount of solar energy at normal incidence outside the atmosphere. The second factor is the elevation of the sun in the sky. The third factor is the quantity of radiation that is reflected back into space by Earth's atmosphere. The fourth factor is the amount of solar radiation that is absorbed by the atmosphere and the amount of radiation reflected by the lower boundary of Earth. Insolation can be expressed as units of watts per square meter (W/m^2).

The level of efficiency of any solar cell depends on the technology and the internal architecture of the cell. The effectiveness of that cell relates to how it receives energy in its environment. This includes cell temperature and the concentration of sunlight received. You must carefully assess the environmental factors of each individual site. The usable amount of solar radiation available at a site is dependent on the following:

- **Local conditions**—Local conditions, such as trees or obstructions, might shade the solar arrays. Other conditions include dust, dirt, or local airborne pollutants, such as diesel or kerosene residues, airflow, mounting, and more.
- **Climate**—Cloudy weather decreases the concentration of the sun's radiation, and snow may cover solar arrays, lowering performance.
- **Latitude**—The location of a site on the planet affects the angle of the sunlight and, thereby, the amount of solar radiation.

The quality of solar radiation and amount of sunlight available at any given location on Earth is dependent on the following:

- **Shape**—Earth's round shape causes sunlight to hit the planet at varying angles.
- **Earth's path around the sun**—Earth's orbit causes sunlight to strike a surface on the planet at varying angles and intensities, hourly, daily, monthly, seasonally, and annually.
- **Elliptical orbit**—Earth revolves around the sun in an ellipse, which brings Earth closer to and farther from the sun.
- **Axis**—During winter in the Northern Hemisphere, the North Pole points away from the sun while the South Pole points toward the sun. This results in differences in available energy between the North and South Poles.The sun's rays strike Earth at an oblique angle beginning at 0 degrees with the sun just above the horizon. When the sun is directly overhead, at solar noon on the equator, the rays hit Earth at 90 degrees. The energy density on a surface becomes reduced because the rays must travel at a more oblique angle.

At zero degrees, there is no strong concentration of the sun's rays. Solar cells cannot work at peak efficiency with the sun's rays are at a zero-degree angle. At 90 degrees, the sun's rays are very concentrated. It is at this angle where solar cells are able to work at maximum efficiency.

The amount of solar irradiance can be as much as 1,000 W/m^2 when the sun's rays hit a site at 90 degrees at solar noon. This is under optimal conditions. Solar irradiance can occasionally reflect off clouds, causing the irradiance level to rise as high as 1,400 W/m^2. This is much lower than the **solar constant**.

Solar irradiance above Earth's atmosphere ranges between 1,325 W/m^2 and 1,412 W/m^2. The solar constant is the average of this range, 1,367 W/m^2. Solar irradiance at Earth's surface is significantly lower because solar rays lose strength as they pass through Earth's atmosphere.

Earth's round shape and declination are the reasons that the North and South Poles receive weak concentrations of sunlight. The axis tilts the poles away from the sun during part of the year and points closer to the sun in the other part of the year.

You measure the value of declination in degrees. Values north of the equator are positive. Values occurring south of the equator are negative. The North and South Poles are measured at +90 degrees and –90 degrees declination, respectively. The celestial equator is 0 degrees.

Earth orbits the sun in an ellipse. Earth is farther from the sun during part of the orbit cycle. Earth's tilted axis causes the Southern Hemisphere to have summer while the Northern Hemisphere is in winter. The sun's rays are weaker in winter because that area of Earth is tilted away from the sun.

Tilt and Rotation

Earth rotates on an axis angled at about 23.5 degrees. This tilt causes longer and shorter days at different times of the year. From the spring equinox to the fall equinox, the Northern Hemisphere experiences longer days while the Southern Hemisphere has shorter days. During the summer, the Northern Hemisphere tilts toward the sun on Earth's axis.

The spring and fall equinoxes are the two days of the year during which daylight hours and dark hours are equal. Earth's North Pole then begins to point away from the sun and the Southern Hemisphere has longer days from the fall equinox to the spring equinox. The longer days occur during the summer months in both hemispheres.

The amount and intensity of sunlight that a site receives changes very drastically from one part of the year to another. Shorter days are caused by Earth's rotation on its axis and position on the ellipse. This, in turn, causes a drastic reduction in the amount of sun radiation a site gets. Earth's elliptical orbit affects the angle the sun's rays must travel to reach Earth and thereby limits the intensity of the rays.

The **sun hour** is a cumulative unit used to describe the amount of irradiance striking a surface at a specific value of 1 kilowatt-hour per meter squared (kWh/m²) per day. In a specific location, there may be more than 1 kWh/m² or less at any given time (per hour) based on a number of factors.

The sun hour takes the following into consideration:

- The incident density of radiation on a specific surface
- The (approximately) 30-year average
- The climate history of a location
- The location's latitude
- The location's slope
- The fact that sun hours can be provided for fixed arrays or tracking arrays

The sun hour is a useful term and value. The energy striking a surface varies all day long and usually takes the shape of a graphed bell curve. The sun hour allows all of the potentially usable energy to be listed in a comparative measure of 1 kWh/m² per day.

For example, in Detroit, Mich., you can expect the number of averaged sun hours for a fixed array in June to be about 5.5 kWh/m² per day. In Phoenix, Ariz., the same value for that month would be 7.54 kWh/m² per day. In the winter, Detroit would have about 2.3 kWh/m² per day in January, whereas Phoenix would have 5.31 kWh/m² per day.

You use sun hours to compute the amount of energy that one PV panel, string, or array produces at a given site. It is essential to understand all of the factors that influence what the performance will be as you complete the design. A location's sun hour total is also referred to as daily average **solar insolation**. As these values change with the Earth-sun relationship, a site experiences different sun hours at different times of the year.

Incidence Angle

If an array could always track the sun directly, the radiation would be falling perpendicular to that surface. You can do this using a multiaxis solar tracker. It achieves the highest level of surface irradiance. However, most PV systems do not track the sun. You must understand the deviation from straight on and how it affects the amount of solar insolation that the PV system will have available to produce electrical energy.

Think of the angle of incidence as the angle that varies between that perfect perpendicular solar input and the deviation continually changing every moment the sun's energy strikes a panel. Once that relationship is understood, the correct amount of irradiance can be considered for determining what the potential system design will produce.

The angle, or tilt, and orientation of the radiated surface affect the total sun hours. Horizontal surfaces are radiated more by sunlight with higher values because the sun has a lower angle of incidence as the sunlight comes closer to striking the array at a perpendicular approach during the summer months. The opposite is true in the winter months.

During the winter months, vertical surfaces have more solar insolation because the sun's rays shine on that surface at lower angles. Sun hours vary from location to location, latitude to latitude, and environment to environment. A city at 7,000 feet in elevation, five miles away from a city at 2,000 feet elevation has a different level of solar insolation and a different number of sun hours.

Principles for Designing High-Quality PV Systems

Every PV location has its own load and location needs. One household may use far more energy than a neighbor with the same size home. A nearby site might have a challenge with shade from trees. Trees shade PV arrays, minimizing output. Because every site is different, every PV system must be individually designed.

This does not mean that if a group of homes or buildings had the same system size or the exact same environmental condition, the design would have to be different. It means that when two houses are next to each other with the same orientation, there are issues of shading, panel, or **inverter** location that might affect system design and installation.

Load

There are different kinds of load descriptions depending on what segment of the PV system discussion is addressed. There are instantaneous design loads for buildings or applications. The instantaneous design loads are the maximum possible load at any moment. This is how a service entrance section (SES) is sized. There are daily loads for determining seasonal maximum and minimum. Average design loads are used for off-grid design requirements. Grid-tied system loads are generally calculated using the past 12 months of existing utility bills.

For standalone systems, the **load** is the amount of energy needed at a specific site. This considers the maximum, minimum, daily, seasonal, and average load requirements. Some loads may be very small like an LED light or large like a dishwasher or AC unit.

A cabin in the woods with very few electrical requirements such as a light and radio has a small load.

A water pump in a remote village that uses PV systems to operate may have a small load if it is a small village with a shallow well. It could be a very large load if it is a large village with a deep well. As loads vary, understanding them will help you determine the number of solar modules and strings needed. It also gives you the knowledge to select the best components.

Households tend to have a broad range of small to large loads. The amount of energy needed to run washers, dryers, water heaters, HVAC systems, and devices such as televisions, computers, and cell phone chargers must all be taken into account.

Many items that make up a household's energy load do not run constantly. But some, like refrigerators, cycle off and on and are in constant need of an energy source. These are the phantom, ghost, or vampire loads. These come from the internal electronics in almost every electrical appliance that draws small amounts of energy.

When designing an off-grid system, you should have a worksheet listing the items that the customer typically operates. Your customer will have some tough decisions to make unless he or she has a large budget to build a system capable of handling very high loads. If there is any load not covered by the system, either it will need to be supplied by backup power like a gas or diesel generator, or the customer will have to do without it.

Residences and businesses are common applications for grid-tied PV systems. This is because grid-tied PV systems are able to reduce the amount of energy purchased from the utility company and can source power from the grid when loads exceed PV-supplied electricity.

To determine the load of a given site, you must list every item that uses energy. A simple table like **TABLE 2-1** is helpful.

Select the important critical loads to the customer when determining load for a grid-tied system with battery backup. This helps the designer determine usage and the number of hours the customer will run those loads. This information is used to size the battery backup system.

GRID-TIED SYSTEM SAFETY

Grid-tied systems without an energy storage device shut down when the grid goes down. This is a function of the inverter called anti-islanding protection. It is required under the NEC and UL 1741 and is harmonized with IEEE 1547. This keeps the inverter from putting power on the grid if the grid goes down, to eliminate the possibility of electrocuting anyone working on the local grid.

SYSTEMS WITH ALTERNATING-CURRENT AND DIRECT-CURRENT GROUNDING REQUIREMENTS

Photovoltaic systems having DC circuits and AC circuits with no direct connection between the DC grounded conductor and the AC grounded conductor shall have a DC grounding system. The DC grounding system shall be bonded to the AC grounding system by one of the following methods:

- Separate DC grounding electrode system bonded to the AC grounding electrode system
- Common DC and AC grounding electrode
- Combined DC grounding electrode conductor and AC equipment grounding conductor (NEC 2011, UL 1741)

Suitability

The fact that PV systems use renewable energy from the sun and do not give off pollutants is a bonus. PV systems are not necessarily always the best option for every site. You must evaluate each potential site and system. Factors affecting the suitability of a site for PV system installation include the following:

- **Energy resource**—Is sufficient sunlight present at the site and is it available at least 75 percent of the year? There may be a site that is shaded by trees, is in the shade of a mountain, or has other objects blocking access to sunlight.

PRACTICE TIP

It is a good practical exercise to use a load calculation sheet and evaluate one or two on-grid applications like your home and a small business. Then do the same for an off-grid site. It will help you understand how energy is wasted. You will also learn how you can enjoy an incredibly bountiful lifestyle by adjusting habits and appliance usage and get more out of a PV system while using less.

TABLE 2-1 LOAD CALCULATION TAB

Load	Hourly daily use		Wattage		Total energy use in watt-hours
Lighting	8	×	30	=	240
Television	2	×	60	=	120
Total daily energy use				=	360

A customer who does not have access to grid-tied energy and has shading challenges might need to consider other sources of energy.

- **Cost**—PV systems cost little to run, but do require routine maintenance and inspection. The initial cost of a PV system and installation today is almost always more than the cost of utility power at today's rates. However, there is more to cost than just the up-front system. What kinds of tax or utility incentives are there to reduce the initial cost? What is the inflation-adjusted cost for the utility power over time? How does that compare with the total cost of the PV system and all of its expenses over time?

PV is also less expensive than running a generator or a fuel cell, unless it is a large industrial generator. PV systems are usually cost-effective in remote locations where the cost of running grid lines is high. Once you pay the bill to connect to the grid, there is still a monthly charge for energy usage and fees.

- **Expandability**—PV systems are easily expandable to accommodate increased loads, especially if expansion or phasing is considered during design.
- **Reliability**—PV systems experience wear and tear over time like all electrical equipment. When properly designed, installed, and maintained, they rarely break down. This is why PV systems are increasingly popular and are becoming essential for individuals and businesses seeking to control energy costs. Every system should have a remote monitoring system so any weakness in performance or system failure is quickly discovered and corrected.
- **Flexibility**—PV systems are easily combined and integrate with other energy sources, such as power grids, generators, small hydro systems, wind, and other energy sources.

Site Adequacy

A detailed site assessment is the best way to know whether a location is a good choice for a PV system. When evaluating a site, make sure you consider both today's challenges and those of tomorrow. These include trees or future construction that will impact your site in the future. The most important factors in determining site adequacy are as follows:

- **Southern exposure**—PV arrays must receive as much direct sunlight as possible, preferably from 8:00 a.m. to 4:00 p.m. The majority of the available energy from the sun is from 9:00 a.m. to 3:00 p.m. Some fringe shading is OK.
- **Obstructions**—The southern exposure of PV modules must be as unobstructed as possible. Obstructions include trees, buildings, mountains, and other objects that might shade the array. Sometimes obstructions are not easy to see. Some examples include flagpoles or power lines, which cast a shadow that sweeps across the array, disrupting electrical production. Always remember and plan for self-shading from other solar panels, including the PV array or any mechanical equipment that may be changed or added later.
- **Terrain and space**—Terrain is very important in placing PV systems. Roofs, shade structures, and flat open areas are prime choices. Rocky inclines, such as mountainsides, may have challenges for excavating or mounting. Sufficient room must be present to place the PV array safely and properly without creating any long-term maintenance or safety issues. It is a bad design habit to break up strings and have the panes at different distances from each other. Sometimes it is best to use a smaller system.

Weather

Clouds, fog, and snow directly affect the amount of solar radiation PV systems receive. Locations with a lot of snow or rainy days produce less energy than sunny locations. Some require extra solar modules.

You must also plan carefully for snow. It should cleanly slough off the panels without piling at the bottom of the array and reducing performance. The reflection from snow sometimes increases light absorption.

Temperature is another key design and performance issue. Solar cells work best in cooler and clear conditions, whereas hot and sunny locations require special attention to panel selection, string sizing, balance-of-system (BOS), and other design considerations. Most PV panels do not perform well in hot environments. You can overcome this with good selection and design practices.

System Balance

Considering the adequacy of the site and the load requirements leads to system balance considerations. You must determine the correct number of modules. Module numbers help you meet loads and compensate for obstructions, weather, and other issues. Balance-of-system (BOS) equipment needed for each PV system must be selected to aid the PV system so it acts like a system and not just a bunch of ill-matched parts.

BOS equipment is all of the additional system components besides panels. BOS equipment must be properly selected and sized to ensure smooth functionality of the entire system while reducing losses. BOS components include batteries, battery charge controllers, inverters, wire (conductors), conduit, grounding circuits, fuses, disconnects, outlets, and module support structures. Choosing the correct BOS components often adds a fractional cost to the expense of a PV system yet pays for itself in months or over just a few years.

Additional Considerations

There are other things that must also be considered in the effective design of a quality PV system. The customer's intention, wants, needs, and goals in buying a PV system are critically important:

- How much does the customer understand about PV, the technologies, and how those technologies are designed to work?
- Does the customer intend to minimize grid dependence?
- What is the budget for the project?
- Does the client have preconceived notions about PV that need to be addressed?
- Is the customer's budget going to be a problem?

Obtaining as much information as possible from the customer will make designing the system easier.

Additional design considerations include the following:

- Ensure that the installation location can handle the weight and wind loading of the system and that the system can be properly mounted.
- Ensure the soundness of the mounting surface. Is it an old roof surface? Are there rotten rafters or sheathing under the roof? Responsibility for a roof-mounted system often lasts more than 10 years.
- Ensure compliance with applicable building and electrical codes.
- You can minimize electrical losses by selecting the right wiring, inverters, fuses, and switches. A high-performance system requires a 1 percent

conductor loss. Be mindful of the losses for long wire runs and multiple connections, and provide a rigorous testing plan to identify losses.

- Ensure proper housing and venting of battery systems for health and safety.
- Meet local utility interconnection requirements.
- Carefully consider design aesthetics. Imagine how the system contributes to the overall view of the house. Avoid creating a system that creates a negative perception of PV, embarrasses the customer, or upsets neighbors. The aesthetics of the system design and installation can be a great benefit when the owner sells the house. On the other hand, it can drastically reduce the value of the home's selling price if it is ugly and degrades the home and neighborhood.
- Consider how the system affects the ability to do maintenance on the structure, particularly the roof.
- Always collect facts about the project and site; never assume anything.

Common PV System Design Types and Options

Though every PV system must be designed specifically for each site, there are many common system design types. You can aid yourself in the design process by understanding the primary types of PV systems. It allows the PV professional to speak a common language with the customer and industry associates.

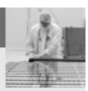
If the customer asks, "How many of the panels do I need to heat my pool?" you need to do some communicating and educating about PV versus other solar system types and issues. PV systems do not use fluids, they do not use heat exchangers, and they do not use tracking trough technologies. If the customer starts to talk about these things, gently ask permission to talk about available technology.

Grid-Interactive PV Systems Without Storage

Grid-interactive or grid-tied PV systems without storage do not include an energy storage device like batteries to store extra PV power. Battery storage is generally not necessary because extra power can be stored on the grid or taken from the connected utility grid when needed.

In a PV system without battery storage, the solar array sends energy to the inverter. The inverter sets the voltage, converting DC power to AC power. Most inverters process the incoming voltage and current to maximize power in watts from the array by using Maximum Power Point Tracking (MPPT). Understanding MPPT for the inverter in a system is important to reducing common losses in systems.

TECH TIPS



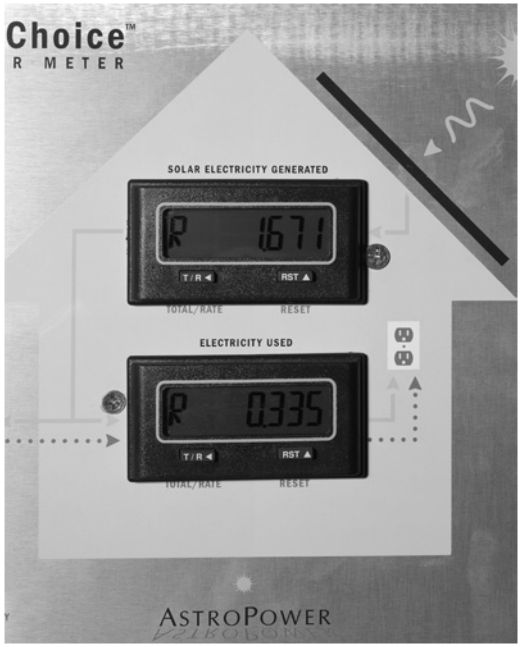
Residential sites benefit from having battery storage if they are located in places with numerous power outages.

Grid-interactive PV systems must use sine-wave inverters. These inverters produce sine waves that synchronize with the wave and frequency of the connected grid. Grid-tied inverters must also disconnect from the grid if the grid goes down or if the grid is not supplying power of sufficient quality in voltage, current, or sine wave.

The **main distribution panel** sends energy first to the internal loads. Depending on the total load at the site, it either sends or passes energy from the utility grid. It is the job of the main distribution panel to act as the conduit to the grid.

The main distribution panel is sized based on how much energy is needed from the sources it serves, and design considerations are based on the National Electrical Code (NEC). In some locations, excess power from the PV system can be sold to the utility company using what is called net metering.

Peak energy production occurs in the late morning through early afternoon because the solar resource is greatest during that time of day. This allows the PV system to collect more energy. The advantage of a net metering program is that it allows the customer to collect energy when it is available and use it when it is needed.



This electronic meter indicates the amount of electricity produced by the solar electric system and the amount of electricity consumed by the house. The house is in Centex's Los Olivos community in Livermore, Calif.

Courtesy of DOE/NREL, Credit: The Stone Group

Grid-Interactive PV Systems with Battery Storage

Residential sites attempting to limit dependence on utility grids often benefit from grid-interactive PV systems that include battery storage and additional PV-produced energy. During daylight hours, the PV system produces energy.

Some of the energy goes straight to the load while a portion is used to bring the batteries to full charge for use in critical loads. If there is a critical load like a computer system that might be affected by voltage shifts, brownouts, or outages, a battery storage system might make sense even if there is not a substantial amount of utility energy disruption.

PROBLEMS WITH GRID-INTERACTIVE PV SYSTEMS WITH BATTERIES

Address the challenges a client will have when discussing and designing a grid-tied system with batteries:

- Batteries as such are not dangerous. However, if not handled and maintained properly, they can create dangerous and even life-threatening situations.
- There is a lot to learn about batteries: what they do, how they operate, what maintenance is required, and how to get the most out of them. Never make assumptions about batteries. Understand how they work and how dangerous they can be if mistreated.
- Batteries are expensive. Depending on the type, quality, environment, and use, they will have to be replaced anywhere from every year to every 30 years. Unless there are critical loads that cannot be reduced or removed, or the customer's site has many disruptive outages, it might be best to add a battery backup or other storage device at a later time.
- Most lead-acid and iron-nickel batteries require regular maintenance. The batteries fail prematurely if maintenance is not continued regularly. Battery choice must be made very carefully, and the customer needs to be thoroughly educated to make a selection that makes sense for the long term.
- Making a commitment to battery backup means that there is a commitment for the battery part of the system for the life of the entire PV system. Even with grid-coupled systems where there are two parallel sets of inverters, the battery portion needs to always have a working battery to operate. Most battery-backed inverter systems must have battery power to disconnect and reconnect to the grid through the internal transfer switches.
- Batteries have temperature sensitivities and it is best to keep them at or around 77 degrees Fahrenheit. High temperatures dramatically shorten the life of batteries and can void the warranty. Freezing damages batteries and requires slow thawing. Always use a charge controller that allows for a temperature sensor to maximize the charging process at different temperatures.
- Batteries require expensive space in a building. If a battery system requires 120 square feet of storage space, for instance, in a house that costs $100 per square foot to build, then the additional cost for battery system space is $12,000. Many people do not consider this cost in their system budget. Commercial space is more expensive. Determining whether to use racking or other ways to reduce space is a good option.
- Always place batteries in a locked and secured location that is not accessible by people or animals. Batteries are potential sources of fire, explosion, burns, and even death, as they can release substantial amounts of energy in a fraction of a second.
- If the charge programming is not properly initiated, batteries can be placed in an endless day-and-night cycle of charging and discharging. This reduces battery life.
- Consider carefully before you recommend that a customer use batteries to load-shift by charging and discharging and/or buying less-expensive power to use during times of more-expensive power. If you crunch the numbers, you're likely to find that the value of the battery portion of the PV system is minimal compared with the cost.

Grid-interactive PV systems with batteries use a **battery charge control device** to control the power generated by the PV array. In this design, the Maximum Power Point Tracking (MPPT) is usually found in the charge controller. When designing grid-tied battery backup systems, it is important to make sure that system settings for inverters and charge controls are correct. This ensures that the batteries remain fully charged.

Modern designs of this type of PV system may or may not send the PV power directly to the inverter from the solar array. You need to fully acquaint yourself with the technology, what its programming capabilities are, how the programming works, and what timing, set point, and other options exist to maximize the batteries' lives while charging them efficiently.

Understanding the batteries is essential for smooth operation of the system. If the load and battery are both full, the inverter sends the excess PV power to the utility grid. If the batteries are discharged, providing settings for solar charging might be far more effective than using the grid to charge the batteries.

Off-Grid PV Systems with Storage

Off-grid customers must understand the operations of their systems and the maintenance that must be completed regularly. If they do not understand the requirements, they will damage the batteries prematurely and may cause harm to themselves or their property.

Some off-grid PV systems are for day use only and do not need storage. Water pumps in remote villages are one example. Many off-grid PV systems do need storage, however, so that power is available at night and during times of marginal insolation. And many sites need backup energy sources as well.

Off-grid PV systems with storage and backup energy producers are called **hybrid systems**. Hybrid systems utilize diesel and gas generators, microhydro, and wind turbines in addition to solar power. This helps guarantee the storage battery does not drain too low, or too quickly. These shorten the battery life span. It also ensures that the system has a broader range of energy input under different usage and environmental circumstances.

Off-grid PV systems with storage but no other power generators have special design considerations. The storage must be properly sized to minimize the probably of loss of load.

In a standalone PV system, the charge controller primarily controls the charging to the battery. The inverter controls the voltage, current, waveform or shape, frequency, and amplitude to the load. The inverter also supplies necessary current surges and reactive power needed by the loads in emergency situations for very short periods of time. It is a bad habit to design for customers to rely on the inverter surge function on a regular basis. The inverter and related electronics also control integrated engine-generator sets.

Engine-generator sets (gen-sets) act as backup power sources that power the loads and recharge the batteries. The usual PV system configuration including a gen-set depends on the inverter/system controls to turn the gen-set on and off. The inverter/system turns the gen-set off once the battery reaches a programmed set point or fully recharges.

Although some PV system controls allow for starting under low voltage, high current demand, and time, it is generally best to control those functions manually unless you are operating loads that must run 24 hours per day, 7 days per week and are usually unattended. The fuel savings can be as much as 30 percent with manual control, if you learn how the system works in sync with the load usage and weather patterns.

Autonomy

Autonomy is the number of hours or days the battery system operates between system charging and meeting the normal planned load. Autonomy is needed during storms, nighttime, or times when the DC part of the system shuts down for technical reasons.

The two most common scenarios for autonomy include the following:

- A large storm affects a standalone system and the PV input is minimal. How many days of autonomy does the customer want or need?
- A grid-tied battery backup system suffers a utility power outage. How many hours must the batteries power the critical load panel and its loads?

The equation for determining the answers of battery size requires addressing the following questions:

- Is there another backup source?
- Are there space limitations?
- What kind of battery is being used and what depth of discharge will the system be programmed for?
- What is the budget? How flexible is the customer?
- How knowledgeable is the customer about power outage or storm-caused energy reduction?

Batteries are expensive to purchase and maintain. Of course, if the battery is the only backup system, it can be very important that it be large enough to power critical loads for extended periods of time. Carefully consider the need for autonomy with the project budget when sizing the battery bank.

Design Requirements

Grid-connected and standalone PV systems have different design requirements because they are used differently. Grid-connected systems do not always need

CONSIDERATIONS IN SELLING TO ELECTRICITY RETAILERS

The late 1970s brought increased energy prices and a new concern for increased capacity, efficiency, and competition in the energy market. The result was the passage of the Public Utilities Regulatory Policies Act, or PURPA.

Under section 210, utilities are required to purchase power from nonregulated power producers. Producers could include cogeneration facilities or small power producers of 80 megawatts (MW) or less. Power may be created from waste, biomass, or renewable sources.

Utility companies are electricity retailers. They are in the business of making money by selling electricity. Many grid-interactive PV system owners have the option of selling extra energy from their PV system to the company that owns the connected portion of the grid. Sometimes you can sell to other wholesale or retail electric buyers.

Buying and selling power in large quantities on the grid is called wheeling. Shopping around for a good deal is important if you are a large or industrial commercial customer. This is not available to residential customers. States and utilities have complex and often confusing rules and requirements for wheeling. If you do have the option to sell to more than one utility and are considering an electricity retailer to sell to, consider the following:

- Billing and payment periods and terms
- Penalty clauses
- Termination fees
- What the meter registers (only the excess from the PV system, or total PV system production?)
- The price the electricity retailer will pay per kilowatt-hour and whether that price is time-of-day or demand sensitive
- The cost of electricity purchased from the grid per kilowatt-hour

Wheeling is the electrical transmission term used to describe the following:

- Transporting large quantities of electric power (usually in the range of megawatts or megavolt-amperes) over sections of transmission lines, which is referred to as the electrical grid
- Providing the services of transporting, buying, selling, or trading electric power over transmission lines

Wheeling works like any other commodity market. Deals take place in seconds with the continual juggling of what energy goes where and who owns it. Being informed when negotiating to sell PV power helps ensure a worthwhile deal.

battery storage. They still have special equipment needs. Standalone PV systems do need battery storage, though they differ more based on application and customer desires.

Special Requirements of Grid-Connected PV Systems

Grid-connected PV power systems are preferred for residential and commercial use. Tying the PV system to the grid generally negates the need for battery storage, because the grid supplies additional energy when needed and at night.

Necessary equipment for a grid-tied PV system includes the following:

- Solar panels or modules
- Long-life, high-efficiency sine-wave inverters
- A mounting system
- Mechanical support accessories
- Electric cables and wiring
- Balance-of-system components

TECH TIPS

A PV system only generates kWh. In other words, the customer is generating power for anything at the location from a light to a large freezer. On grid, there are no PV limits to how big the load is, only how much energy will be produced.

NOTE

The PV modules and inverters make up the majority of cost of a PV system.

PV System Installation and Cost

PV component and installation costs vary significantly depending on system design. You can classify system designs as subprime, moderate, and high performance. Each classification has different pricing. This is caused by product selection, quality of design and installation, and the ability to test and monitor the system. Other related expenses that fluctuate include the following:

- Equipment costs
- Shipping costs
- Labor costs
- Operations costs
- Maintenance costs
- Service costs
- Warranty costs

Prices are dynamic due in part to market conditions, availability of product, market manipulation, and the ability to buy where pricing is lower for volume. Other considerations, including the skill and knowledge to buy the right equipment, also factor into pricing.

You must understand energy loads when marketing and designing grid-connected PV systems. There is no average. No simple formula exists for determining system size other than analyzing usage. This is usually done with a year or more of utility bills or doing a year's worth of intensive individual load study. Utility bills provide the most accurate measure of load.

There is no accepted accurate way to compare technology as sold and used in the market today unless you look at system performance. Some people mistakenly think of system performance almost exclusively in terms of panel efficiency, least cost, and assembly of first-cost parts.

Performance is the total amount of energy produced in kilowatt-hours divided by the total cost of the system over 20 years. It can be reflected in $/kWh or kWh/$. When you pay $0.16/kWh, you know exactly what you are buying. At that price, you are buying 6.25 kilowatt-hours per dollar. For accuracy it is important to include all maintenance costs. That is clear and simple.

The kilowatt-hour (kWh) is an electrical generation measure. It is a measurable amount of energy. It is based on all of the system's costs from install through operation and maintenance costs over a fixed time period. The kilowatt-hour (kWh) is the *quantifiable measure* of energy produced. It does not vary from product to product or from system to system like the DC watt.

Chapter 2 Summary

Earth's shape, axis, and orbit, combined with environmental issues, are the primary factors in determining the amount of solar radiation of a given site. Earth's round shape affects the angle at which the sun's rays radiate a given site. Earth sits on a tilted axis, which is responsible for creating seasons and the amount of sunlight a given site receives throughout the year. Earth also orbits the sun in an elliptical orbit, constantly changing distance from the sun and the strength of the sun's radiation.

Knowledge of the sun's path and hours are critical to understanding the basics of how to design a high-quality PV system. Calculations can be performed based on this knowledge to estimate the amount of energy available at a given site. From here, load considerations are added to the equation. Put this information together and a quality PV system can be designed, whether grid-tied or standalone.

Key Concepts and Terms

Battery charge control device
Daily load
Hybrid system
Inverter
Load
Main distribution panel
Solar constant
Solar insolation
Sun hour

Chapter 2 Assessment

System Design Considerations

1. A grid-tied inverter must be able to automatically disconnect from the grid.
   - ❑ **A.** True
   - ❑ **B.** False
2. What does an inverter do?
   - ❑ **A.** Convert one DC voltage to another DC voltage
   - ❑ **B.** Convert one AC voltage to a different AC voltage
   - ❑ **C.** Convert DC voltage to AC voltage
   - ❑ **D.** Convert AC voltage to DC voltage
3. Why must grid-tied PV systems have sine wave inverters?
   - ❑ **A.** Sine-wave inverters are the most efficient kind of inverter.
   - ❑ **B.** Sine-wave inverters have the ability to sync with the grid to operate effectively.
   - ❑ **C.** Sine-wave inverters are the only inverters that can automatically disconnect from the grid.
   - ❑ **D.** Only sine-wave inverters have enough power to connect to the grid.

4. The solar radiation at a given site is dependent on:
- ❑ **A.** the site owners.
- ❑ **B.** the inverter.
- ❑ **C.** whether the system is standalone or grid-interactive.
- ❑ **D.** latitude and environmental considerations.

5. Why do the North and South Poles receive weak concentrations of sunlight? (*Select two.*)
- ❑ **A.** Earth's axis tilts them away from the sun.
- ❑ **B.** Earth's round shape causes the light to travel farther to reach the poles.
- ❑ **C.** They don't have horizons.
- ❑ **D.** They are cold.

6. What is the most expensive PV system component?
- ❑ **A.** The panels
- ❑ **B.** The inverter
- ❑ **C.** The mounting structure
- ❑ **D.** The wiring accessories

7. What kind of PV system is most common for residential use?
- ❑ **A.** Standalone
- ❑ **B.** Water heating
- ❑ **C.** Pool heating
- ❑ **D.** Grid-tied

8. The best kind of PV system for remote applications is:
- ❑ **A.** standalone.
- ❑ **B.** water heating.
- ❑ **C.** pool heating.
- ❑ **D.** grid-tied.

9. The total amount of energy needed by a site is called the:
- ❑ **A.** energy need.
- ❑ **B.** load.
- ❑ **C.** sun hour.
- ❑ **D.** system design.