What You Will Find In This Chapter

This chapter describes the different types of photovoltaic systems, how they work, what components make up the systems, and how those components work.

It is strongly suggested you read this chapter before starting work on a photovoltaic system or before reading other sections of this manual.

This chapter does not contain many of the cautions and warnings about specific components and operations that other chapters do. Read the appropriate chapters for specific operations as well as this one.

2.1.1 Introduction. This section describes the similarities and differences between photovoltaic and "conventional" AC (Alternating Current) electricity. Knowing this information will help you to better understand the systems and the service operations.

For this section, you need to know that a photovoltaic module is the smallest unit of solar electricity-producing equipment you will normally work on. A photovoltaic array is a group of one or more modules.

2.1.2 Impact of Load. The amount of electricity produced by a photovoltaic system to operate lights, motors, electronics, and other loads is not infinite. For this reason, an oversized load, or one which operates too many hours per day, will cause problems. These problems range from an interruption of the load to damage to the photovoltaic system or the load.

Loads are described in more detail in Section 2.4

2.1.3 DC Electricity. Photovoltaic electricity is DC (Direct Current). The current has a polarity, that is, it flows in one direction. This has an impact on wiring methods and equipment. In photovoltaic systems, grounding methods must be complete and correct. Wire color conventions are critical, not only to protect equipment from reverse polarity, but also to protect service personnel and system users.

Section 2.5.7 has more information on polarity and color conventions.

2.1.4 Current-Limited System. When the electrical lines from a utility company's AC power supply are crossed, the resultant short circuit causes an almost infinite current flow. For this reason, fuses and circuit breakers are used to provide over-current protection.

Photovoltaic modules are current-limited. A short-circuited photovoltaic module will produce current only up to a certain level. In fact, a common check of system performance is to deliberately short-circuit the photovoltaic modules and measure the current flow. This does not damage the modules (Figure 2-1).

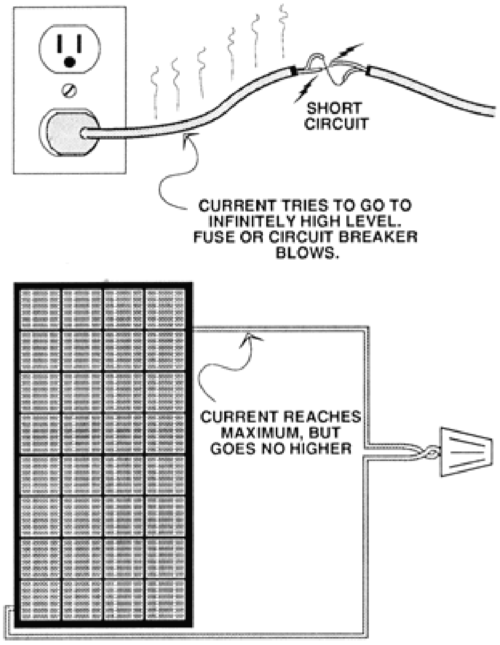


FIGURE 2-1
Short Circuits in AC Circuits (Top)
and Photovoltaic Module Circuits (Bottom)

WARNING!

Photovoltaic modules can be short-circuited without damage. However, a short circuit in other system components may cause component damage and dangerous, even lethal, conditions. This is particularly true of storage batteries. Always be sure to open a disconnect switch between the short circuit and the batteries.

Never attempt to short-circuit storage batteries!

2.1.5 Low Voltage Does Not Mean Harmlessness. Whenever working on or around photovoltaic systems remember three very important points:

1) Even at low voltages, photovoltaic systems may be able to deliver substantial current. The amount of available current may be high enough to kill you.

2) Photovoltaic systems can have two power supplies, not just one. Both the batteries and the modules in a system can deliver current.

3) Small "harmless" shocks can still injure you. For example, an arc created when making a wiring connection can ignite the hydrogen gas given off by storage batteries, causing an explosion. Likewise, a small shock can startle you, resulting in a fall from a ladder.

2.1.6 Voltage Drops. Unlike most AC systems, photovoltaic systems can suffer from a substantial voltage drop between the power source and the load. Good design practices minimize this drop.

As an extreme example, the available voltage at the photovoltaic array might be 16 volts. After traveling through hundreds of feet of undersized wire, it could be as low as 11 volts (Figure 2-2).

The system would not be able to recharge a 12 volt storage battery. This is because the available voltage is not higher than the voltage of the battery.

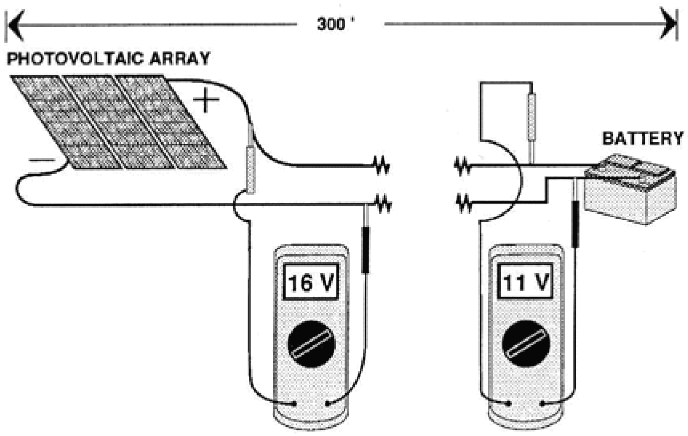


FIGURE 2-2
Voltage Drop in a Photovoltaic System

FIGURE 2-2

Voltage Drop in a

Photovoltaic System

Wire runs must be kept as short as possible. Wire must be large enough to minimize the voltage drop. Use the charts in Appendix C to determine these sizes. Notice that the wire sizes in photovoltaic systems are much larger than those in AC systems.

2.1.7 Connect/Disconnect Sequences. Connect/Disconnect Sequences. Unlike AC systems, the sequence of connection and disconnection is critical to many photovoltaic system components.

It should be noted that explosive hydrogen gas may be present near batteries. Making the last connection at the battery may create a spark which could result in an explosion. The best sequence of battery terminal connection might be as follows and as shown in Figure 2.3:

1) positive connection at battery.

2) positive connection at load.

3) negative connection at battery.

4) negative connection at load.

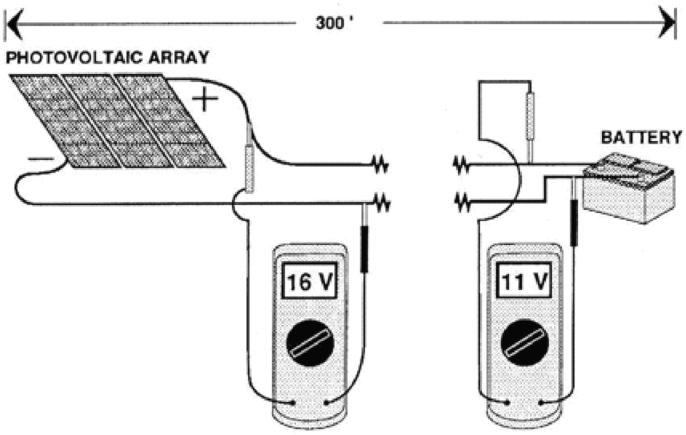


FIGURE 2-3
Battery Terminal
Connection Sequence

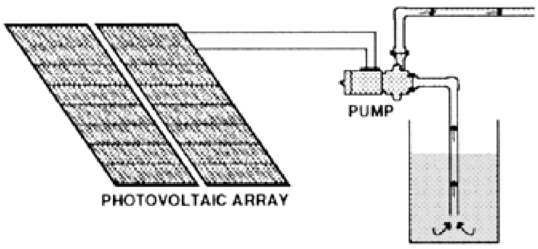
Other components are equally sensitive to connect/disconnect sequences. Charge controllers, in particular, may need to be connected in the correct sequence to prevent damage.

2.2 BASIC SYSTEM CONFIGURATIONS

2.2.1 Direct (Direct Coupled) DC System. The simplest photovoltaic system is made up of an array connected directly to a load. If the array includes more than one module, bypass diodes are used (Figure 2-4).

Applications requiring the most power during the sunniest part of the day are ideal for this type of system. Pumping water for irrigation or to a storage tank, running a fan for ventilation, or operating a pump to collect solar heat are examples of appropriate applications. Lighting and other loads which are rarely used during the daylight hours would probably never be supplied with power by a system of this type.

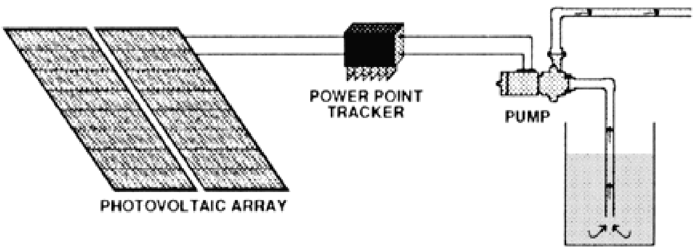
Figure 2-4
Direct DC System



The load must run on DC (Direct Current) electricity. This normally means a DC motor is used to run a pump, fan, or other device. As the sunlight gets more intense, the motor runs faster. Thus, the more sunlight, the more water or air that is moved.

2.2.2 Power Point Tracking DC System. The performance of a direct DC system can be increased by adding a power point tracker (Figure 2-5).

Figure 2-5
Power Point
Tracking
DC System



The power point tracker constantly monitors the system performance and makes electrical adjustments to keep the system operating as close as possible to its maximum output. More information on power point tracking can be found in Section 2.5.5.

2.2.3 Self-Regulated DC System. If battery storage is added to the system, some means must be used to prevent overcharging the batteries. The simplest way to do this is to use self-regulating modules. These modules are designed to deliver a voltage that is too low to overcharge the battery. (Figure 2-6). Careful matching of component sizes and loads is critical.

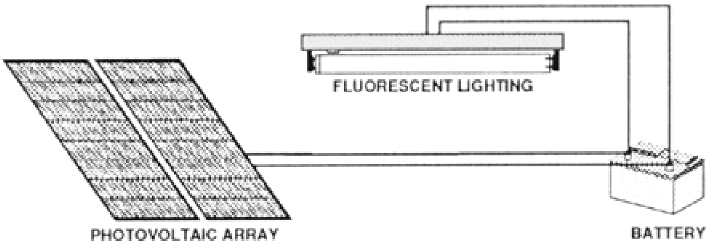


FIGURE 2-6
Self-Regulated DC
System

Again, the loads are DC only. If adequate battery storage is provided, and the loads are used consistently, this can be a reliable system. Because electricity is stored, lighting and other devices can be used after dark or during cloudy weather.

2.2.4 Regulated DC System. Most systems do not have self-regulated modules. Furthermore, many systems require some way to prevent damaging the batteries from charge levels which are too high or too low.

A charge controller, sometimes called a charge regulator, is used to keep the batteries from being overcharged. An optional feature of many controllers is a load cutoff. This turns off some or all of the loads whenever the batteries' state of charge gets too low (Figure 2-7).

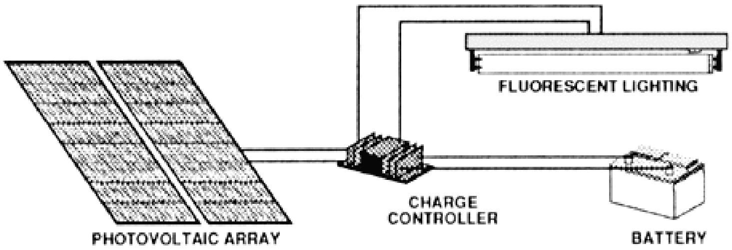


FIGURE 2-7
Regulated DC
System

Although the additional component adds to the complexity of the system, draws additional power, and can reduce overall reliability, the charge controller extends the battery life.

This is probably the most common photovoltaic system. More information about charge controllers is in Section 2.5.2.

2.2.5 Direct AC System. In some cases, such as deep well water pumping, AC loads must be provided with power, but only during the day. If the DC output of a photovoltaic array is converted to AC with an inverter, it can supply the AC load directly (Figure 2-8)

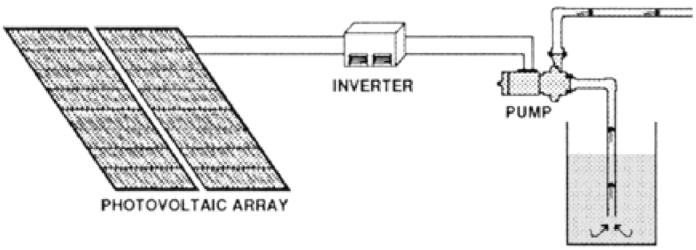


FIGURE 2-8
Direct AC
System

This system is appropriate for many of the same situations as the direct DC system. The inverter must be protected from temperature extremes and inclement weather. The cost of an inverter is significant, and it reduces the overall system efficiency. However, if the application requires a device which cannot operate on or be converted to DC, this is the simplest way to do the job.

2.2.6 AC System with Storage. If the AC load must run during periods when the photovoltaic array cannot supply power, battery storage and a charge controller must be included (Figure 2-9).

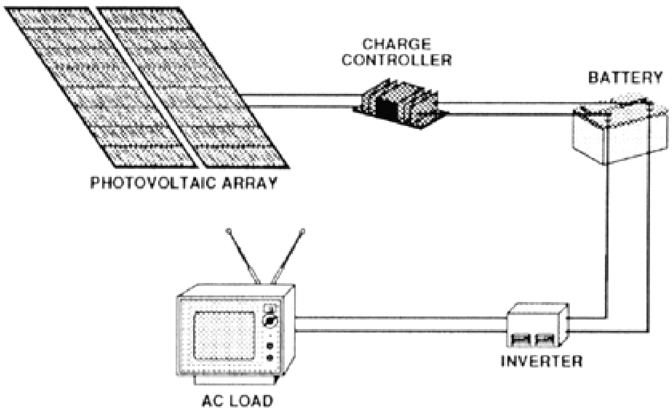
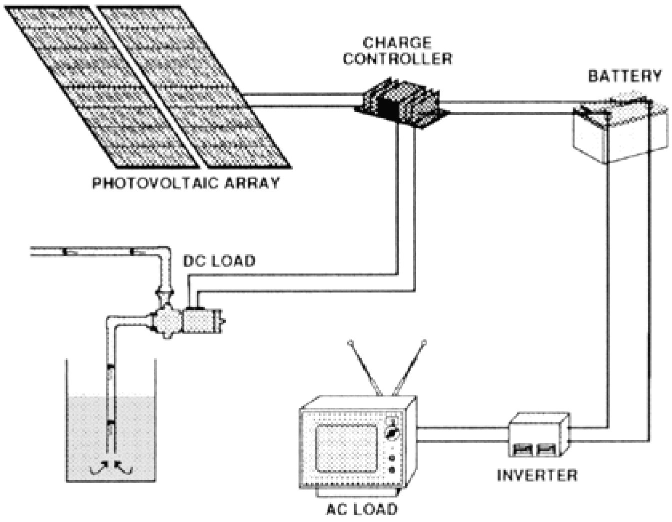


FIGURE 2-9
AC System
with Storage

The combined inefficiencies of the batteries and the inverter reduce overall system performance. Nevertheless, AC applications exist which will require the complexity and expense of this type of photovoltaic system.

2.2.7 Mixed AC/DC System. A good compromise is to supply every possible need with a DC device, and use AC only for those loads for which there is no alternative (Figure 2-10).

FIGURE 2-10
Mixed AC/DC
System



This compromise allows the most effective use of the energy available from the photovoltaic array, while satisfying the load requirements.

2.3 COMPONENT OPERATION

2.3.1 Photovoltaic Cells. At the present time, most commercial photovoltaic cells are manufactured from silicon, the same material from which sand is made. In this case, however, the silicon is extremely pure. Other, more exotic materials such as gallium arsenide are just beginning to make their way into the field.

The four general types of silicon photovoltaic cells are:

- Single-crystal silicon.
- Polycrystal silicon (also known as multicrystal silicon).
- Ribbon silicon.
- Amorphous silicon (abbreviated as "aSi," also known as thin film silicon).

Single-crystal silicon

Most photovoltaic cells are single-crystal types. To make them, silicon is purified, melted, and crystallized into ingots. The ingots are sliced into thin wafers to make individual cells. The cells have a uniform color, usually blue or black (Figure 2-11).

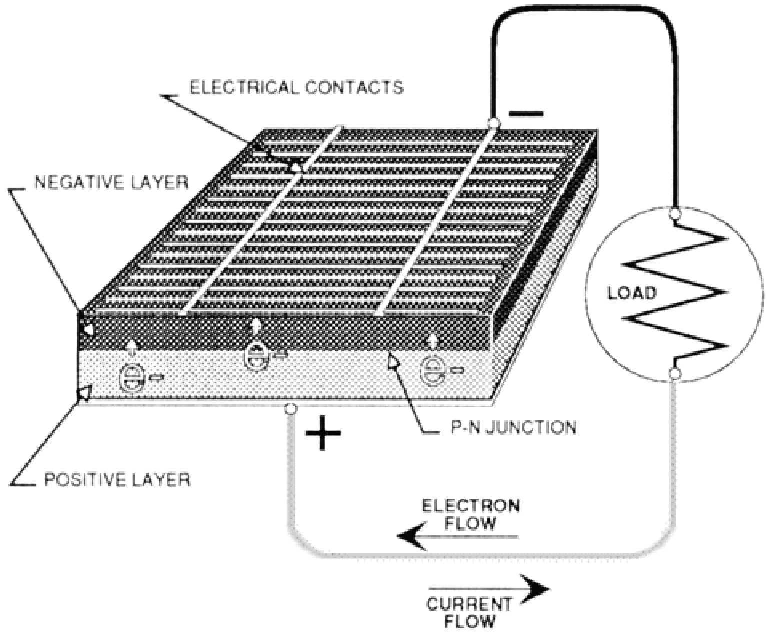
Figure 2-11
Single-Crystal Cells

Typically, most of the cell has a slight positive electrical charge. A thin layer at the top has a slight negative charge.

The cell is attached to a base called a "backplane." This is usually a layer of metal used to physically reinforce the cell and to provide an electrical contact at the bottom.

Since the top of the cell must be open to sunlight, a thin grid of metal is applied to the top instead of a continuous layer. The grid must be thin enough to admit adequate amounts of sunlight, but wide enough to carry adequate amounts of electrical energy (Figure 2-12)

Figure 2-12
Operation of a
Photovoltaic Cell



Light, including sunlight, is sometimes described as particles called "photons." As sunlight strikes a photovoltaic cell, photons move into the cell.

When a photon strikes an electron, it dislodges it, leaving an empty "hole". The loose electron moves toward the top layer of the cell. As photons continue to enter the cell, electrons continue to be dislodged and move upwards (Figure 2-12)

If an electrical path exists outside the cell between the top grid and the backplane of the cell, a flow of electrons begins. Loose electrons move out the top of the cell and into the external electrical circuit. Electrons from further back in the circuit move up to fill the empty electron holes.

Most cells produce a voltage of about one-half volt, regardless of the surface area of the cell. However, the larger the cell, the more current it will produce.

Current and voltage are affected by the resistance of the circuit the cell is in. The amount of available light affects current production. The temperature of the cell affects its voltage. Knowing the electrical performance characteristics of a photovoltaic power supply is important, and is covered in the next section.

Polycrystalline silicon

Polycrystalline cells are manufactured and operate in a similar manner. The difference is that a lower cost silicon is used. This usually results in slightly lower efficiency, but polycrystalline cell manufacturers assert that the cost benefits outweigh the efficiency losses.

Figure 2-13
Polycrystalline
Silicon Cells

The surface of polycrystalline cells has a random pattern of crystal borders instead of the solid color of single crystal cells (Figure 2-1 3).

Ribbon silicon

Ribbon-type photovoltaic cells are made by growing a ribbon from the molten silicon instead of an ingot. These cells operate the same as single and polycrystal cells.

The anti-reflective coating used on most ribbon silicon cells gives them a prismatic rainbow appearance.

Amorphous or thin film silicon

The previous three types of silicon used for photovoltaic cells have a distinct crystal structure. Amorphous silicon has no such structure. Amorphous silicon is sometimes abbreviated "aSi" and is also called thin film silicon.

Amorphous silicon units are made by depositing very thin layers of vaporized silicon in a vacuum onto a support of glass, plastic, or metal.

Amorphous silicon cells are produced in a variety of colors (Figure 2-1 4).

Since they can be made in sizes up to several square yards, they are made up in long rectangular "strip cells." These are connected in series to make up "modules." Modules of all kinds are described in Section 2.3.2.

Figure 2-14
An Amorphous
Silicon Module

Photo Courtesy
of Arco Solar,
Inc.

Because the layers of silicon allow some light to pass through, multiple layers can be deposited. The added layers increase the amount of electricity the photovoltaic cell can produce. Each layer can be "tuned" to accept a particular band of light wavelength.

The performance of amorphous silicon cells can drop as much as 15% upon initial exposure to sunlight. This drop takes around six weeks. Manufacturers generally publish post-exposure performance data, so if the module has not been exposed to sunlight, its performance will exceed specifications at first.

The efficiency of amorphous silicon photovoltaic modules is less than half that of the other three technologies. This technology has the potential of being much less expensive to manufacture than crystalline silicon technology. For this reason, research is currently under way to improve amorphous silicon performance and manufacturing processes.

2.3.2 Photovoltaic Modules. For almost all applications, the one-half volt produced by a single cell is inadequate. Therefore, cells are connected together in series to increase the voltage. Several of these series strings of cells may be connected together in parallel to increase the current as well.

These interconnected cells and their electrical connections are then sandwiched between a top layer of glass or clear plastic and a lower level of plastic or plastic and metal. An outer frame is attached to increase mechanical strength, and to provide a way to mount the unit. This package is called a "module" or "panel" (Figure 2-15). Typically, a module is the basic building block of photovoltaic systems. Table 2-1 is a summary of currently available modules.

Figure 2-15
A Photovoltaic
Module

Photo Courtesy
of Arco Solar,
Inc.

TABLE 2-1: Summary of Current Photovoltaic Technology

Groups of modules can be interconnected in series and/or parallel to form an "array." By adding "balance of system" (BOS) components such as storage batteries, charge controllers, and power conditioning devices, we have a complete photovoltaic system.

2.3.3 Describing Photovoltaic Module Performance. To insure compatibility with storage batteries or loads, it is necessary to know the electrical characteristics of photovoltaic modules.

As a reminder, "I" is the abbreviation for current, expressed in amps. "V" is used for voltage in volts, and "R" is used for resistance in ohms.

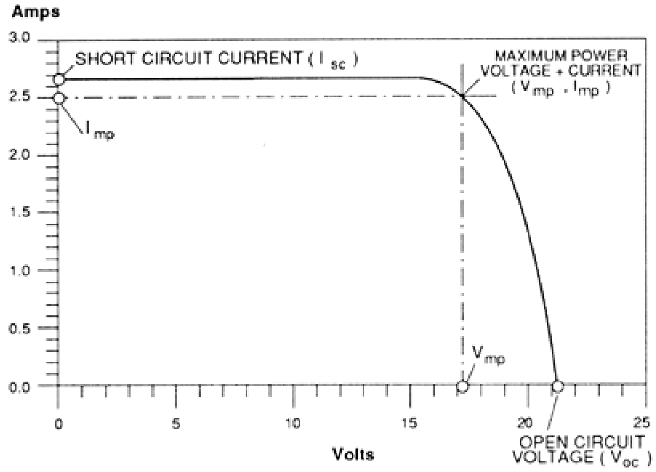
A photovoltaic module will produce its maximum current when there is essentially no resistance in the circuit. This would be a short circuit between its positive and negative terminals.

This maximum current is called the short circuit current, abbreviated I(sc). When the module is shorted, the voltage in the circuit is zero.

Conversely, the maximum voltage is produced when there is a break in the circuit. This is called the open circuit voltage, abbreviated V(oc). Under this condition the resistance is infinitely high and there is no current, since the circuit is incomplete.

These two extremes in load resistance, and the whole range of conditions in between them, are depicted on a graph called a I-V (current-voltage) curve. Current, expressed in amps, is on the vertical Y-axis. Voltage, in volts, is on the horizontal X-axis (Figure 2-16).

Figure 2-16
A Typical Current-Voltage Curve



As you can see in Figure 2-16, the short circuit current occurs on a point on the curve where the voltage is zero. The open circuit voltage occurs where the current is zero.

The power available from a photovoltaic module at any point along the curve is expressed in watts. Watts are calculated by multiplying the voltage times the current (watts = volts x amps, or W = VA).

At the short circuit current point, the power output is zero, since the voltage is zero.

At the open circuit voltage point, the power output is also zero, but this time it is because the current is zero.

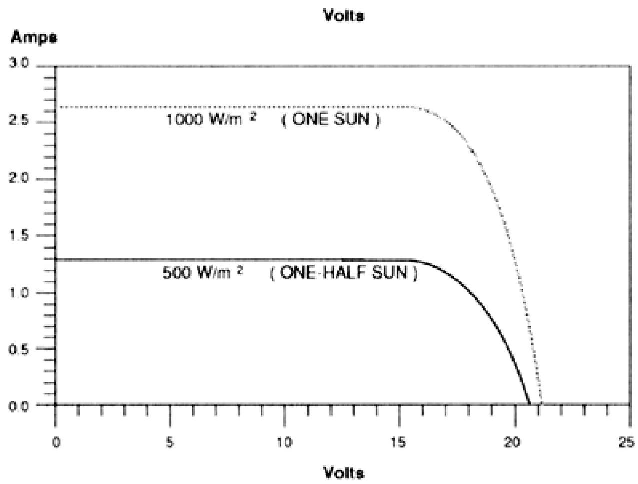
There is a point on the "knee" of the curve where the maximum power output is located. This point on our example curve is where the voltage is 17 volts, and the current is 2.5 amps. Therefore the maximum power in watts is 17 volts times 2.5 amps, equaling 42.5 watts.

The power, expressed in watts, at the maximum power point is described as peak, maximum, or ideal, among other terms. Maximum power is generally abbreviated as "I (mp)." Various manufacturers call it maximum output power, output, peak power, rated power, or other terms.

The current-voltage (I-V) curve is based on the module being under standard conditions of sunlight and module temperature. It assumes there is no shading on the module.

Standard sunlight conditions on a clear day are assumed to be 1000 watts of solar energy per square meter (1000 W/m2or lkW/m2). This is sometimes called "one sun," or a "peak sun." Less than one sun will reduce the current output of the module by a proportional amount. For example, if only one-half sun (500 W/m2) is available, the amount of output current is roughly cut in half (Figure 2-17).

Figure 2-17
A Typical Current-Voltage Curve at One Sun and One-half Sun



For maximum output, the face of the photovoltaic modules should be pointed as straight toward the sun as possible. Section 2.3.5 contains information on determining the correct direction and module tilt angle for various locations and applications.

Because photovoltaic cells are electrical semiconductors, partial shading of the module will cause the shaded cells to heat up. They are now acting as inefficient conductors instead of electrical generators. Partial shading may ruin shaded cells.

Partial module shading has a serious effect on module power output. For a typical module, completely shading only one cell can reduce the module output by as much as 80% (Figure 2-18). One or more damaged cells in a module can have the same effect as shading.

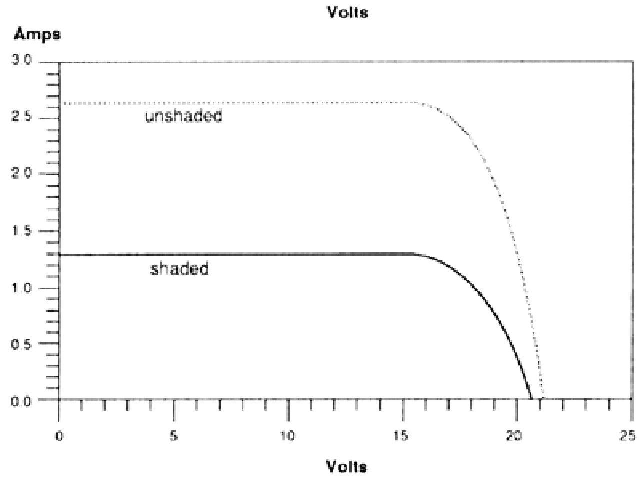


Figure 2-18
A Typical Current-Voltage Curve for an Unshaded Module and for a Module with One Shaded Cell

This is why modules should be completely unshaded during operation. A shadow across a module can almost stop electricity production. Thin film modules are not as affected by this problem, but they should still be unshaded.

Module temperature affects the output voltage inversely. Higher module temperatures will reduce the voltage by 0.04 to 0.1 volts for every one Celsius degree rise in temperature (0.04V/0C to 0.1V/0C). In Fahrenheit degrees, the voltage loss is from 0.022 to 0.056 volts per degree of temperature rise (Figure 2-19).

This is why modules should not be installed flush against a surface. Air should be allowed to circulate behind the back of each module so it's temperature does not rise and reducing its output. An air space of 4-6 inches is usually required to provide proper ventilation.

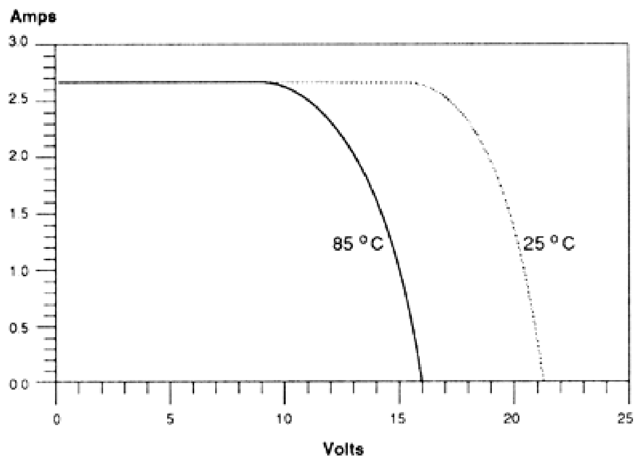
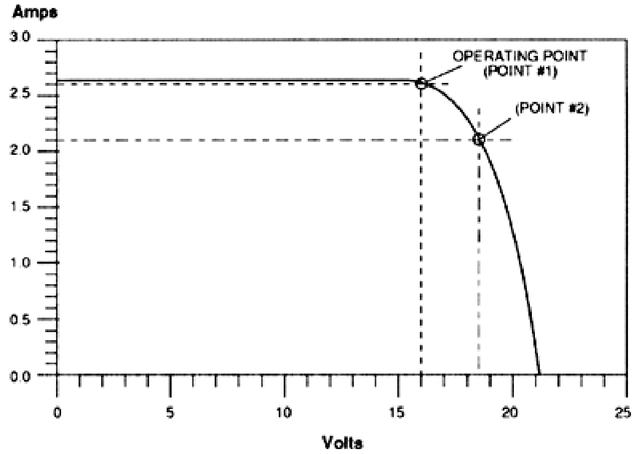


Figure 2-19
A Typical Current-Voltage Curve for a Module at 25°C (77°F) and 85°C (185°F)

The last significant factor which determines the power output of a module is the resistance of the system to which it is connected. If the module is charging a battery, it must supply a higher voltage than that of the battery.

If the battery is deeply discharged, the battery voltage is fairly low. The photovoltaic module can charge the battery with a low voltage, shown as point #1 in Figure 2-20. As the battery reaches a full charge, the module is forced to deliver a higher voltage, shown as point #2. The battery voltage drives module voltage.

Figure 2-20: Operating Voltages During a Battery Charging Cycle



Eventually, the required voltage is higher than the voltage at the module's maximum power point. At this operating point, the current production is lower than the current at the maximum power point. The module's power output is also lower.

To a lesser degree, when the operating voltage is lower than that of the maximum power point (point #1), the output power is lower than the maximum. Since the ability of the module to produce electricity is not being completely used whenever it is operating at a point fairly far from the maximum power point, photovoltaic modules should be carefully matched to the system load and storage.

Using a module with a maximum voltage which is too high should be avoided nearly as much as using one with a maximum voltage which is too low.

The output voltage of a module depends on the number of cells connected in series. Typical modules use either 30, 32, 33, 36, or 44 cells wired in series.

The modules with 30-32 cells are considered self regulating modules. 36 cell modules are the most common in the photovoltaic industry. Their slightly higher voltage rating, 16.7 volts, allows the modules to overcome the reduction in output voltage when the modules are operating at high temperatures.

Modules with 33 - 36 cells also have enough surplus voltage to effectively charge high antimony content deep cycle batteries. However, since these modules can overcharge batteries, they usually require a charge controller.

Finally, 44 cell modules are available with a rated output voltage of 20.3 volts. These modules are typically used only when a substantially higher voltage is required.

As an example, if the module is sometimes forced to operate at high temperatures, it can still supply enough voltage to charge 1 2 volt batteries.

Another application for 44 cell modules is a system with an extremely long wire run between the modules and the batteries or load. If the wire is not large enough, it will cause a significant voltage drop. Higher module voltage can overcome this problem.

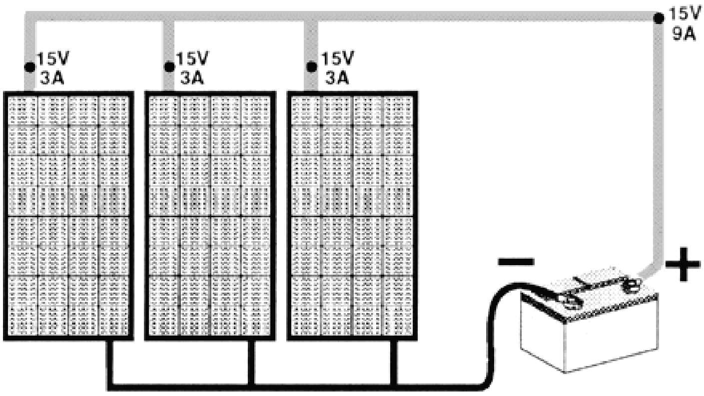
It should be noted that this approach is similar to putting a larger engine in a car with locked brakes to make it move faster. It is almost always more cost effective to use an adequate wire size, rather than to overcome voltage drop problems with more costly 44 cell modules.

Section 2.5.5 discusses maximum power point trackers. These devices are used to bring the module to a point as close as possible to the maximum power point. They are used mostly in direct DC systems, particularly with DC motors for pumping.

2.3.4 Photovoltaic Arrays. In many applications the power available from one module is inadequate for the load. Individual modules can be connected in series, parallel, or both to increase either output voltage or current. This also increases the output power.

When modules are connected in parallel, the current increases. For example, three modules which produce 15 volts and 3 amps each, connected in parallel, will produce 15 volts and 9 amps (Figure 2-21).

Figure 2-21: Three Modules Connected in Parallel

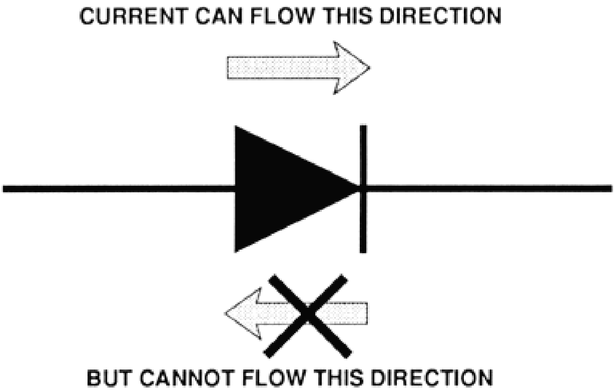


If the system includes a battery storage system, a reverse flow of current from the batteries through the photovoltaic array can occur at night. This flow will drain power from the batteries.

A diode is used to stop this reverse current flow. Diodes are electrical devices which only allow current to flow in one direction (Figure 2-22). A blocking diode is shown in the array in Figure 2-23.

Diodes with the least amount of voltage drop are called schottky diodes, typically dropping .3 volts instead of .7 volts as in silicon diodes.

Figure 2-22: Basic Operation of a Diode



Because diodes create a voltage drop, some systems use a controller which opens the circuit instead of using a blocking diode.

If the same three modules are connected in series, the output voltage will be 45 volts, and the current will be 3 amps.

If one module in a series string fails, it provides so much resistance that other modules in the string may not be able to operate either. A bypass path around the disabled module will eliminate this problem (Figure 2-23). The bypass diode allows the current from the other modules to flow through in the "right" direction.

Many modules are supplied with a bypass diode right at their electrical terminals. Larger modules may consist of three groups of cells, each with its own bypass diode.

Built in bypass diodes are usually adequate unless the series string produces 48 volts or higher, or serious shading occurs regularly.

Combinations of series and parallel connections are also used in arrays (Figure 2-24). If parallel groups of modules are connected in a series string, large bypass diodes are usually required.

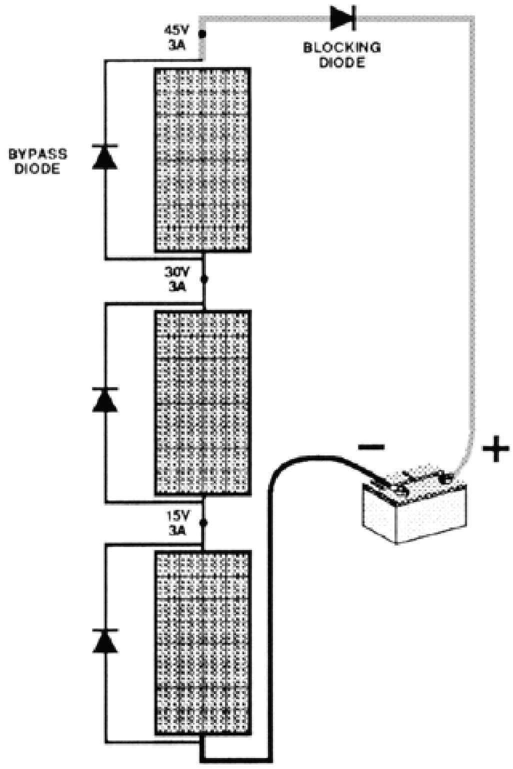


Figure 2-23:
Three Modules
Connected in Series
with a Blocking Diode
and Bypass Diodes

Isolation diodes are used to prevent the power from the rest of an array from flowing through a damaged series string of modules. They operate like a blocking diode. They are normally required when the array produces 48 volts or more. If isolation diodes are used on every series string, a blocking diode is normally not required.

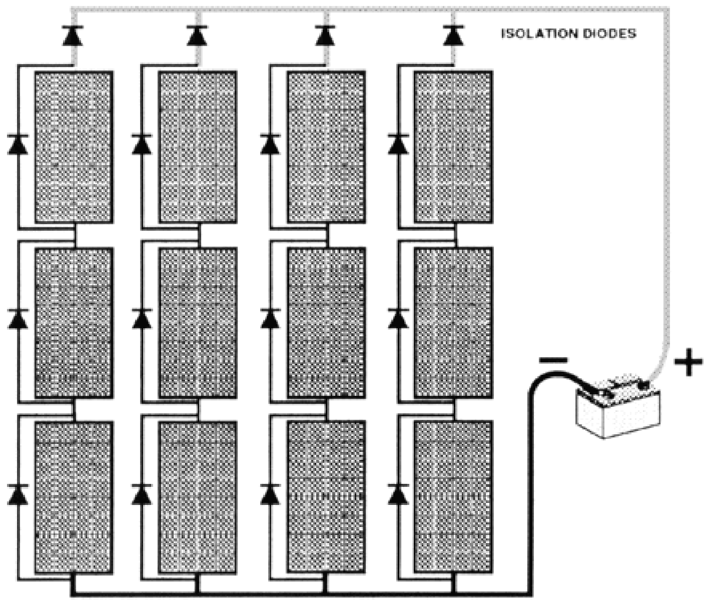


Figure 2-24:
Twelve Modules in
a Parallel-Series
Array with Bypass
Diodes and
Isolation Diodes

Flat-plate stationary arrays

Stationary arrays are the most common. Some allow adjustments in their tilt angle from the horizontal. These changes can be made any number of times throughout the year, although they are normally changed only twice a year. The modules in the array do not move throughout the day (Figure 2-25).

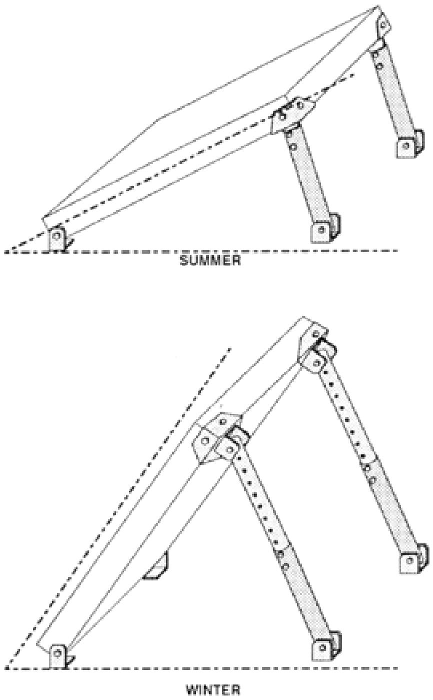


Figure 2-25:
Adjustable Array Tilted for Summer and Winter Solar Angles

Although a stationary array does not capture as much energy as a tracking array that follows the sun across the sky, and more modules may be required, there are no moving parts to fail. This reliability is why a stationary array is often used for remote or dangerous locations. Section 2.3.5 contains information on determining the correct tilt angle and orientation for different photovoltaic applications.

Portable arrays

A portable array may be as small as a one square foot module easily carried by one person to recharge batteries for communications or flashlights. They can be mounted on vehicles to maintain the engine battery during long periods of inactivity. Larger ones can be installed on trailers or truck beds to provide a portable power supply for field operations (Figures 2-26 and 2-27)

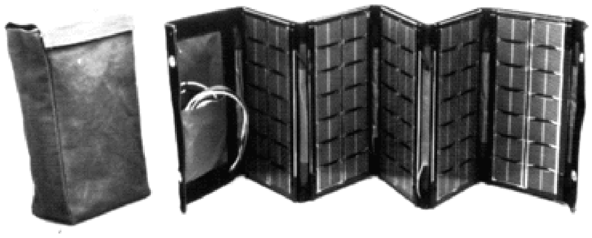


Figure 2-26:
Personal Photovoltaic Array

Photo Courtesy of Arco Solar, Inc.

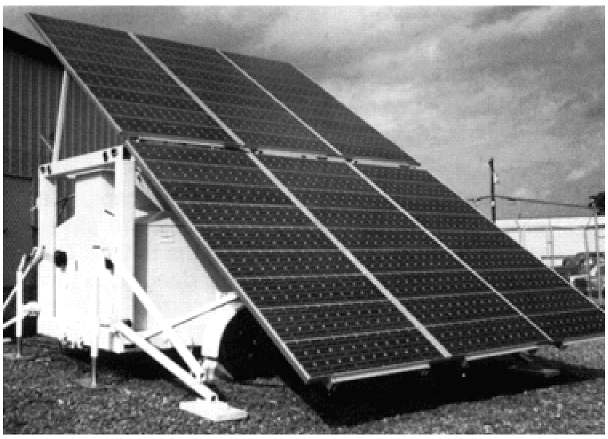


Figure 2-27
Portable Power Supply

Photo Courtesy of Integrated Power Corp

Tracking arrays

Arrays that track, or follow the sun across the sky, can follow the sun in one axis or in two (Figure 2-28). Tracking arrays perform best in areas with very clear climates. This is because following the sun yields significantly greater amounts of energy when the sun's energy is predominantly direct. Direct radiation comes straight from the sun, rather than the entire sky.

Normally, one axis trackers follow the sun from the east to the west throughout the day. The angle between the modules and the ground does not change. The modules face in the "compass" direction of the sun, but may not point exactly up at the sun at all times.

Two axis trackers change both their east-west direction and the angle from the ground during the day. The modules face straight at the sun all through the day. Two axis trackers are considerably more complicated than one axis types.

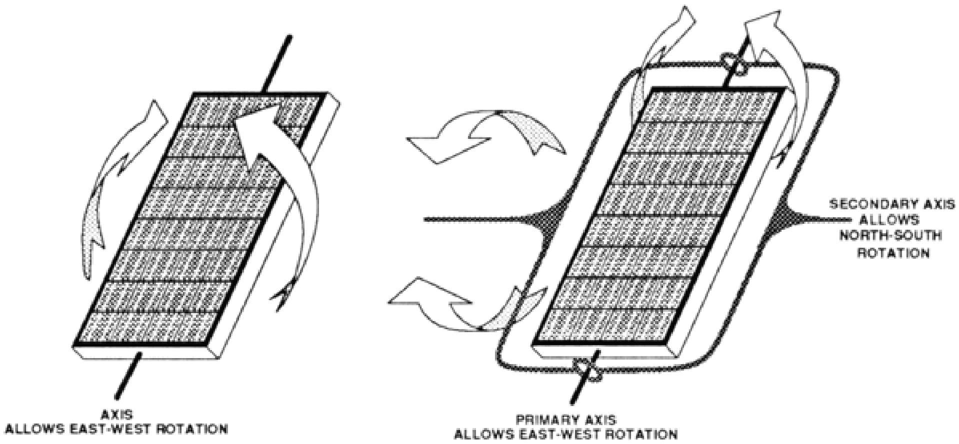


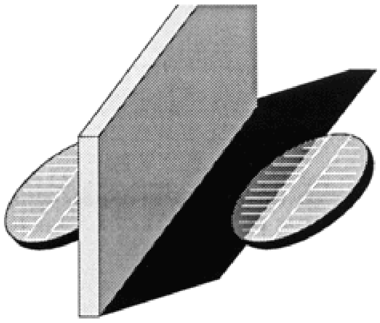
Figure 2-28
One Axis and Two Axis Tracking Arrays

Three basic tracking methods are used. The first uses simple motor, gear, and chain systems to move the array. The system is designed to mechanically point the modules in the direction the sun should be. No

sensors or devices actually confirm that the modules are facing the right way.

The second method uses photovoltaic cells as sensors to orient the larger modules in the array. This can be done by placing a cell on each side of a small divider, and mounting the package so it is facing the same way as the modules (Figure 2-29).

FIGURE 2-29
Photovoltaic Cells
Used as Solar
Orientation Sensor



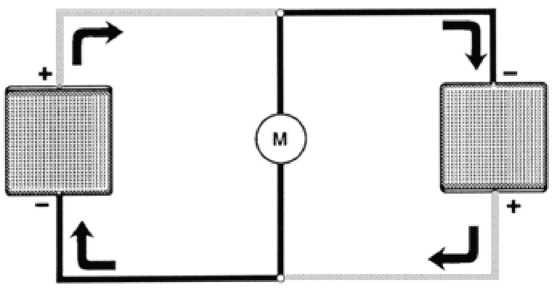
An electronic device constantly compares the small current flow from both cells. If one is shaded, the device triggers a motor to move the array until both cells are exposed to equal amounts of sunlight.

At night or during cloudy weather, the output of both sensor cells is equally low, so no adjustments are made. When the sun comes back up in the morning, the array will move back to the east to follow the sun again.

Although both methods of tracking with motors are quite accurate, there is a "parasitic" power consumption. The motors take up some of the energy the photovoltaic system produces.

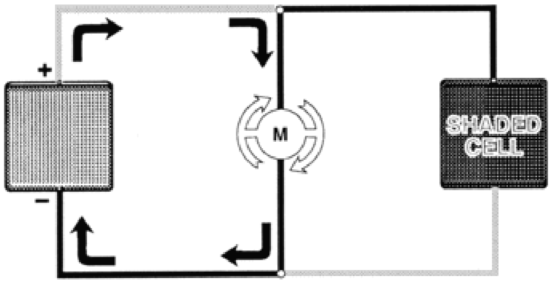
A method which has no parasitic consumption uses two small photovoltaic modules to power a reversible gear motor directly. If both modules are in equal sunlight, as shown in Figure 2-30, current flows through the modules and none flows through the motor.

FIGURE 2-30
Current Flow with Both
Modules in Equal Sunlight



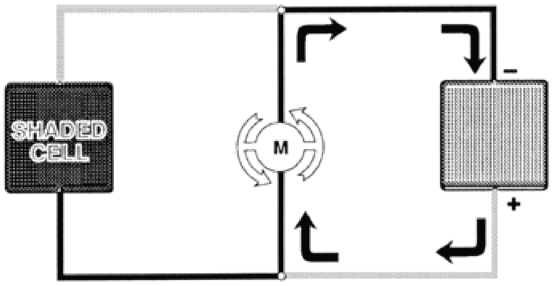
If the right module is shaded, it acts as a resistor (Figure 2-31). Now the current will flow through the motor, turning it in one direction.

FIGURE 2-31
Current Flow with One Module Shaded



If the other module, shown in Figure 2-32 on the left, is shaded, the current from the right module flows in the opposite direction. The motor will turn in the opposite direction as well.

FIGURE 2-32
Current Flow with the Other Module Shaded



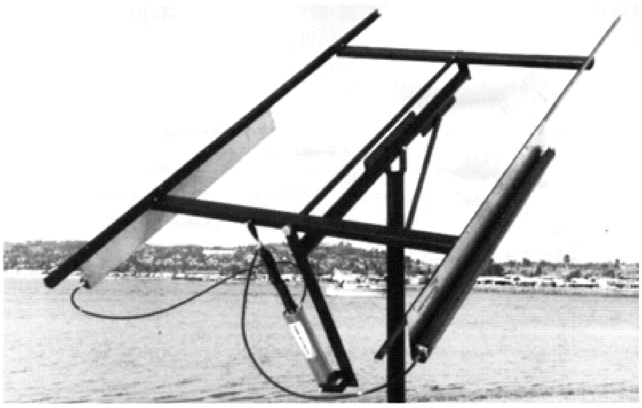
The motor must be able to turn in both directions.

A third tracking method uses the expansion and contraction of fluids to move the array. Generally, a container is filled with a fluid that vaporizes and expands considerably whenever it is in the sun. It condenses and contracts similarly when in the shade. These "passive" tracking methods have proven to be reliable and durable, even in high wind situations.

One system, the 9'SUN SEEKER" TM from Robbins Engineering, uses the pressure of the expansion and contraction to operate a hydraulic cylinder. Flexible piping from two containers filled with freon goes to opposite sides of a piston in the cylinder (Figure 2-33).

FIGURE 2-33
Sun Seeker System without Modules

Photo Courtesy of Robbins Engineering, Inc.



If the array is facing the sun, the pressure in both containers stays the same, and the piston will not move in the cylinder. However, when the sun moves the shading on the containers changes, placing them under different pressures.

The pressure difference, brought to the cylinder by the piping, will move the piston. The shaft from the piston will move the array. When the array is pointed back at the sun, the pressure stops increasing in the cylinder, and the piston and rod stop moving.

Another way to move the array with an expansive fluid is to use the change in fluid weight when it vaporizes. The Solar Track Rack TM by Zomeworks uses this method (Figures 2-34 and 2-35).

FIGURE 2-34
Solar Track Rack without Modules

Photo Courtesy of Zomeworks Corp.

The fluid-filled containers are integrated into the sides of the array mounting structure. They are connected together flexible piping, which is protected in the mounting structure. As long as the array is facing directly at the sun, the shades cover each container equally.

When the array is no longer facing directly at the sun, one container is exposed to more heat from the sun. This causes the fluid in that container to boil out of that container into the other one. Now the shaded container has more fluid in it and is heavier. The array will drop down like a "teeter-totter" in the direction of the shaded container until the shading equalizes on the two containers again.

FIGURE 2-35
Solar Track Rack without Modules Mounted

Photo Courtesy of Zomeworks Corp.

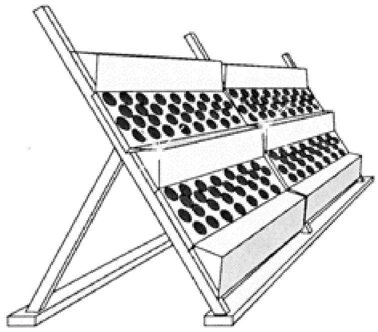
Since this method is more sensitive, wind can move the array. A shock absorber is included in the system to absorb such rapidly applied forces.

Reflectors

Reflectors are sometimes used to increase the amount of solar energy striking the modules (Figure 2-36). Since reflectors cost less than photovoltaic modules, this method may be used for some applications. There are several problems with reflectors, however.

Not all photovoltaic modules are designed for the higher temperatures reflectors cause. The performance and physical structure of many modules will suffer if reflectors are used with them. Remember that higher module temperatures mean lower output voltages.

FIGURE 2-36
Reflectors on a Fixed
Photovoltaic Array



Another problem is that reflectors work mostly with sunlight coming directly from the sun. Since a great deal of the sun's energy in cloudy climates comes to the earth's surface from all parts of the sky, reflectors are most effective in clear climates.

In all but the clearest of climates, the amount of direct solar energy is rarely high enough to justify the use of reflectors all year.

By increasing the overall surface area of the array, reflectors also increase the array's wind loading characteristics.

Finally, some type of tracking system may be required. This increases the system cost, may add a parasitic power loss, and can reduce the system reliability. Poorly designed or improperly installed reflectors have been known to shade modules.

Concentrators

Concentrators use lenses or parabolic reflectors to focus light from a larger area onto a photovoltaic cell of smaller area. The cells are spread out more than a typical module, and must be a high temperature type. They may have a heat removal system to keep module temperatures down and output voltages up. These systems have the same disadvantages of reflectors, and are higher in cost. As a consequence, large systems feeding a utility grid are usually the only ones using reflectors or concentrators.

Bracket mounting

Small arrays of one or two modules can use simple brackets to secure the modules individually to a secure surface (Figure 2-25). The surface may be a roof, wall, post, pole, or vehicle. Brackets can include some method to adjust the tilt angle of the module.

The brackets are usually aluminum. If steel is used, it should be painted or treated to prevent corrosion. Galvanized steel is normally avoided, because the continuous grounding used on arrays aggravates the galvanic corrosion that occurs between galvanized steel and almost all other metals.

Fastener hardware should be stainless steel or cadmium plated to prevent corrosion. Identical metals should be used for components and fasteners whenever possible.

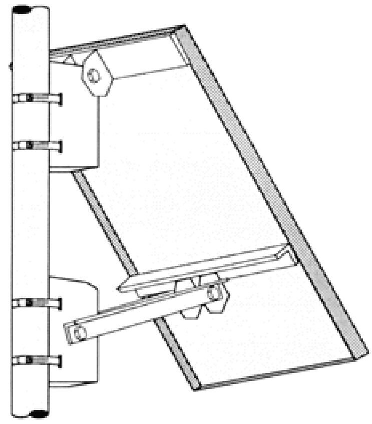
Pole mounting

Typically, up to four modules can be connected together and mounted on a pole (Figure 2-37). Typically, 2 1/2" nominal steel pipe (O.D. of 3") is used.

Black iron or steel pipe can be used, if painted. Galvanized pipe, rarely available in this size, can be used if compatible fasteners are used. Larger arrays can be pole mounted, if hardware sizes are appropriately increased.

The same types of materials used for bracket mounting should be used for pole mounting.

FIGURE 2-37
Pole Mount of Photovoltaic Array



Ground mounting

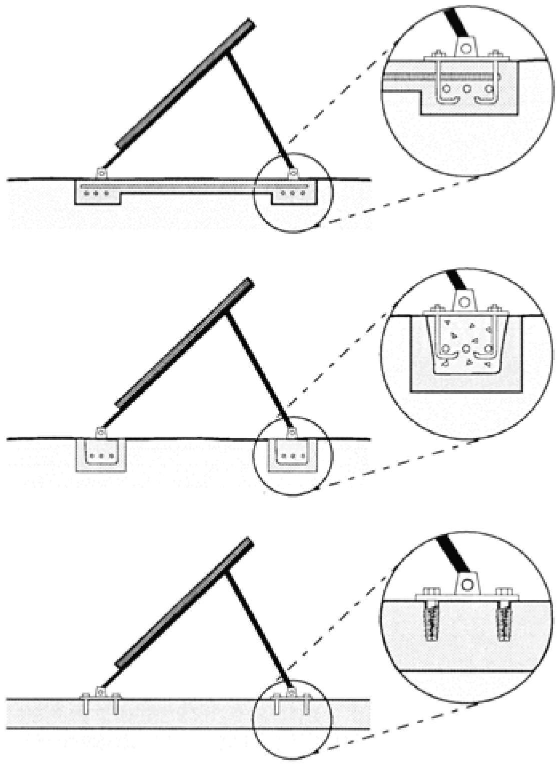
For arrays of eight or more modules, ground mounting is usually the most appropriate technique. The greatest concern is often the uplifting force of wind on the array. This is why most ground mounted arrays are on some kind of sturdy base, usually concrete.

Concrete bases are either piers, a slab with thicker edges, or footings at the front and rear of the array (Figure 2-38). All three usually include a steel reinforcement bar.

In some remote sites it may be more desirable to use concrete block instead of poured concrete. The best way to do this is to use two-web bond-beam block, reinforce it with steel, and fill the space between the webs with concrete or mortar.

Pressure-treated wood of adequate size is sometimes used for ground mounting. This can work well in fairly dry climates, but only if the beams are securely anchored to the ground, and regular inspection and maintenance is provided.

FIGURE 2-38
Concrete Bases



The array's mounting hardware can be bolted to an existing slab. With

extensive shimming, some mountaintop arrays are bolted to exposed rock. In either case, adequately sized expansion-type anchor bolts are used. The heads of the bolts should be covered with some type of weatherproof sealant. Silicone sealant is the best choice.

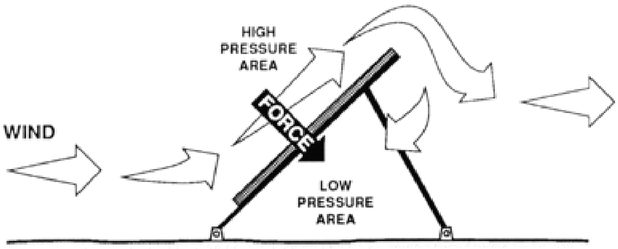
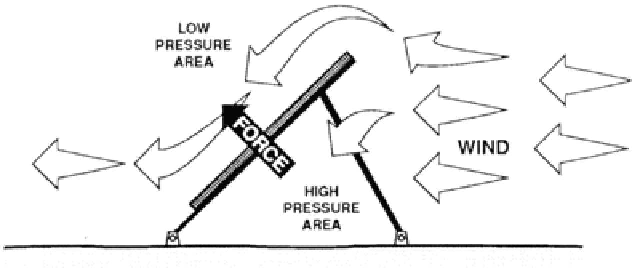


FIGURE 2-39
Forces on a
Photovoltaic Array



Structure mounting

Photovoltaic modules mounted on buildings or other structures are subjected to downward force when the wind hits their front surfaces. When the wind strikes the back of the modules, upward force is generated (Figure 2-39).

For this reason, the attachment to the building of modules with exposed backs is designed to resist both directions of force.

Another consideration when modules are mounted to a structure is the trapped heat between the module and the structure. Remember that module voltage drops with increased temperature.

Generally, photovoltaic arrays are mounted on structures in such a way that air can maturely circulate under the modules. This keeps the modules operating at the lowest possible temperature and highest possible output voltage. Access to the back of the modules also simplifies service operations.

2.3.5 Module Tilt and Orientation. Permanently mounted modules should be tilted up from the horizontal (Figure 2-40 and Table 2-2). The correct tilt angle varies with the times of year the system is used, and the latitude of the site. The tilt angle is measured from the horizontal, not from a pitched roof or hillside.

The tilt should be within 10 degrees of the listed angle. For example, a system used throughout the year at a latitude of 350 can have a tilt angle of 250 to 450 without a noticeable decrease in annual performance.

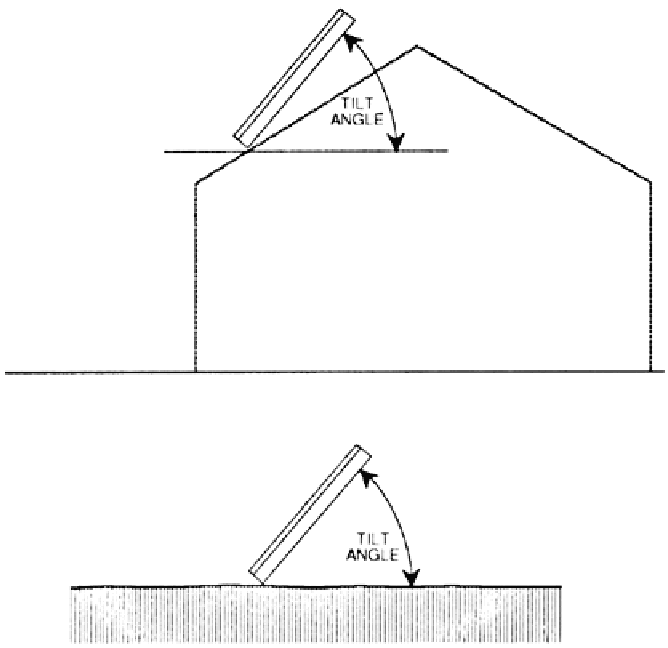


FIGURE 2-40
Module Tilt
Measured form
the Horizontal on
Level and Tilted
Surfaces

Table 2-2 Photovoltaic Module Tilt Angles

Time of Year System is Used the Most	Recommended Tilt Angle
All Year	Latitude
Mostly Winter	Latitude + 15°
Mostly Summer	Latitude - 15°
Mostly Fall or Spring	Latitude

For proper operation, the modules must be oriented as close as possible toward the equator. In the Northern Hemisphere, this direction is true south. In most areas, this varies from the magnetic south given by a compass. A simple correction must be made.

First, find the magnetic variation from an isogonic map. This is given in degrees east or west from magnetic south (Figure 2-41).

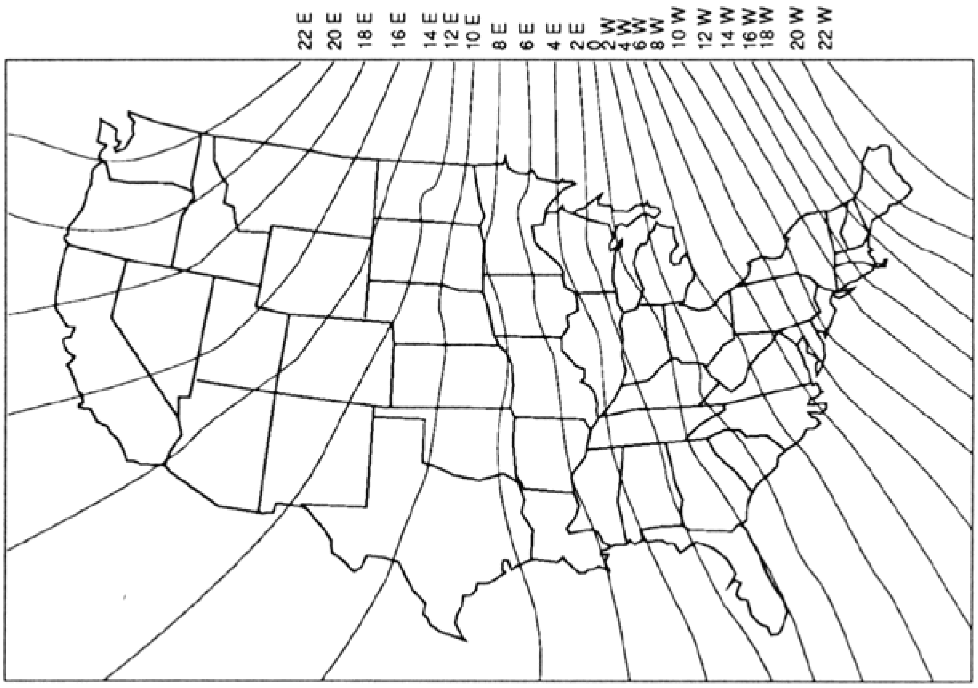
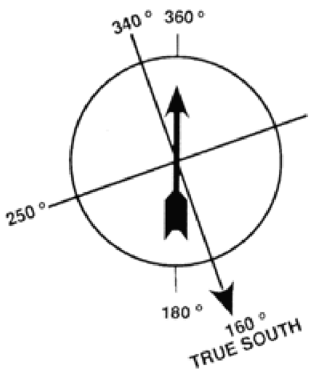


Figure 2-41: Isogonic Map of the United States

For example, a site in Montana has a magnetic variation of 200 east. This means that trne south is 200 east of magnetic south. On a compass oriented so the north needle is at 3600, true south is in the direction indicated by 1600 (Figure 2-42).

FIGURE 2-42
Directions on a Compass at
20° East Magnetic Variation



The modules should be installed within 200 of true south. In areas with morning fog, the array can be oriented up to 200 toward the west to compensate. Conversely, arrays in areas with a high incidence of afternoon storms can be oriented toward the east.

If the array is located in the Southern Hemisphere, the array must face true north.

Small portable arrays are usually just pointed at the sun, and moved every hour or so to follow the sun across the sky.

2.4 TYPICAL APPLICATIONS

2.4.1 DC Loads.

Effect of loads on the system

Loads directly influence the performance of the entire photovoltaic system. Oversize or extra loads can cause a system to fail if the loads require more power than the modules can generate or than the battery can store.

Likewise, the efficiency of the load influences the photovoltaic system's performance. All loads should be as efficient as oossible.

Lighting and other resistive loads

Incandescent or quartz halogen lighting for general purposes, security, or navigational aids is available in DC versions, and can be supplied with power by a photovoltaic system.

Timers, motion detectors, or photocells (to determine dusk and dawn) should be used whenever possible, to eliminate leaving the lights on when they are not needed.

The lamp, fixture, and general system design should be as efficient as possible. The use of DC lighting equipment is a good way to avoid the inefficiencies of the inverter needed to convert DC to AC. DC fluorescent and low pressure sodium systems are available, are much more efficient, and are discussed below under inductive loads.

"Heating" loads are a poor use of PV generated electricity. These include resistive heating appliances and tools such as toasters, coffee makers, soldering irons, space and water heaters.

Because of the high amount of energy they consume, these loads should be used only when there is no other option, or if the load will only be used occasionally. Oversized or inappropriate loads often result in system failure.

Inductiveloads

Inductive loads are those involving a motor or an electromagnet. Many photovoltaic systems supply energy to DC motors driving power tools, fans, pumps, and appliances.

Inductive loads also include solenoids, which use electricity to create a magnetic field to open or close valves or perform other operations in a variety of mechanical systems.

Again, the efficiency of the load should be as high as possible. One advantage to DC motors is that they are more efficient than AC motors.

DC lighting systems using a ballast, such as low pressure sodium and fluorescent systems, are also inductive loads (Figure 2-43). They should be used whenever possible, as they are considerably more efficient than incandescent or quartz halogen systems.

FIGURE 2-43
Low Pressure
Sodium Light

Photo Courtesy of
Thin-Lite Corp

2.4.2 AC Loads.

AC loads can be used if the photovoltaic system includes an inverter. In general, it is best to try to limit AC loads because of the energy lost in the conversion of DC to AC in an inverter. Inverters are discussed in detail in Section 2.5.3.

Lighting and other resistive loads

Sometimes, the availability of AC power makes the use of small amounts of AC incandescent lighting reasonably appropriate. With photovoltaic systems, incandescent lighting should be minimized because of its poor efficiency. AC fluorescent and low pressure sodium lighting systems are more efficient. Using DC power directly from the battery to operate DC versions of these lighting systems is an even better choice.

The use of AC appliances and tools such as toasters, dryers, soldering irons, and heat guns (which are primarily resistance heaters) should be minimized.

Inductive loads

Many appliances and power tools are only available with AC motors. These motors generally require a "clean" source of AC power, and thus a more sophisticated inverter. More information on inverters can be found in Section 2.5.3.

Motors operating on a power source which is not clean enough will waste electrical energy. The wasted energy is dissipated through the motor as heat. This can shorten the lifetime of the motor.

Combination 120V AC/DC motors are available which can operate on either power source. These can be used as a portable DC device in the field with a photovoltaic system, and "plugged in" to a utility's AC supply at other times. It should be noted, however, that the majority of the DC systems installed are rarely 1 20 volts.

Microwave ovens require a fairly clean AC power supply, and are an inductive load. The power supply requires the peak voltage of a sine wave (clean power to operate properly).

For lighting, high pressure sodium lighting systems offer the most efficiency, followed in order by low pressure sodium, metal halide, mercury vapor, and fluorescent. For indoor lighting, fluorescent is probably the best choice, since the others supply light with poor color rendering.

Electronic loads

Some electronic devices, including communications devices and small computers, will operate satisfactorily on the output of simple inverters. Other devices, such as video and audio equipment, require the cleaner output of more sophisticated inverters. Again, more information on inverters can be found in Section 2.5.3.

A good example of the difficulty of categorizing electronic loads is a personal computer. The computer itself may run without any problems on the output of a simple inverter. The video monitor and printer, however, will not. Therefore, the entire package should be run with the cleaner power supply of a more sophisticated inverter. Clocks may run fast on an inverter that produces a square or quai-sine wave.

Another way to categorize electronic loads is their sensitivity to RFI (Radio Frequency Interference) or EMI (ElectroMagnetic Interference). Simpler inverters can create significant RFI or EMI "noise," which may interfere with the operation of some equipment. This is particularly true of two-way communication equipment, televisions, and radios.

2.5 SYSTEM COMPONENT OPERATION

2.5.1 Battery and Other Storage. Batteries store the electrical energy generated by the modules during sunny periods, and deliver it whenever the modules cannot supply power.

Normally, batteries are discharged during the night or cloudy weather. But if the load exceeds the array output during the day, the batteries can supplement the energy supplied by the modules.

The interval which includes one period of charging and one of discharging is described as a "cycle." Ideally, the batteries are recharged to 1 00% capacity during the charging phase of each cycle. The batteries must not be completely discharged during each cycle.

No single component in a photovoltaic system is more affected by the size and usage of the load than storage batteries. If a charge controller is not included in the system, oversized loads or excessive Use can drain the batteries' charge to the point where they are damaged and must be replaced. If a controller does not stop overcharging, the batteries can be damaged during times of low or no load usage or long periods of full sun.

For these reasons, battery systems must be sized to match the load. In addition, different types and brands of batteries have different "voltage set point windows." This refers to the range of voltage the battery has available between a fully discharged and fully charged state.

As an example, a battery may have a voltage of 14 volts when fully charged, and 11 when fully discharged. Assume the load will not operate properly below 12 volts. Therefore, there will be times when this battery cannot supply enough voltage for the load. The battery's voltage window does not match that of the load.

Performance

The performance of storage batteries is described two ways. These are (1) the amp-hour capacity, and (2) the depth of cycling.

Amp-hour capacity

The first method, the number of amp-hours a battery can deliver, is simply the number of amps of current it can discharge, multiplied by the number of hours it can deliver that current.

System designers use amp-hour specifications to determine how long the system will operate without any significant amount of sunlight to recharge the batteries. This measure of "days of autonomy" is an important part of design procedures.

Theoretically, a 200 amp-hour battery should be able to deliver either 200 amps for one hour, 50 amps for 4 hours, 4 amps for 50 hours, or one amp for 200 hours.

This is not really the case, since some batteries, such as automotive ones, are designed for short periods of rapid discharge without damage. However, they are not designed for long time periods of low discharge. This is why automotive batteries are not appropriate for, and should not be used in, photovoltaic systems.

Other types of batteries are designed for very low rates of discharge over long periods of time. These are appropriate for photovoltaic applications. The different types are described later.

Charge and discharge rates

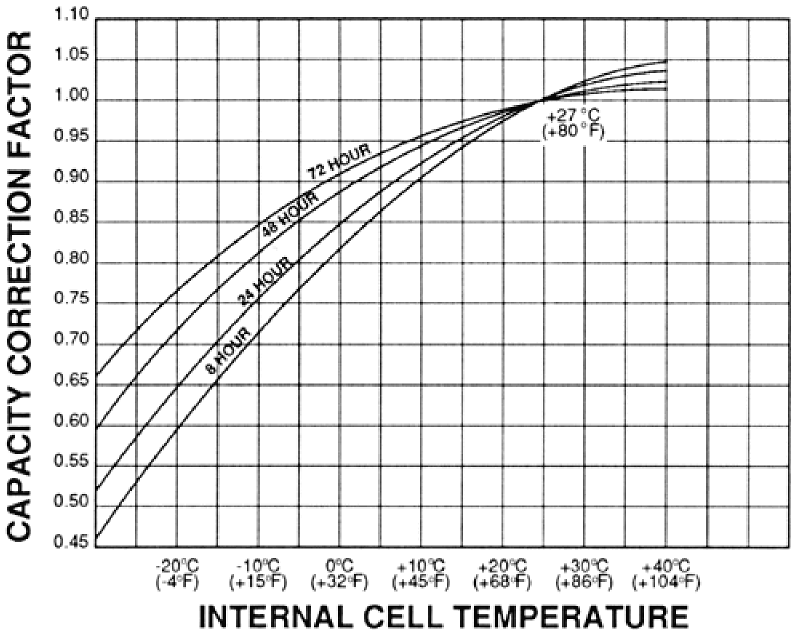
If the battery is charged or discharged at a different rate than specified, the available amp-hour capacity will increase or decrease. Generally, if the battery is discharged at a slower rate, its capacity will probably be slightly higher. More rapid rates will generally reduce the available capacity.

The rate of charge or discharge is defined as the total capacity divided by some number. For example, a discharge rate of C/20 means the battery is being discharged at a current equal to 1/20th of its total capacity. In the case of a 400 amp-hour battery, this would mean a discharge rate of 20 amps.

Temperature

Another factor influencing amp-hour capacity is the temperature of the battery and its surroundings. Batteries are rated for performance at 800F. Lower temperatures reduce amp-hour capacity significantly. Higher temperatures result in a slightly higher capacity, but this will increase water loss and decrease the number of cycles in the battery life (Figure 2-44).

FIGURE 2-44
Battery Capacity at Different Temperatures



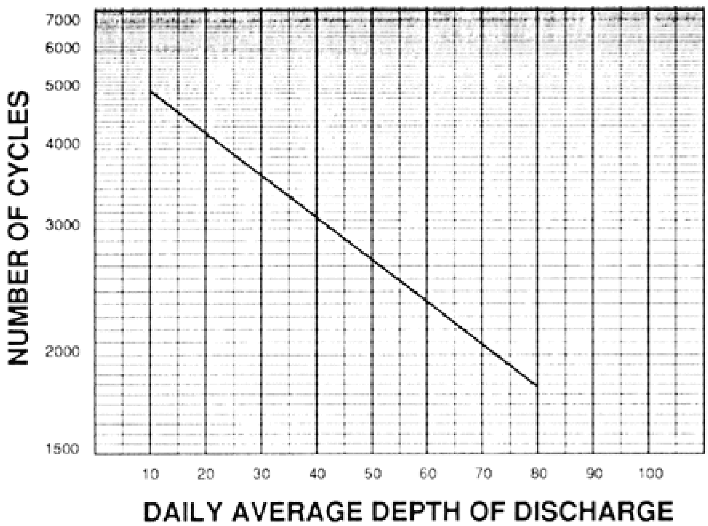
Depth of discharge

The second description of performance is depth of discharge. This describes how much of the total amp-hour capacity of the battery is used during a charge-recharge cycle.

As an example, "shallow cycle" batteries are designed to discharge from 10% to 25% of their total amp-hour capacity during each cycle. In contrast, most "deep cycle" batteries designed for photovoltaic applications are designed to discharge up to 80% of their capacity without damage. Manufacturers of deep cycle "Ni cad" batteries claim their product can be totally discharged without damage.

Even deep cycle batteries are affected by the depth of discharge. The deeper the discharge, the smaller the number of charging cycles the battery will last (Figure 2-45). They are also affected by the rate of discharge and their temperature.

FIGURE 2-45
Number of Cycles for Different Discharge Depths



Vented lead acid batteries

Although automotive batteries are not appropriate for photovoltaic applications, deep cycle lead acid batteries similar to automotive types, are referred to as marine type batteries and are used more often.

These batteries are true deep cycle units. They can be discharged as much as 80%, although less discharge depth will result in more charge cycles and thus a longer battery life.

Internal construction

These batteries are made up of lead plates in a solution of sulfuric acid. The plates are a lead alloy grid with lead oxide paste dried on the grid. The sulfuric acid and water solution is normally called "electrolyte."

The grid material is an alloy of lead because pure lead is a physically weak material. Pure lead would break during transportation and service operations involving moving the battery

The lead alloy is normally lead with 2-6% antimony. The lower the antimony content, the less resistant the battery will be to charging. Less antimony also reduces the production of hydrogen and oxygen gas during charging, thereby reducing water consumption. On the other hand, more antimony allows deeper discharging without damage to the plates. This in turn means longer battery life. Lead-antimony batteries are deep cycle types.

Cadmium and strontium are used in place of antimony to strengthen the grid. These offer the same benefits and drawbacks as antimony, but also reduce the amount of self-discharge the battery has when it is not being used.

Calcium also strengthens the grid and reduces self-discharge. However, calcium reduces the recommended discharge depth to no more than 25%. Therefore, lead-calcium batteries are shallow cycle types.

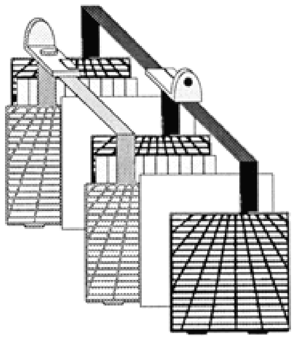
Both positive and negative plates are immersed into a solution of sulfuric acid and subjected to a "forming" charge by the manufacturer. The direction of this charge causes the paste on the positive grid plates to convert to lead dioxide. The negative plates' paste converts to "sponge" lead. Both materials are highly porous, allowing the sulfuric acid solution to freely penetrate the plates.

The plates are alternated in the battery, with separators between each plate. The separators are made of porous material to allow the flow of electrolyte. They are electrically non-conductive. Typical materials include mixtures of silica and plastics or rubber. (Originally, spacers were made of thin sheets of cedar.)

Separators are either individual sheets or "envelopes." Envelopes are sleeves, open at the top, which are put on only the positive plates.

A group of negative and positive plates, with separators, makes up an "element" (Figure 2-46). An element in a container immersed in electrolyte makes up a battery "cell."

FIGURE 2-46
Element Construction
of a Lead Acid Battery

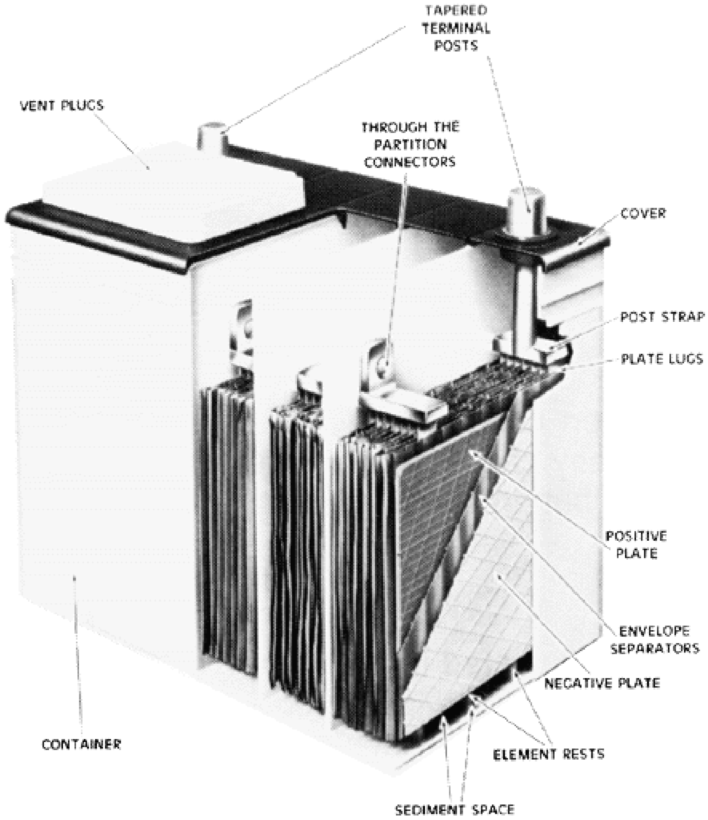


Larger plates, or more of them, will increase the amp-hours the battery can deliver. Thicker plates, or less plate count per cell, will allow a greater number of cycles and longer lifetime from the battery (Figure 2-47).

Regardless of the size of the plates, a cell will only deliver a nominal 2 volts. Therefore, a battery is typically made up of several cells connected in series, internally or externally, to increase the voltage the entire battery can deliver.

FIGURE 2-47
Complete Battery Construction

Photo Courtesy of Battery Council International



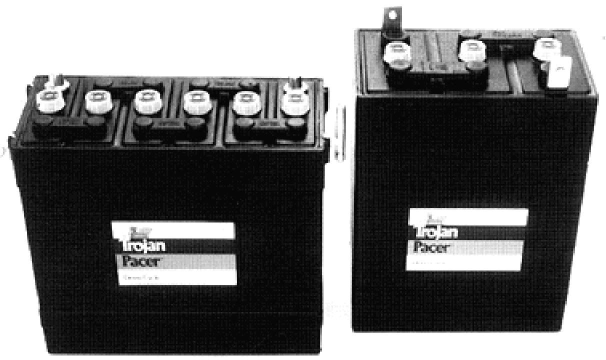
This is why a six volt battery has three cells, and 12 volt batteries have six (See Figure 2-48). Some batteries used in photovoltaic systems have only one cell, allowing the user to have any number of volts in the battery system, as long as it is a multiple of two.

Terminals

The internal straps which make these internal connections are brought up to the top of the battery and connected to the external terminals. The most familiar terminal is the tapered top type. The taper allows for a wide variety of cable clamp sizes. The positive terminal is slightly larger than the negative one to reduce the chance of accidentally switching the cables. Figure 2-48 shows a variety of battery terminals. Other terminal types used more often in photovoltaic battery applications include "L" terminals, wing-nut terminals and "universal" terminals. The type of terminal used may depend on the number and type of interconnections between the batteries and the balance of the system.

FIGURE 2-48
Various Battery Terminals

Photo Courtesy of Trojan Battery Co.



Interconnections can be made with short cables, #2 AWG or larger. The cables end in appropriate terminals. They can also be made with bus bars made specifically for this purpose by the battery manufacturer.

Venting

The cells of a vented lead acid battery are vented to allow the hydrogen and oxygen gas to escape during charging, and to provide an opening for adding water lost during gas production. Section 3.1.7 provides more information on battery venting requirements.

Although open caps are most common, the caps may be a flame arrester type, which prevents a flame from outside the battery from entering the cell.

"Recombinant" type caps are also available. These contain a catalyst that causes the hydrogen and oxygen gases to recombine into water, significantly reducing the water requirements of the battery

WARNING!

Never smoke or have open flames or sparks around batteries! As the batteries charge, explosive hydrogen gas is produced.

Always make sure battery banks are adequately vented and that a No Smoking sign is posted in a highly visible place.

Sulfation

If a lead acid battery is left in a deeply discharged condition for a long period of time, it will become "sulfated". Some of the sulfur in the acid will combine with lead from the plates to form lead sulfate. If the battery is not refilled with water periodically, part of the plates will be exposed to air, and this process will be accelerated.

Lead sulfate coats the plates so the electrolyte cannot contact it. Even the addition of new water will not reverse the permanent loss in battery capacity.

Treeing

Treeing is a short circuit between positive and negative plates caused by misalignment of the plates and separators. The problem is usually caused by a manufacturing defect, although rough handling is another cause.

Mossing

Mossing is a build-up of material on top of the battery elements. Circulating electrolyte brings small particles to the top of the battery where they are caught on the element tops. Mossing causes shorts between negative and positive plates. Heavy mossing causes a short between the element plates and the plate strap above them.

To avoid mossing, the battery should not be subjected to continuous overcharging or rough handling.

State of charge. specific gravity. and voltage

The percentage of acid in the electrolyte is measured by the "specific gravity" of the fluid. This measures how much the electrolyte weighs compared to an equal quantity of water. Specific gravity is measured with a hydrometer.

The greater the state of charge, the higher the specific gravity of the electrolyte. The voltage of each cell, and thus the entire battery, is also higher. Measuring specific gravity during the discharge of a battery will be a good indicator of the state of the charge. During the charging of a flooded battery, the specific gravity will lag the state of charge because complete mixing of the electrolyte does not occur until gassing commences near the end of charge. Because of the uncertainty of the level of mixing of the electrolyte, this measurement on a fully charged battery is a better indicator of the health of the cell. Therefore, this should not be considered an absolute measurement for capacity and should be combined with other techniques. (Figure 2-49).

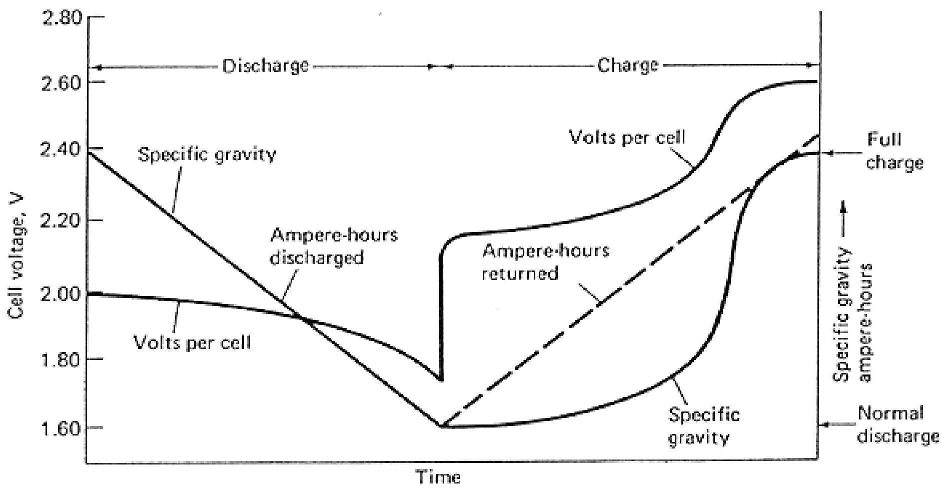


Figure 2-49
Typical Voltage and Specific Gravity Characteristics of a Lead-acid Cell (constant-rate discharge and charge).

Freezing point

Since lead acid batteries use an electrolyte which is partially water, they can freeze. The sulfuric acid in a battery acts as an antifreeze, however. The higher the percentage of acid in the water, the lower the freezing temperature. However, even a fully charged lead acid battery will freeze at some extremely low temperature.

As Table 2-3 shows, at a 50% charge, a typical lead acid battery will freeze around -1 00F. Notice that as the state of charge goes down, the specific gravity goes down as well The acid is becoming weaker and weaker, and lighter and lighter, until it is only slightly denser than water.

NOTE

The information in Table 2-3 and Figures 2-50 and 2-51 is for deep cycle lead acid batteries. Shallow cycle automotive batteries have slightly different values.

As you can see, lead acid batteries should be kept above 200F if they are ever allowed to be fully discharged. If they cannot be kept warmer than this, they should be maintained at a high enough charge to prevent freezing of the electrolyte.

This can be done automatically, with a charge controller capable of disconnecting the load when the battery voltage drops to a preset level. However, this method cannot be used if the load is critical and cannot be turned off.

TABLE 2-3:
States of Charge, Specific Gravities, Voltages, and Freezing Points for Typical Deep Cycle Lead Acid Batteries

State of Charge	Specific Gravity	Voltage per Cell (volts)	Voltage of 12V (6 cell) Battery	Freezing Point (°F)
Fully Charged	1.265	2.12	12.70	-71
75% Charged	1.225	2.10	12.60	-35
50% Charged	1.190	2.08	12.45	-10
25% Charged	1.155	2.03	12.20	+3
Fully Discharged	1.120	1.95	11.70	+17

The charging characteristics of lead acid batteries changes with electrolyte temperature. The colder the battery, the lower the rate of charge it will accept. Higher temperatures allow higher charge rates.

If a battery will be used in a climate that will continuously be extremely hot or cold, with minimum temperature swings, it would be wise to adjust the electrolyte specific gravity for the temperature. This will help extend the life and enhance the performance of the battery under these extreme conditions. This adjustment should be done at the battery manufacturer, or through their supervision.

For example, a typical lead acid battery which is half charged will only accept two amps at 00F. At 800F, it will accept over 25 amps. This is why most charge controllers equipped with temperature compensation change their voltage settings with temperature. A few measure the battery temperature, and adjust the charging rate (current flow) accordingly.

A final characteristic of lead acid batteries is their fairly high rate of self discharge. When not in service they may loose from 5% per month to 1% per day of their capacity, depending on temperature and cell chemistry. The higher the temperature, the faster the rate of self-discharge.

FIGURE 2-50

Terminal Voltages and States of Charge for 12 Volt Lead Acid Batteries

Note: Divide these voltages by two for 6 volt batteries

Courtesy of Home Power Magazine

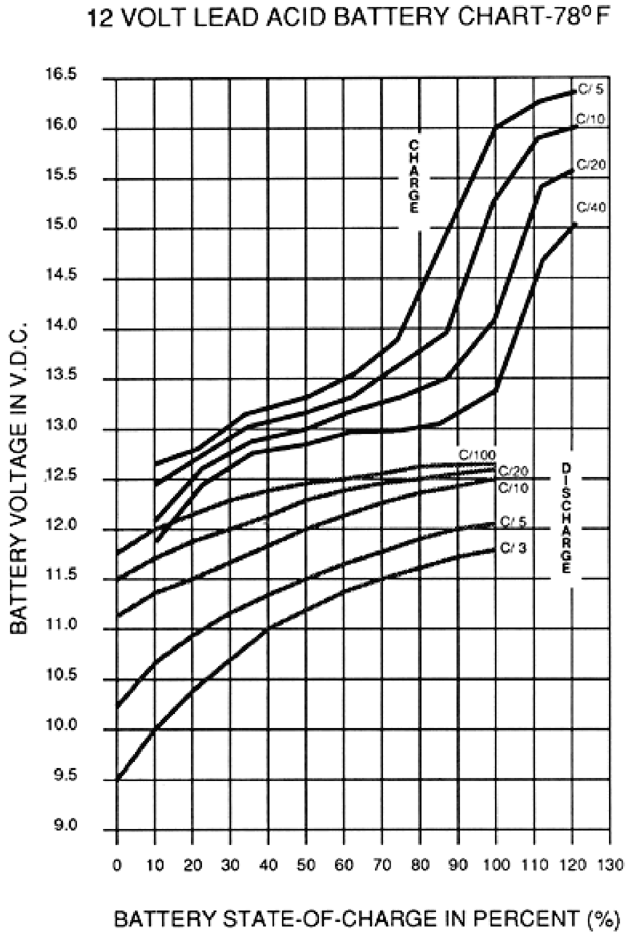
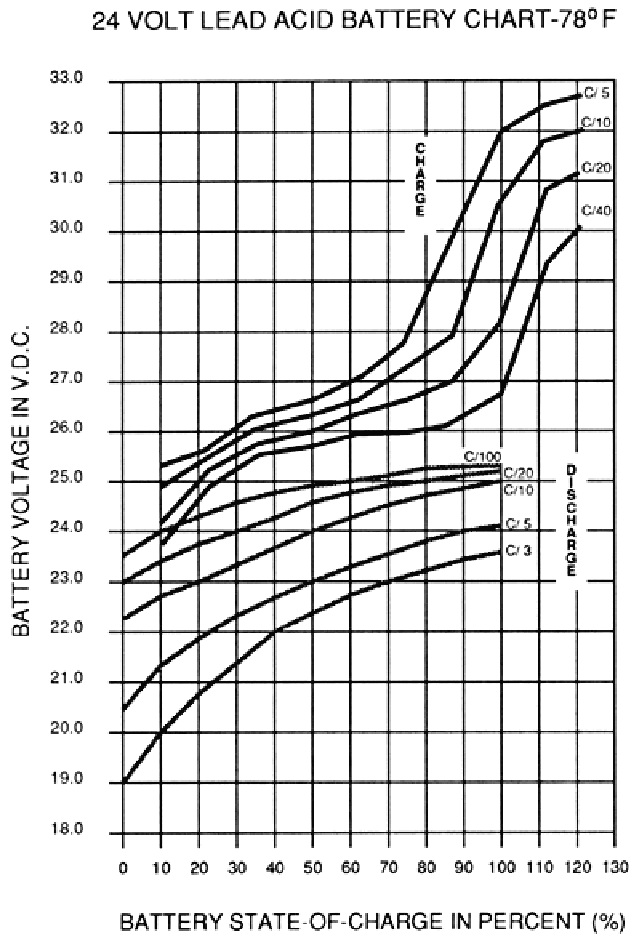


FIGURE 2-51

Terminal Voltages and States of Charge for 24 Volt Lead Acid Batteries

Courtesy of Home Power Magazine



<u>Sealed flooded (wet) lead acid batteries</u>

As described before, the use of less antimony, or using calcium, cadmium, or strontium in place of antimony, results in less gassing and lower water consumption. However, these batteries should not be discharged more than 15-25%, or the life of the battery will be dramatically shortened.

Self discharge is less of a factor with sealed lead acid batteries due to the fact that these batteries are typically lead-calcium or lead-calcium/antimony hybrids. Self discharge can be minimized by storing batteries in cool areas between 5-150C.

The rate of water loss may be so low that the vent plugs for each cell can be nearly or completely sealed . In most of these batteries, there is still some production of hydrogen gas. Therefore, a venting system is still required, but it is typically a pressure valve regulated system.

The temperature range sealed batteries can accommodate is about the same as unsealed batteries. Since the specific gravity cannot be measured with a hydrometer, many sealed batteries have a built in hydrometer.

A built-in hydrometer is a captive float in the electrolyte. If the specific gravity is high enough, the float comes up against a window at the top of the battery. If the float is visible in the window, the battery is nearly fully charged. In PV systems, sometimes this float gets stuck and the battery should be lightly tapped to ensure free movement of the hydrometer.

If the battery is not fully charged, the float will sink, and cannot be seen in the window.

The charging characteristics of sealed lead acid batteries also changes with electrolyte temperature. Charge controllers used on these batteries should include temperature compensation for battery temperatures below 700F.

Captive electrolyte batteries

Batteries with a gelled (Gel) or absorbed glass mat (AGM) electrolyte are available completely sealed (Figure 2.52). These batteries are sometimes referred to as "Valve Regulated Batteries." Some of the newer batteries have catalytic recombiners internal to their battery to aid in the reduction of water loss. All sealed batteries will vent if they are overcharged to the point of excessive gassing to prevent extreme pressures from building up in the battery case. This electrolyte is then lost forever and the life of the battery may be shortened. This problem can be reduced or eliminated by properly charging the battery as recommended by the manufacturer and by using temperature compensation in the charge controller.

FIGURE 2-52
Sealed Lead Acid
Captive Electrolyte
Gelled Batteries Photo

Courtesy of
Power-Sonic Corp.

This type of battery is generally a lead calcium or lead calcium/antimoninal hybrid. Because the electrolyte is captive, there is no need to charge the battery high enough to gas the electrolyte. The battery can be used in any position, even upside down. Since the electrolyte does not flow away from the plates, the battery still delivers full capacity. The manufacturer should be consulted for the proper regulation voltage for their specific battery.

These batteries are typically shallow cycle batteries. Discharging these batteries greater than 20% will significantly reduce the lifetime of the battery. (Figures 2-53 and 2-54).

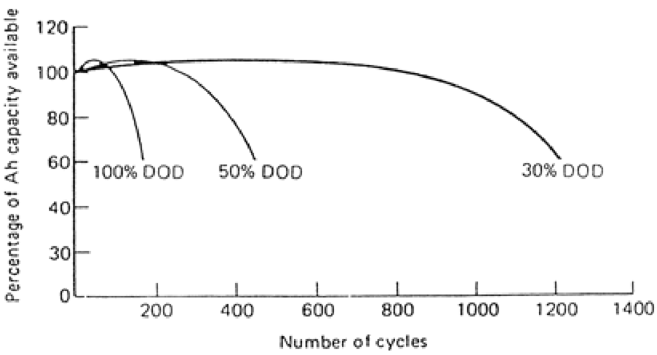


Figure 2-53 Cycle Service Life of a Gel Cell Lead-Acid Battery in Relation to Depth of Discharge (20°C)

Linden, Handbook of Batteries

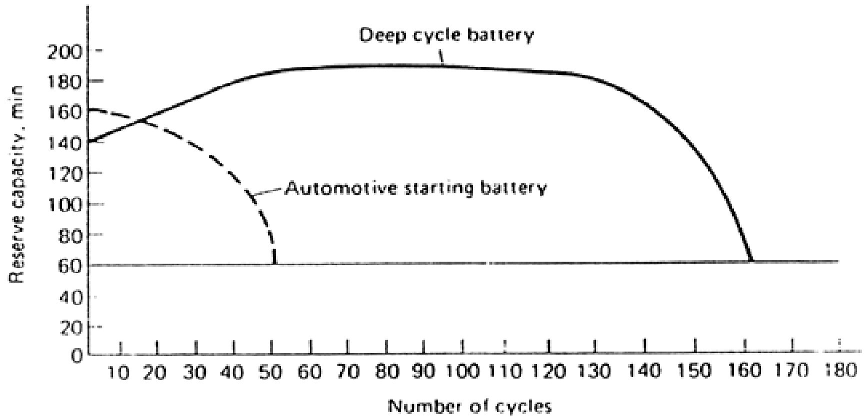


Figure 2-54 Cycle Life Characteristics at a Low Discharge Rate (25A)

GNB Batteries SL Paul Minnesota

These batteries have shown some temperature limitations, typically ranges in excess of -20 to +50 degrees C should be avoided. Self discharge rates are very low, comparable to lead calcium batteries or better.

<u>Nickel cadmium (Ni cad) batteries</u>

Ni cad batteries have a physical structure similar to lead acid batteries. Instead of lead plates, they use nickel hydroxide for the positive plates and cadmium oxide for the negative plates. The electrolyte is potassium hydroxide.

The cell voltage of a typical Ni cad battery is 1.2 volts, rather than the two volts per cell of a lead battery (Figure 2-55).

Ni cad batteries can survive freezing and thawing without any effect on performance. High temperatures have less of an effect than they have on lead acid batteries. Self-discharge rates range from 3-6% per month.

Ni cad batteries are less affected by overcharging. They can be totally discharged without damage. They are not subject to sulfation. Their ability to accept charging is independent of temperature.

Although the initial cost of Ni cad batteries is higher than lead acid types, their lower maintenance costs and longer lives make them a logical choice for many photovoltaic installations. This is particularly true if the system is in a remote or dangerous location.

FIGURE 2-55
Ni Cad Batteries

Photo Courtesy of
Power-Sonic Corp

Since battery maintenance is a major part of all photovoltaic system maintenance, significant reductions in service time and costs can be achieved.

However, Ni cad batteries cannot be tested as accurately as a "wet" lead-acid battery. If state of charge monitoring is necessary, Ni cad may not be the best choice.

<u>Future Prospects for batteries</u>

An electrical storage method now being developed is a redox battery. Redox is short for reduction-oxidation, which is a cycle of chemical reactions.

This battery uses two chemicals, chromium chloride and iron chloride, which are pumped through a stack of cells with electrodes. A special membrane keeps the fluids physically separated, but allows electrical energy to move between them and the electrodes.

Another battery being tested uses nickel and iron instead of lead oxides.

A battery being investigated for electric vehicles is the lithium-metal sulfide type. This battery uses lithium, alloyed with aluminum, for the negative electrodes, iron sulfide for the positive electrodes, and magnesium oxide for the separators.

The lithium-metal sulfide battery operates at a temperature of almost 8500F. It requires a special container to maintain that temperature.

A polymer battery is being developed which uses no liquid or dangerous materials, and can be molded into any shape. It is not expected to be available until at least 1995.

<u>Batteries in series and Parallel</u>

Batteries, like photovoltaic cells, can be connected in <u>series</u> to increase the voltage. They can be connected in parallel to increase the amp-hour capacity of the battery system. Interconnected groups of batteries are usually called "battery banks" (Figure 2-56).

Connecting batteries in both series and parallel will increase the voltage and the amp-hour capacity.

The connections and wiring of the batteries plays a large role in how well the batteries are treated. The quality and method of wiring these systems is very important to maintain acceptable battery health and lifetime. A large voltage drop in the system between the battery and the battery charge controller will change how the battery charge controller operates. This voltage drop, measured during full charging rates, will reduce the voltage regulation set point the battery is charged to and reduce the capacity and lifetime of the battery

Fuses and switches, if not properly chosen, can develop a large voltage drop and can develop into a problem area. Attention should be paid to using "DC Rated" fuses and switches to reduce system problems.

When paralleling batteries, it is best to reduce the effects of voltage (unequal resistances) between parallel branches. This will allow all batteries in the system to operate at an equal voltage and current level.

The best method is to ensure that the battery cable to the parallel battery is sized to reduce the voltage drop to a minimum during peak current demand in the system. This is calculated by using the maximum charging or load currents multiplied by the resistance of the wire. Multistrand welding cable is typically used.

The other method is to use the same length of cable from each battery terminal to a central junction point. The positive and negative do not necessarily have to be the same length. This eliminates the uneven voltage drop between batteries and permits each battery to perform equally during peak current demand. This method allows you to use a smaller size battery cable.

A split bolt is the best way to connect multiple wires, covered with waterproof electrical tape. Wire nuts are not recommended for any connections within the system. When possible, a soldered connection will provide the best system performance and reliability.

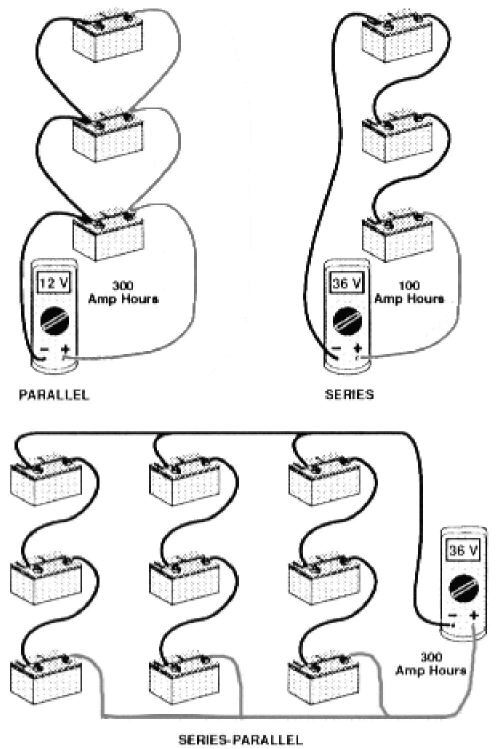


FIGURE 2-56
Batteries Connected in Series, Parallel, and Series-Parallel

WARNING!

Even when only partially charged, an interconnected battery bank can deliver enough voltage and current to arc weld! Always be careful around battery banks. Never allow tools to fall onto the terminals or connections. Never allow the construction or use of shelves above the batteries, as objects can fall off the shelves onto the batteries. Battery banks must always be adequately vented.

Table 2-4 summarizes the characteristics of the various types of batteries.

TABLE 2-4: Summary of Battery Characteristics

	Lead acid, unsealed, flooded (deep cycle)	Lead acid, sealed, flooded (shallow cycle)	captive electrolyte (gelled cell or AGM)	Ni cad

Depth of Discharge	40-80%	15-25%	15-25%	100%
Self-discharger rate, %month	5%	1-4%	2-3%	3-6%
Typical capacity, Amp-hours/ft.ł	1000	700	250	500
Range of Capacities Amp-hrs/ft.ł	200 to1425	164 to1389	104 to 464	103 to 990
Typical capacity, Amp-hrs/lb.	5.5	4.6	2.2	5.0
Range of capacities, Amp-hrs/lb.	1.9 to12.1	1.1 to 9.2	1.0 to 6.3	1.2 to 9.5
Minimum Environment Temperature (°F)	+20	+20	0	-50

Other storage methods

Some photovoltaic systems are only used for pumping water. If the water is pumped into a storage tank for later use, battery storage is unnecessary.

Similarly, a refrigerator with a freezer may be able to "coast" by making ice in the freezer during sunny times and letting it melt at night or during cloudy weather.

2.5.2 Charge Controllers.

The primary function of a charge controller in a stand-alone PV system is to protect the battery from overcharge and over discharge. Any system that has unpredictable loads, user intervention, optimized or undersized battery

storage (to minimize initial cost), or any characteristics that would allow excessive battery overcharging or over discharging requires a charge controller and/or low-voltage load disconnect. Lack of a controller may result in shortened battery lifetime and decreased load availability (Reference 1).

Systems with small, predictable, and continuous loads may be designed to operate without a battery charge controller. If system designs incorporate oversized battery storage and battery charging currents are limited to safe finishing charge rates (C/SO flooded or C/1OO sealed) at an appropriate voltage for the battery technology, a charge controller may not be required in the PV system (See references 2,3,4, and 5).

Proper operation of a charge controller should prevent overcharge or over discharge of a battery regardless of the system sizing/design and seasonal changes in the load profile and operating temperatures. The algorithm or control strategy of a battery charge controller determines the effectiveness of battery charging and PV array utilization, and ultimately the ability of the system to meet the load demands. Additional features such as temperature compensation, alarms, and special algorithms can enhance the ability of a charge controller to maintain the health, maximize capacity, and extend the lifetime of a battery.

Basics of charge controller theory

While the specific control method and algorithm vary among charge controllers, all have basic parameters and characteristics. Manufacturer's data generally provides the limits of controller application such as PV and load currents, operating temperatures, losses, set points, and set point hysteresis values. In some cases the set points may be intentionally dependent upon the temperature of the battery and/or controller, and the magnitude of the battery current. A discussion of the four basic charge controller set points follows:

Regulation set point (VR): This set point is the maximum voltage a controller allows the battery to reach. At this point a controller will either discontinue battery charging or begin to regulate the amount of current delivered to the battery. Proper selection of this set point depends on the specific battery chemistry and operating temperature.

Regulation hysteresis (VRH): The set point is voltage span or difference between the VR set point and the voltage when the full array current is reapplied. The greater this voltage span, the longer the array current is interrupted from charging the battery. If the VRH is too small, then the control element will oscillate, inducing noise and possibly harming the

switching element. The VRH is an important factor in determining the charging effectiveness of a controller.

Low voltage disconnect (LVD): The set point is voltage at which the load is disconnected from the battery to prevent over discharge. The LVD defines the actual allowable maximum depth-of-discharge and available capacity of the battery. The available capacity must be carefully estimated in the system design and sizing process. Typically, the LVD does not need to be temperature compensated unless the batteries operate below 00C on a frequent basis. The proper LVD set point will maintain good battery health while providing the maximum available battery capacity to the system.

Low voltage disconnect hysteresis (LVDH): This set point is the voltage span or difference between the LVD set point and the voltage at which the load is reconnected to the battery. If the LVDH is too small, the load may cycle on and off rapidly at low battery state-of-charge, possibly damaging the load and/or controller. If the LVDH is too large, the load may remain off for extended periods until the array fully recharges the battery. With a large LVDH, battery health may be improved due to reduced battery cycling, but this will reduce load availability. The proper LVDH selection will depend on the battery chemistry, battery capacity, and PV and load currents.

Charge controller algonthms

Two basic methods exist for controlling or regulating the charging of a battery from a PV module or array - series and shunt regulation. While both of these methods can be effectively used, each method may incorporate a number of variations that alter basic performance and applicability. Following are descriptions of the two basic methods and variations of these methods.

Shunt controller

A shunt controller regulates the charging of a battery by interrupting the PV current by short-circuiting the array. A blocking diode is required in series between the battery and the switching element to keep the battery from being shortened when the array is shunted. This controller typically requires a large heat sink to dissipate power. Shunt type controllers are usually designed for applications with PV currents less than 20 amps due to high current switching limitations (Figures 2-57).

Shunt-linear: This algorithm maintains the battery at a fixed voltage by using a control element in parallel with the battery. This control element

turns on when the VR set point is reached, shunting power away from the battery in a linear method (not on/off), maintaining a constant voltage at the battery. This relatively simple controller design utilizes a Zener power diode which is the limiting factor in cost and power ratings.

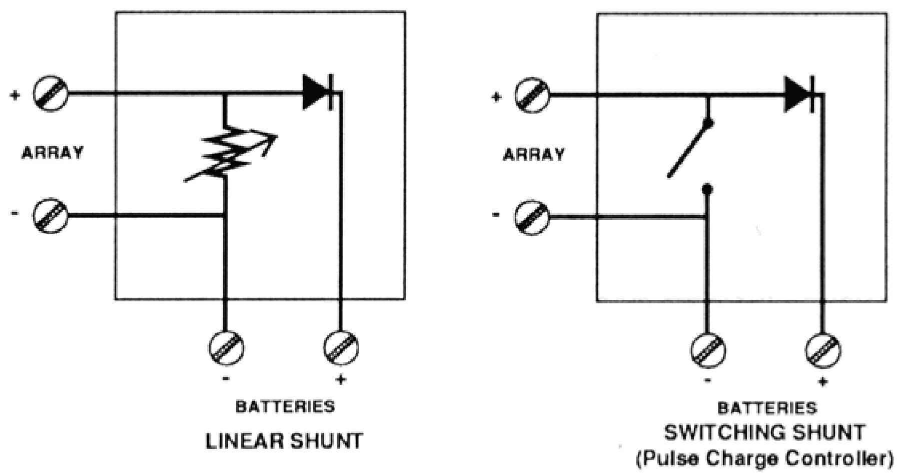


FIGURE 2-57
Block Diagram of Linear and Switching Shunt Charge Controllers

Shunt-interrupting: This algorithm terminates battery charging when the VR set point is reached by short-circuiting the PV array. This algorithm has been referred to as "pulse charging" due to the pulsing effect when reaching the finishing charge state. This should not be confused with Pulse-Width Modulation (PWM).

Series Controller

Several variations of this type of controller exist, all of which use some type of control element in series between the array and the battery (Figures 2-58, 2-59, and 2-60).

Series-interrupting: This algorithm terminates battery charging at the VR set point by open-circuiting the PV array. A blocking diode may or may not