



PDHonline Course E297 (4 PDH)

Photovoltaic Power Systems

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Photovoltaic Power Systems

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Photo credit: The photograph on the cover is the sun tracking heliostats near Barstow, California.
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Introduction

The world is closing in on the notion that global warming may be a real threat and we must find ways to reduce carbon emissions to protect the environment. As a result, there is a heightened interest in renewable energy production that can reduce the future demand for coal and natural gas fired power plants. Renewable power production technologies such as wind farms, photovoltaics, geothermal, hydroelectric, and biomass systems are all receiving a lot of attention.

In this course, we will look at photovoltaic systems. The term *photovoltaic* is derived from the Greek term “photo”, which means “light” and from name of the Italian physicist, Alessandro Volta, who developed the electric battery and for whom the term “volt” is derived. Photovoltaic systems use solar cells to generate electricity from the power of the sun. These systems are quiet, unobtrusive, and require very little maintenance.

Photovoltaic systems are not new. The concept was first discovered by the French physicist, Alexandre Becquerel in 1839. As a footnote to history, Alexandre’s son, Henri, is often – and incorrectly - given credit for this discovery. It was not until 1954 that photovoltaic systems were developed that could generate any useful amount of electricity. These early photovoltaic systems, which were developed by Bell Labs, were used in applications such as satellites.

The energy crisis of the 1970’s created interest in more widespread use of photovoltaics for energy production, but the systems of that era were prohibitively expensive with prices of over \$1,000 per peak watt. Since the 1970’s, the industry has continued to research and design more cost-effective solar cells for photovoltaic systems. By the year 2000, the cost of photovoltaic systems had dropped to about \$8.00 per peak watt and the cost continues to decline. In 2019 was around \$3.25 per watt. Installed costs for a small 5,000-watt residential application is around \$16,000. These prices are generally higher than traditional generation sources and some claim that the cost of manufacturing solar cells may use more energy than the solar cells will ever produce, but the technology continues to evolve and may become a viable generation source for general applications. Photovoltaic systems have already found applications for remote radio repeaters and other sites where grid connected power is not available.

Chapter 1

Overview

The term *solar power* can be used to denote either solar thermal systems or photovoltaic systems. Solar thermal systems use the heat generated by sunlight to heat air or water. Photovoltaic systems do not depend on sun's heat to generate electricity. Photovoltaic systems generate electricity by using the interaction of sunlight with a semi-conducting material, which frees electrons in the material to create an electric current.

The solar cells used in a photovoltaic system are made from a semi-conducting material that will produce a voltage and current when exposed to sunlight. The current generated by a photovoltaic solar cell is a direct current (DC) like the current that is generated from a common household battery. The amount of current produced by a solar cell is directly proportional to the amount of sunlight falling on the solar cell.

In general, a photovoltaic solar cell is a small silicon disk about ½-inch in diameter. Many cells are connected in together either in parallel to increase the current capacity, or in series to increase the voltage. These modules of solar cells are further connected with other modules to create a solar array of the proper voltage and current rating. Most solar arrays are set at a fixed relationship to the sun to gather the most sunlight. However, some large sophisticated solar arrays have tracking systems that continuously adjust the tilt of the array to maintain an optimum relationship with the sun throughout the day.

In addition to the actual solar array, a photovoltaic system will also include several other components such as a charge controller, storage batteries, an inverter, a disconnect device, and metering equipment. These items are sometimes referred to as the balance-of-system (BOS) equipment. The specific components are included in a system are based on the type of photovoltaic system employed.

There are three primary types of photovoltaic systems. They are,

- Stand-Alone DC System
- Stand-Alone AC System
- Grid Interactive AC System

The following is a brief overview of each system type.

Stand-Alone DC System

The simplest form of photovoltaic system is a stand-alone DC system. A block diagram of a stand-alone DC system is shown in Figure 1. This system includes the solar array, charge controller, and storage battery. The DC current generated by the solar array is used to either directly serve the DC load, such as a lighting system, or to recharge the storage battery for later use.

One popular consumer application of stand-alone DC systems is outdoor accent lighting for residential homes. These systems often use low power LED's for lighting, are relatively inexpensive (less than \$100.00), and use common sized rechargeable batteries for storage.

Stand-Alone DC System

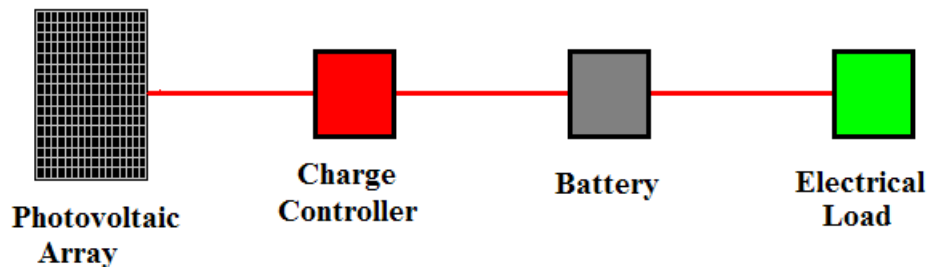


Figure 1

Stand-Alone AC System

Most electrical loads use alternating current (AC), therefore a photovoltaic system that can supply AC power is more versatile than a DC-only system. A stand-alone AC system is like a DC system, except for the addition of an inverter to convert the DC power to AC power. An inverter is a solid-state electronic device, but some energy – up to 15% - is lost in the conversion from DC and AC power. In the United States, inverters are designed to convert the DC voltage to either 120-VAC, 60Hz or 240-VAC, 60Hz. Figure 2 shows a typical stand-alone AC system.

Stand-Alone AC System

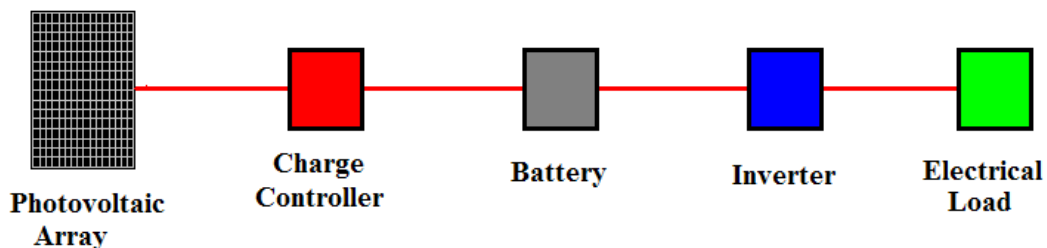


Figure 2

The load is served from the battery through the inverter and the charge controller regulates the flow of power into the battery.

Grid Interactive AC System

A more complicated approach is the grid interactive AC system. This system is similar to a stand-alone AC system except the system must be designed to utility-grade standards for interconnection to the electrical grid. Additional equipment is required to interconnect and the equipment must be capable of disconnecting from the grid during faulted conditions. Figure 3 is an example of a grid interactive system.

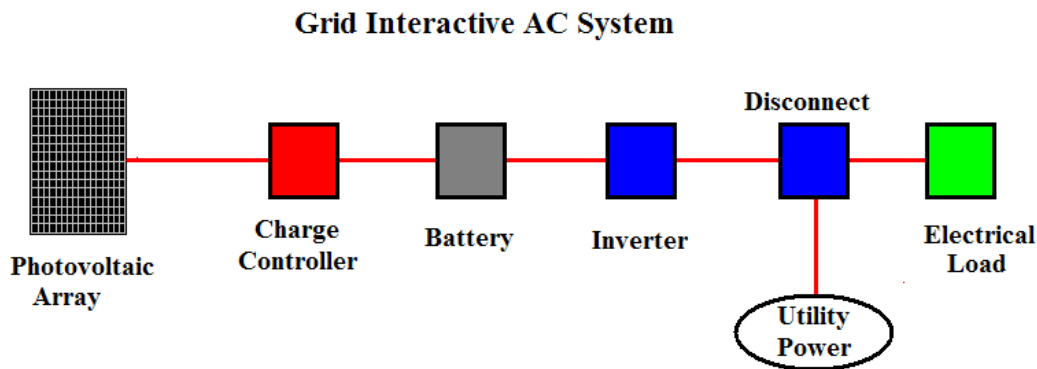


Figure 3

In this application, the photovoltaic system supplies the load and if the solar generated power is not sufficient to supply the load, the utility power will supply the deficiency. When the electrical load is not present, or if the solar generated power exceeds the electrical load, then the excess solar generated power is supplied onto the grid to the electric utility company.

In most cases, the electric utility is required to buy the excess power from the photovoltaic system. There are two ways the utilities buy power from renewable sources such as a photovoltaic system. The most common method is to sell power to the customer at the company's full retail rate, which includes generation, transmission, distribution, and service costs. The photovoltaic supplied power is purchased by the utility at its *avoided generation cost*, which does not include transmission, distribution, and service costs since these costs must still be recovered by the utility. Some utilities are beginning to buy renewable energy using a "net metering" arrangement where the electric utility meter effectively is run backwards when excess solar power is generated, giving the customer full retail credit for any solar generation. The net metering concept shifts utility infrastructure costs to other ratepayers, but promotes renewable energy projects.

Chapter 2

Solar Radiation

Solar radiation is radiant energy emitted by the sun, particularly electromagnetic energy. About one-half of the solar radiation is in the form of visible light with the remainder being infrared and a little ultraviolet radiation.

Sunlight reaches every spot on the Earth's surface at least sometime during the year. The amount of solar radiation that reaches any given location is dependent on several factors including the geographic location, time of day, season, local landscape, and area weather.

Because the Earth is round, the sun strikes the surface at different angles ranging from 0° (just above the horizon) to 90° (directly overhead). When the sun's rays are vertical, the Earth's surface gets all the energy possible. The more slanted the sun's rays are, the longer they travel through the atmosphere, becoming more scattered and diffuse.

The 23.5° tilt in the Earth's axis of rotation is a significant factor in determining the amount of sunlight striking the Earth at a particular location. Tilting results in longer days in the northern hemisphere from the spring equinox to the fall equinox. Days and nights are both exactly 12 hours long on the equinoxes, which occur each year on or around March 23rd and September 22nd.

The United States, which lies in the middle latitudes, receives more solar energy in the summer because the days are longer, and the sun is nearly overhead. The sun's rays are far more slanted during the shorter days of the winter months. Cities like Denver, Colorado, receive nearly three times more solar energy in June than they do in December.

The rotation of the Earth is responsible for hourly variations in sunlight. In the early morning and late afternoon, the sun is low in the sky. Its rays travel further through the atmosphere than at noon when the sun is at its highest point. On a clear day, the greatest amount of solar energy reaches a solar collector around solar noon.

The photovoltaic industry defines two standard terrestrial solar spectral irradiance distributions. They are the direct normal spectral irradiance and the standard total global spectral irradiance. The direct normal spectrum, which is also known as direct beam solar radiation, is a component of the total spectrum. The solar radiation that reaches the Earth's surface without being diffused is called *direct beam solar radiation*. As sunlight passes through the atmosphere, some of it is absorbed, scattered, and reflected. This scattering is caused by air molecules, water vapor, clouds, dust, pollutants, forest fires, and volcanoes. This is called *diffuse solar radiation*. Even

on a clear day the direct beam solar radiation may be reduced by 10% due to normal atmospheric conditions and on especially cloudy days there may not be any direct beam solar radiation. The sum of the diffuse and direct solar radiation is called global solar radiation.

The *solar constant* is the amount of incoming solar electromagnetic radiation per unit area measured on the outer surface of the earth's atmosphere in a plane perpendicular to the rays and is 1,366 watts per square meter. The average incoming radiation is known as solar insolation and is one-fourth the solar constant, or 342 watts/m².

Insolation is the amount of solar energy received on the surface of the earth over a period and is measured in kilowatt-hours per square meter (kWh/m²). *Irradiance* is the amount of solar power received on the surface of the earth at a given time and is measured in kilowatts per square meter (kW/m²).

Insolation is greatest when the surface is normal to the Sun. As the angle increases beyond a direction normal to the surface and the sunlight, the insolation is reduced in proportion to the cosine of the angle.

Table 1 shows the average annual solar radiation for several cities in the United States. From the table, we see that Atlanta, GA can expect 5.1 kWh/m²/day of solar radiation. In comparison, Anchorage, AK only receives 3.0 kWh/m²/day.

Table 1 Solar Radiation	
Location	kWh/m²/day
Atlanta, GA	5.1
Miami, Fl	5.2
Omaha, NE	4.9
Concord, NH	4.6
Seattle, WA	3.7
Anchorage, AK	3.0
Chicago, IL	4.4
Lexington, KY	4.5
Hartford, CT	4.4
Albuquerque, NM	6.4

Figure 4 is a graphical representation of the average annual solar radiation in the continental United States for a flat plate collector tilted South at an angle equal to the latitude of the location. As you can see from the map, the Southwest has the highest solar radiation and the Pacific Northwest has the lowest solar radiation in the continental United States.

Average Daily Solar Radiation

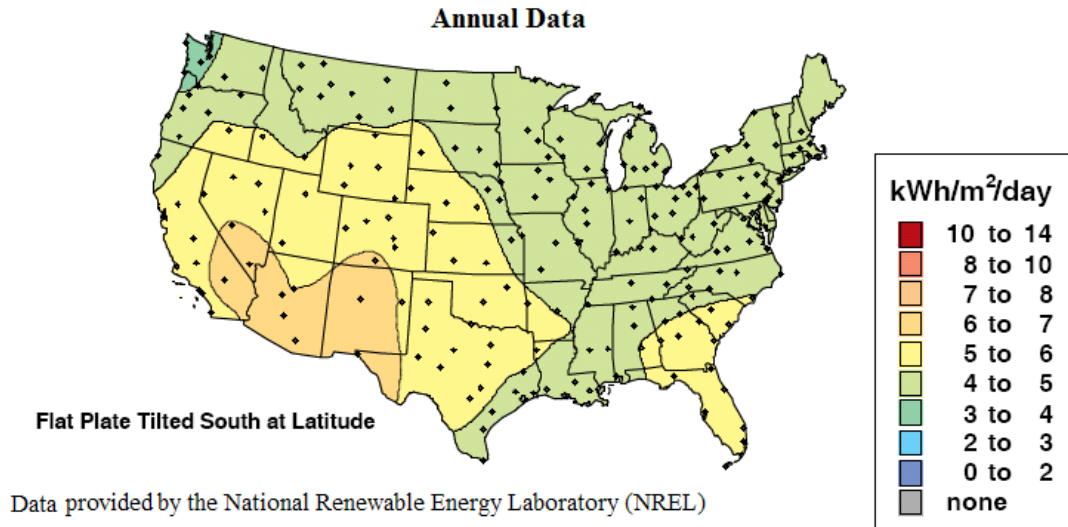


Figure 4

Chapter 3 Solar Cells

The heart of a photovoltaic system is the solar cell. In this chapter, we will look at the theory behind the operation of a solar cell, characteristics of solar cell material, the types of material used to make solar cells, and finally, a complete photovoltaic solar array.

Solar Cell Theory

A solar cell is a device that converts light energy into electrical energy. What follows is a somewhat technical explanation of how solar energy is converted into electrical energy. For a simple overview of the operation of a solar cell see the insert on the right.

The energy for a solar cell is the electromagnetic radiation from the sun. Visible light behaves like a wave phenomenon, but in some respects, it acts like a stream of high-speed, submicroscopic particles. The energy in an electromagnetic field is made up of discrete packets. The term *photon*, which means visible-light particle, is used to describe these energy packets. Particle-like behavior is not restricted to just the visible-light portion of the electromagnetic spectrum. Photons travel through empty space at the speed of light. This is true no matter what the electromagnetic wavelength. A photon has no mass, but it can be absorbed by matter and will transfer energy and momentum in proportion to its frequency.

Simple Explanation of a Solar Cell

1. Sunlight is absorbed by the solar cell.
2. The solar energy knocks electrons loose from its atoms in the solar cell.
3. "Holes" or openings are created in other atoms in the solar cell.
4. The loose electrons are free to move to other atoms where openings exist.
5. By connecting a circuit to the solar cell, the electrons will flow through the circuit looking for holes.
6. The movement of electrons is called an electric current.

The basis for a solar cell is the semiconductor and the purpose of the semiconductor is to use solar energy to generate charge carriers in a light-absorbing material and to separate the charge carriers into an electrical circuit. A *semiconductor* is a device whose electrical conductivity can be controlled. It has properties of both an insulator and a conductor and can dynamically change states from insulating to conducting.

The properties of a semiconductor can be modified by adding impurities to the silicon during the manufacturing process. This process is known as doping. Doping will either add an electron or a "hole" depending on the type of impurity added. If the resulting material has a preponderance of electrons it is known as n-type material. P-type material has more "holes".

An example of a semiconductor is a simple p-n junction. A p-n junction is a device with a layer of n-type material bonded to a layer of p-type material. The boundary between the two materials is called the depletion zone. See figure 5 below.

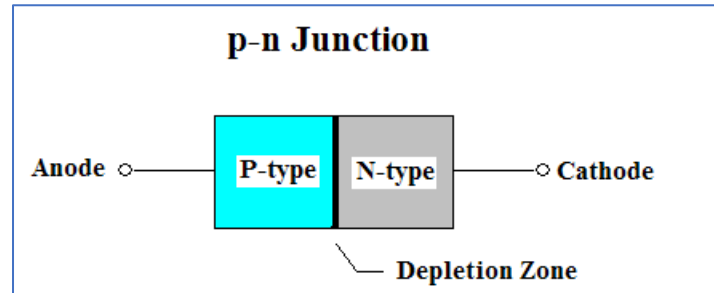


Figure 5

A solar cell is a p-n junction semiconductor. In a p-n junction some of the free electrons in the n-region diffuse across the junction and combine with holes. Filling a hole makes a negative ion and leaves behind a positive ion on the n-side and a space charge builds up, creating the *depletion region* which inhibits any further electron transfer, until some other action occurs such as the introduction of photon energy. If an electrical circuit is connected to a p-n junction semiconductor, the electrons on the n-side of the junction will travel through the circuit to the p-side of the junction.

A certain amount of energy is required to change the semiconductor from an insulator to a conductor so that electrons can freely flow. The amount of energy required to move an electron from its bound state within the atom to its free state is known as the *bandgap* energy. The lower energy level of a semiconductor is called the valence band. The higher energy level where an electron is free to roam is known as the conduction band. The difference between the valence and conduction band is known as the bandgap. Photons with energy levels below the bandgap energy cannot free an electron so the photon energy is not absorbed but is instead converted into heat energy.

When a photon makes contact with a solar cell (let's assume that it is a silicon based cell) the photon will either be absorbed by the silicon and generate electron-hole pairs, which can be used to generate electricity, or if the photons are not absorbed, they will generate heat. The ability of a material to absorb photons is based on the material's absorption coefficient and the higher the absorption coefficient the greater the ability of the material to absorb photons.

When a photon is absorbed its energy is transferred to an electron in the valence band of the atoms in the silicon material. The energy from the photon causes the electron to move into the conduction band of the atom where it is free to move within the silicon semiconductor material. The atoms have *covalent bonds*, so as an electron moves into the conduction band a hole is left in

the valence band and an electron from an adjacent atom can then move into the hole. Therefore, photons that are absorbed by a semiconductor material create mobile electron-hole pairs.

Covalent bonds occur when two atoms share an electron, creating a bond between the two atoms.

The energy conversion efficiency is a measure of how much of the solar energy is converted into electrical energy. The calculation for the energy conversion factor is,

$$\eta = \frac{P_m}{(E \cdot A)} * 100$$

Where,

η = Energy conversion factor, percent.

P_m = Maximum power output, watts.

E = Solar energy, irradiance, watts per square meter.

A = Area of the solar cell, square meters.

For example, what is the energy conversion efficiency of a 325-watt solar panel that measures 1.05 x 1.59 meters, if the solar irradiance is 1,000 w/m²?

Since the area of the solar cell is $1.05 * 1.59 = 1.67 \text{ m}^2$, the efficiency is,

$$\eta = \frac{325}{(1,000 * 1.67)} * 100$$

$$\eta = 19.5\%.$$

This unit converts 19.5% of the available solar energy into electrical energy.

Solar Cell Material Characteristics

Important characteristics in the design and manufacture of solar cells include the crystallinity of the material, the absorption characteristics of the material, its bandgap, and the structures in the cell. In addition, the manufacturing complexity, and the associated cost of manufacture, is an important consideration in the selection of a solar cell material.

Crystallinity

The *crystallinity* of a material indicates how perfectly ordered the atoms are in the crystal structure. Silicon, as well as other solar cell semiconductor materials, can come in various forms: single-crystalline, multi-crystalline, poly-crystalline, or amorphous. In a single-crystal material, the atoms making up the framework of the crystal are repeated in a very regular, orderly manner

from layer to layer. In contrast, in a material composed of numerous smaller crystals, the orderly arrangement is disrupted moving from one crystal to another.

Absorption

The *absorption coefficient* of a material indicates how far light can penetrate the material before being absorbed. A small absorption coefficient means that light is not readily absorbed by the material. The absorption coefficient of a solar cell depends on two factors: the material making up the cell, and the wavelength or energy of the light being absorbed. Solar cell material has an abrupt edge in its absorption coefficient. The reason is that light, whose energy is below the material's bandgap, cannot free an electron, so it is not absorbed.

Bandgap

The *bandgap* of a semiconductor material is the minimum energy needed to move an electron from its bound state within an atom to a free state. This free state is where the electron can be involved in conduction. The lower energy level of a semiconductor is called the “valence band.” The higher energy level where an electron is free to roam is called the “conduction band.” The bandgap is the energy difference between the conduction band and valence band.

Complexity of Manufacturing

The most important parts of a solar cell are the semiconductor layers, because this is where electrons are freed, and the electric current is created. Several different semiconductor materials are used to make the layers in different types of solar cells, and each material has its benefits and drawbacks.

The cost and complexity of manufacturing may vary across these materials and device structures based on many factors, including deposition in a vacuum environment, amount and type of material utilized, number of steps involved, need to move cells into different deposition chambers or processing processes, and others.

The make up of a typical solar cell is shown in Figure 6 below.

Structure of Photovoltaic Solar Cell

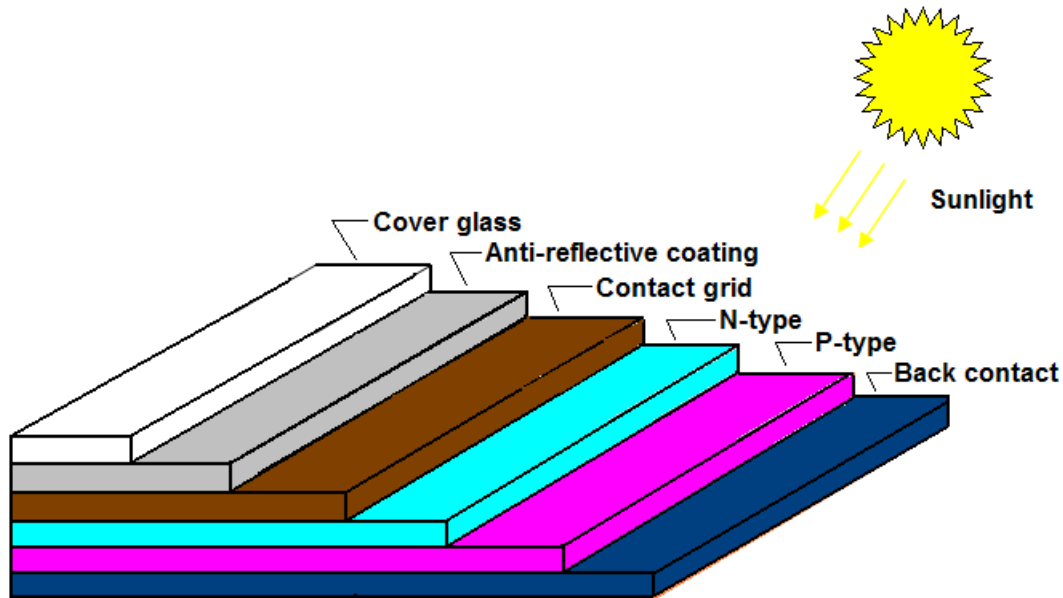


Figure 6

This solar cell consists of a glass or plastic cover, an antireflective layer, a front contact to allow electrons to enter a circuit, a back contact to allow them to complete the circuit, and the semiconductor layers where the electrons begin and complete their journey.

Solar Cell Structures

The actual structure of a photovoltaic device depends on the limitations of the material used. We will look briefly at four basic device designs commonly used with the materials we have discussed.

1. Homojunction
2. Heterojunction
3. p-i-n/n-i-p
4. Multijunction

1. Homojunction

Crystalline silicon is the primary example of a homojunction cell. The crystalline silicon material is altered so that one side is p-type, dominated by positive holes, and the other side is n-type, dominated by negative electrons. The p-n junction is located so that the maximum amount of light is absorbed near it. The free electrons and holes generated by light deep in the silicon diffuse to the p-n junction, and then separate to produce a current if the silicon is of sufficiently high quality.

Several aspects of the homojunction design can be varied to increase conversion efficiency:

- Depth of the p-n junction below the cell's surface
- Amount and distribution of dopant atoms on either side of the p-n junction
- Crystallinity and purity of the silicon

Some homojunction cells are designed with the positive and negative electrical contacts on the back of the cell. This geometry eliminates the shadowing caused by the electrical grid on top of the cell. A disadvantage is that the charge carriers, which are mostly generated near the top surface of the cell, must travel farther—all the way to the back of the cell—to reach an electrical contact. To be able to do this, the silicon must be of very high quality, without crystal defects that cause electrons and holes to recombine.

2. Heterojunction Device

An example of a heterojunction device is a CIS cell, where the junction is formed by contacting two different semiconductors—CdS and CuInSe₂. This structure is often chosen for producing cells made of thin-film materials that absorb light much better than silicon. The top and bottom layers in a heterojunction device have different roles. The top layer is a material with a high bandgap selected for its transparency to light. The top layer allows almost all incident light to reach the bottom layer, which is a material with low bandgap that readily absorbs light. This light then generates electrons and holes very near the junction, which helps to effectively separate the electrons and holes before they can recombine.

Heterojunction devices have an inherent advantage over homojunction devices, which require materials that can be doped both p- and n-type. Many photovoltaic materials can be doped either p-type or n-type, but not both. Because heterojunction devices do not have this constraint, many promising photovoltaic materials can be investigated to produce optimal cells.

Also, a high-bandgap top layer reduces the cell's series resistance. The top layer material can be made highly conductive, and the thickness can be increased without reducing the transmittance of light. As a result, light-generated electrons can easily flow laterally in the top layer to reach an electrical contact.

3. p-i-n and n-i-p Devices

Typically, amorphous silicon thin-film cells use a p-i-n structure, whereas CdTe cells use an n-i-p structure. The basic scenario is as follows: A three-layer sandwich is created, with the middle, undoped (called the intrinsic, or i-type layer) layer between an n-type layer and a p-type layer. This geometry sets up an electric field between the p-type and n-type regions that stretches across the middle intrinsic resistive region. Light generates free electrons and holes in the intrinsic region, which are then separated by the electric field.

In the p-i-n amorphous silicon cell, the top layer is p-type silicon, the middle layer is intrinsic silicon, and the bottom layer is n-type silicon. Amorphous silicon has many atomic-level electrical defects when it is highly conductive. Very little current would flow if an amorphous silicon cell had to depend on diffusion. However, in a p-i-n cell, current flows because the free electrons and holes are generated *within* the influence of an electric field, rather than having to move toward the field.

In a CdTe cell, the device structure is like the amorphous silicon cell, except the order of layers is flipped upside down. Specifically, in a typical CdTe cell, the top layer is p-type cadmium sulfide (CdS), the middle layer is intrinsic CdTe, and the bottom layer is n-type zinc telluride (ZnTe).

4. Multi-junction Devices

This structure, also called a cascade or tandem cell, can achieve a higher total conversion efficiency by capturing a larger portion of the solar spectrum. In the typical multi-junction cell, individual cells with different bandgaps are stacked on top of one another. The individual cells are stacked in such a way that sunlight falls first on the material having the largest bandgap. Photons not absorbed in the first cell are transmitted to the second cell, which then absorbs the higher-energy portion of the remaining solar radiation while remaining transparent to the lower-energy photons. These selective absorption processes continue through to the final cell, which has the smallest bandgap.

Figure 7 shows a multi-junction device with a stack of individual single-junction cells in descending order of bandgap. The top cell captures the high-energy photons and passes the rest of the photons on to be absorbed by lower-bandgap cells.

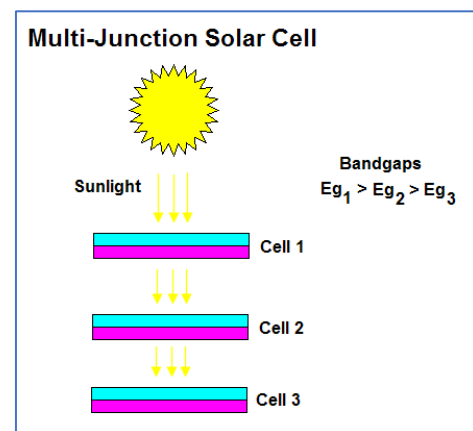


Figure 7

A multi-junction cell can be made in two different ways. In the mechanical stack approach, two individual solar cells are made independently, one with a high bandgap and one with a lower bandgap. Then the two cells are mechanically stacked, one on top of the other. In the monolithic approach, one complete solar cell is made first, and then the layers for the second cell are grown or deposited directly on the first.

This multi-junction device has a top cell of gallium indium phosphide, then a "tunnel junction" to allow the flow of electrons between the cells, and a bottom cell of gallium arsenide.

Solar Cell Materials

The most prevalent material used to manufacture solar cells is crystalline silicon. The second generation of solar cell material are known as thin-films and recently a newer, third generation, process known as nano-crystalline cells are entering production. Solar cells can be made from a wide range of semiconductor materials. We will discuss the following materials,

- Silicon
- Poly-Crystalline thin films
- Single-Crystalline thin films

Silicon

Silicon is the most popular material for solar cells. However, to be useful as a semiconductor material in solar cells the silicon must be refined to a purity of 99.9999%.

In single-crystal silicon, the molecular structure is uniform, because the entire structure is grown from the same crystal. This uniformity is ideal for transferring electrons efficiently through the material. To make an effective photovoltaic cell, however, silicon must be "doped" with other elements to make it n-type and p-type.

Semi-crystalline silicon, in contrast, consists of several smaller crystals or grains, which introduce boundaries. These boundaries impede the flow of electrons and encourage them to recombine with holes to reduce the power output of the solar cell. However, semi-crystalline silicon is much less expensive to produce than single-crystalline silicon. There are three forms of silicon solar cells that we will consider. They are,

- Single-Crystal Silicon
- Multi-Crystalline Silicon
- Amorphous Silicon

Single-Crystal Silicon

The most widely used technique for making single-crystal silicon is the Czochralski process, in which a seed of single-crystal silicon contacts the top of molten silicon. As the seed is slowly raised, atoms of the molten silicon solidify in the pattern of the seed and extend the single-crystal structure.

After growing the silicon ingot, it is sawn into thin wafers for further processing into photovoltaic cells.

To create silicon in a single-crystal state, high-purity silicon is first melted. Then it is allowed to reform very slowly in contact with a single crystal “seed.” The silicon adapts to the pattern of the single-crystal seed as it cools and gradually solidifies. Since this process starts from a seed, it is called “growing” a new rod (often called a “boule”) of single-crystal silicon out of molten silicon.

Several different processes can be used to grow a boule of single-crystal silicon. The most established and dependable processes are the Czochralski method and the float-zone technique. Another process that is used is called the “ribbon-growth” process.

In the *Czochralski process*, a seed crystal is dipped into a crucible of molten silicon and withdrawn slowly, pulling a cylindrical single crystal as the silicon crystallizes on the seed.

The *float-zone process* produces purer crystals than the Czochralski method, because they are not contaminated by the crucible used in growing Czochralski crystals. In the float-zone process, a silicon rod is set atop a seed crystal and then lowered through an electromagnetic coil. The coil's magnetic field induces an electric field in the rod, heating and melting the interface between the rod and the seed. Single-crystal silicon forms at the interface, growing upward as the coils are slowly raised.

Once the single-crystal rods are produced, by either the Czochralski or float zone method, they must be sliced or sawn to form thin wafers. Such sawing, however, wastes as much as 20% of the valuable silicon. The resulting thin wafers are then doped to produce the necessary electric field. They are then treated with a coating to reduce reflection and coated with electrical contacts to form functioning photovoltaic cells.

Although single-crystal silicon technology is well developed, the Czochralski and float-zone processes are complex and expensive. Another group of crystal-producing processes are called the *ribbon growth* methods. These single crystals cost less than other processes, because they form the silicon directly into thin, usable wafers of single-crystal silicon. These methods involve forming thin crystalline sheets directly, thus avoiding the slicing step required of cylindrical rods. Cells made from ribbon growth methods are not as efficient as cells created using the other methods.

One ribbon growth technique—edge-defined film-fed growth—starts with two crystal seeds that grow and capture a sheet of material between them as they are pulled from a source of molten silicon. A frame entrains a thin sheet of material when drawn from a melt. This technique does not waste much material, but the quality of the material is not as high as with Czochralski and float zone produced silicon.

Multi-Crystalline Silicon

Multi-Crystalline silicon devices are generally less efficient than those of single-crystal silicon, but they can be less expensive to produce. The multi-crystalline silicon can be produced in a variety of ways. The most popular commercial methods involve a casting process in which molten silicon is directly cast into a mold and allowed to solidify into an ingot. The starting material can be refined lower-grade silicon, rather than the higher-grade semiconductor grade required for single-crystal material. The cooling rate is one factor that determines the final size of crystals in the ingot and the distribution of impurities. The mold is usually square, producing an ingot that can be cut and sliced into square cells that fit more compactly into a photovoltaic module. (Round cells have spaces between them in modules, but square cells fit together better with a minimum of wasted space).

Amorphous Silicon

Amorphous solids, like common glass, are materials whose atoms are not arranged in any order. They don't form crystalline structures at all, and they contain large numbers of structural and bonding defects. But they have some economic advantages over other materials that make them appealing for use in photovoltaic systems.

Amorphous silicon absorbs solar radiation 40 times more efficiently than does single-crystal silicon, so a film only about one micrometer thick can absorb 90% of the usable light energy shining on it. This is one of the chief reasons that amorphous silicon could reduce the cost of photovoltaics. Other economic advantages are that it can be produced at lower temperatures and can be deposited on low-cost substrates such as plastic, glass, and metal. These characteristics make amorphous silicon the leading thin-film photovoltaic material.

Amorphous silicon's random structural characteristics cause deviations like "dangling bonds." Dangling bonds provide places for electrons to recombine with holes, but they may be neutralized somewhat with hydrogen.

Amorphous silicon does not have the structural uniformity of single-crystalline or multi-crystalline silicon. Small deviations in this material result in defects such as "dangling bonds," where atoms lack a neighbor to which they can bond. These defects provide places for electrons to recombine with holes, rather than contributing to the electrical circuit. Ordinarily, this kind of material would be unacceptable for electronic devices, because defects limit the flow of current. But amorphous silicon can be deposited so that it contains a small amount of hydrogen, in a process called "hydrogenation." The result is that the hydrogen atoms combine chemically with many of the dangling bonds, essentially removing them and permitting electrons to move through the material.

Instability is the greatest stumbling block for amorphous silicon. These cells experience the *Staebler-Wronski effect*, where their electrical output decreases over a period when first exposed to sunlight. Eventually, however, the electrical output stabilizes. This effect can result in up to a 20% loss in output before the material stabilizes. Exactly why this effect occurs is not fully understood, but part of the reason is likely related to the amorphous hydrogenated nature of the material. One way to mitigate this effect is to make amorphous silicon cells that have a multi-junction design.

Because of amorphous silicon's unique properties, solar cells are designed to have a thin (0.008 micrometer) p-type top layer, a thicker (0.5 to 1 micrometer) intrinsic middle layer, and a very thin (0.02 micrometer) n-type bottom layer. This design is called a “p-i-n” structure, being named for the types of the three layers. The top layer is made so thin and relatively transparent that most light passes right through it, to generate free electrons in the intrinsic layer. The p- and n-layers produced by doping the amorphous silicon create an electric field across the entire intrinsic region, thus inducing electron movement in that i-layer. A typical amorphous silicon cell employs a p-i-n design, in which an intrinsic layer (i-layer) is sandwiched between a p-layer and an n-layer.

Poly-Crystalline Thin Film

One scientific discovery of the computer semiconductor industry also has great potential in the photovoltaic industry is thin-film technology. The “thin film” term comes from the method used to deposit the film, not from the thinness of the film. Thin-film cells are deposited in very thin, consecutive layers of atoms, molecules, or ions. Thin-film cells have many advantages over their “thick-film” counterparts. For example, they use much less material. The cell's active area is usually only 1 to 10 micrometers thick, whereas thick films typically are 100 to 300 micrometers thick. Also, thin-film cells can usually be manufactured in a large-area process, which can be an automated, continuous production process. Finally, they can be deposited on flexible substrate materials.

Several different deposition techniques can be used, and all of them are potentially less expensive than the ingot-growth techniques required for crystalline silicon. The techniques are broadly classified as physical vapor deposition, chemical vapor deposition, electrochemical deposition, or a combination. Like amorphous silicon, the layers can be deposited on various low-cost substrates such as glass, stainless steel, or plastic in virtually any shape.

Single-crystal silicon cells must be individually interconnected into a module. In contrast, thin-film devices can be made as a single unit with layer upon layer being deposited sequentially on some substrate, including deposition of an antireflection coating and transparent conducting oxide.

Unlike most single-crystal cells, a typical thin-film device does not have a metal grid for the top electrical contact. Instead, it uses a thin layer of a transparent conducting oxide, such as tin oxide. These oxides are highly transparent and conduct electricity very well. A separate antireflection coating might top off the device, unless the transparent conducting oxide serves that function.

Polycrystalline thin-film cells are made of many tiny crystalline grains of semiconductor materials. The materials used in these polycrystalline thin-film cells have properties that are different from those of silicon. So, it seems to work better to create the electric field with an interface between two different semiconductor materials.

The typical polycrystalline thin film has a very thin top layer. The top layer's role is to absorb light energy from only the high-energy end of the spectrum. It must be thin enough and have a wide enough bandgap (2.8 eV or more) to let all available light through the interface to the absorbing layer. The absorbing layer under the top layer, usually doped p-type material, must have a high absorptivity for high current and a suitable band gap to provide a good voltage.

Polycrystalline thin-film cells have a heterojunction structure, in which the top layer is made of a different semiconductor material than the bottom semiconductor layer. The top layer, usually n-type, is a window that allows almost all the light through to the absorbing layer, usually p-type. An "ohmic contact" is often used to provide a good electrical connection to the substrate.

The four most common polycrystalline thin film materials are:

1. Copper indium diselenide (CIS)
2. Copper indium gallium diselenide (CIGS)
3. Cadmium telluride (CdTe)
4. Thin film silicon

The following is a brief explanation of these four polycrystalline thin film materials.

1. Copper Indium Diselenide (CIS)

Copper Indium Diselenide (CuInSe₂ or "CIS") has an extremely high absorptivity, which means that 99% of the light shining on CIS will be absorbed in the first micrometer of the material. Cells made from CIS are usually heterojunction structures. The most common material for the top layer in CIS devices is cadmium sulfide (CdS), although zinc is sometimes added to improve transparency.

2. Copper Indium Gallium Diselenide (CIGS)

A variation on the Copper indium diselenide “CIS” cell is the Copper indium gallium diselenide “CIGS” cell. A CIGS cell is made by adding a small amount of gallium to the lower absorbing CIS layer to boost its bandgap from its normal 1.0 electron-volt (eV). This improves the voltage and therefore the efficiency of the device.

3. Cadmium Telluride (CdTe)

Cadmium telluride is another prominent polycrystalline thin-film material. With a nearly ideal bandgap of 1.44 eV, CdTe also has a very high absorptivity. Although CdTe is most often used in photovoltaic devices without being alloyed, it is easily alloyed with zinc, mercury, and a few other elements to vary its properties. Like CIS, films of CdTe can be manufactured using low-cost techniques.

Also, like CIS, the best CdTe cells employ a heterojunction interface, with cadmium sulfide (CdS) acting as a thin top layer. Tin oxide is used as a transparent conducting oxide and antireflection coating. One problem with CdTe is that p-type CdTe films tend to be highly resistive, which leads to large internal resistance losses. A solution is to allow the CdTe layer to be intrinsic (neither p-type nor n-type, but natural), and add a layer of p-type zinc telluride (ZnTe) between the CdTe and the back electrical contact. Although the n-type CdS and the p-type ZnTe are separated, they still form an electrical field that extends through the intrinsic CdTe. When it comes to making CdTe cells, a wide variety of methods are possible, including closed-space sublimation, electro deposition, and chemical vapor deposition.

4. Thin-Film Silicon

The term “thin-film silicon” typically refers to silicon-based photovoltaic devices other than amorphous silicon cells and single-crystalline silicon cells (where the silicon layer is thicker than 200 micrometers). These films have high absorptivity of light and may require cell thicknesses of only a few micrometers or less. Nano-crystalline silicon and small-grained polycrystalline silicon may be able to replace amorphous silicon alloys as the bottom cell in multi-junction devices. As with other thin films, advantages include the savings of material, monolithic device design, use of inexpensive substrates, and manufacturing processes that are low temperature and possible over large areas.

Single-Crystalline Thin Film

The most common form of single-crystalline thin film is gallium arsenide. Gallium arsenide (GaAs) is a compound semiconductor: that is, a mixture of two elements, gallium and arsenic. Gallium is a by-product of the smelting of other metals, notably aluminum and zinc, and it is rarer than gold. Gallium arsenide has been developed for use in solar cells at about the same

time that it's been developed for light-emitting diodes, lasers, and other electronic devices that use light.

GaAs is especially suitable for use in multi-junction and high-efficiency solar cells, for several reasons:

- The GaAs bandgap is 1.43 eV, which is nearly ideal for single-junction solar cells.
- GaAs has absorptivity so high it requires a cell only a few microns thick to absorb sunlight.
- GaAs cells are relatively insensitive to heat.
- Alloys made from GaAs and aluminum, phosphorus, antimony, or indium have characteristics that are complementary to those of gallium arsenide, allowing great flexibility in cell design.
- GaAs is highly resistant to radiation damage.

One of the greatest advantages of gallium arsenide and its alloys as photovoltaic cell materials is that it is amenable to a wide range of designs. A cell with a GaAs base can have several layers of slightly different compositions. This allows a cell designer to precisely control the generation and collection of electrons and holes. To accomplish the same thing, silicon cells have been limited to variations in the level of doping.

This degree of control allows cell designers to push efficiencies closer and closer to theoretical levels. For example, one of the most common GaAs cell structures has a very thin top layer made of aluminum gallium arsenide. This thin layer allows electrons and holes to be created close to the electric field at the junction.

The greatest barrier to the success of GaAs cells has been the high cost of a single-crystal GaAs substrate. For this reason, GaAs cells are used primarily in concentrator systems, in which a typical concentrator cell measures only about 0.25 cm² in area but can produce ample power at high concentrations. In this configuration, the cost is low enough to make GaAs cells competitive, if module efficiencies are between 25% and 30% and that the rest of the photovoltaic system is cost-effective.

Photovoltaic Array

Individual photovoltaic solar cells are the basic building block of a solar electric system. However, each individual cell is usually very small with limited power capability. Individual cells are connected to form a solar module. Then, to boost the capability of the system, individual cells are connected in parallel (to increase current capability) and in series (to increase the voltage rating) to form a photovoltaic array that has the voltage and current ratings needed

for a specific application. Figure 8 is a diagram of how individual solar cells are a component of a photovoltaic array.

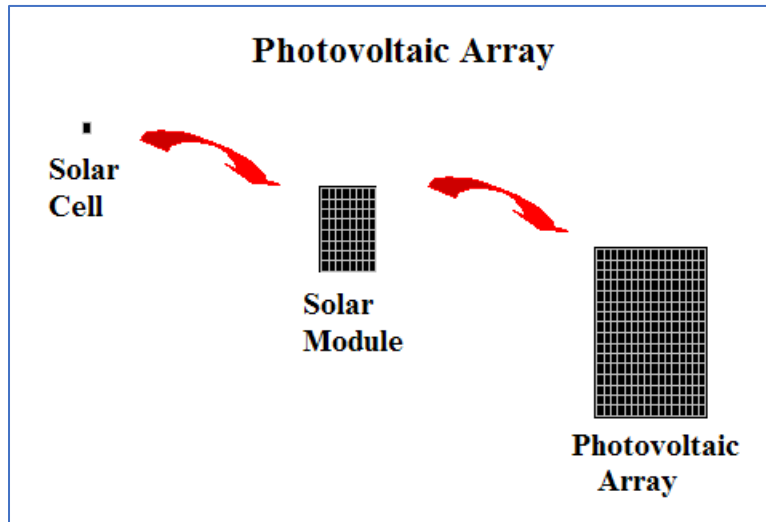


Figure 8

Photovoltaic systems can be classified into two general categories: flat-plate systems or concentrator systems.

Flat-Plate Photovoltaic Systems

The most common array design uses flat-plate photovoltaic modules or panels. These panels can either be fixed in place or allowed to track the movement of the sun. They respond to sunlight that is either direct or diffuse.

The simplest photovoltaic array consists of flat-plate photovoltaic panels in a fixed position. The advantages of fixed arrays are that they lack moving parts, there is virtually no need for extra equipment, and they are relatively lightweight. These features make them suitable for many locations, including most residential roofs. Because the panels are fixed in place, their orientation to the sun is usually at an angle that may be less than optimal for many hours in the day. Therefore, less energy per unit area of array is collected compared with that from a tracking array.

Concentrator Photovoltaic Systems

The primary reason for using concentrators is to be able to use less solar cell material in a photovoltaic system. Photovoltaic cells are the most expensive components of a photovoltaic system, on a per-area basis. A concentrator makes use of relatively inexpensive materials such as plastic lenses and metal housings to capture the solar energy shining on a large area and focus

that energy onto a smaller area, where the solar cell is. One measure of the effectiveness of this approach is the concentration ratio – a measure of how much concentration the cell is receiving.

There are several advantages of concentrator photovoltaic systems, as compared to flat-plate systems. Concentrator systems increase the power output while reducing the size or number of cells needed. An additional advantage is that a solar cell's efficiency increases under concentrated light. How much that efficiency increases depend largely on the design of the solar cell and the material used to make it. Another advantage is that a concentrator can be made of small individual cells. This is an advantage because it is harder to produce large-area, high-efficiency solar cells than it is to produce small-area cells.

Several challenges exist to using concentrators. For example, the required concentrating optics are significantly more expensive than the simple covers needed for flat-plate solar systems, and most concentrators must track the sun throughout the day and year to be effective. Thus, achieving higher concentration ratios means using not only expensive tracking mechanisms, but also, more precise controls than those of flat-plate systems with stationary structures.

Both reflectors and lenses have been used to concentrate light for photovoltaic systems. The most promising lens for photovoltaic applications is the Fresnel lens, which uses a miniature saw tooth design to focus incoming light. When the teeth run in straight rows, the lenses act as line-focusing concentrators. And when the teeth are arranged in concentric circles, light is focused at a central point. However, no lens can transmit 100% of the incident light. The best that lenses can transmit is only 90% to 95%, and in practice, most transmit less. Furthermore, concentrators cannot focus diffuse sunlight, which makes up about 20% of the solar radiation available on a clear day.

High concentration ratios also introduce a heat problem. When excess radiation is concentrated, so is the amount of heat produced. Cell efficiencies decrease as temperatures increase, and higher temperatures also threaten the long-term stability of solar cells. Therefore, the solar cells must be kept cool in a concentrator system.

One of the most important design considerations is to minimize electrical resistance where the external electrical contacts carry off the current generated by the cell. Wide fingers in the contacting electrical grid are ideal for low resistance, but they block too much light from reaching the cell because of their shadow. One solution to the problems of resistance and shadowing is prismatic covers. These special covers act like a prism and direct incoming light to parts of the cell's surface that are between the metal fingers of the electrical contact grid. Another solution is a back-contact cell, which differs from conventional cells in that both the positive and negative electrical contacts are on the back. Placing all the electrical contacts on the

back of the cell eliminates power losses from shadowing, but it also requires exceptionally good-quality silicon material.

Chapter 4

Balance of System (BoS) Equipment

After the solar cell, all other equipment in a photovoltaic system is known as the balance of system, or “BoS” equipment. The balance of system equipment includes the charge controller, batteries, and inverters, and any other equipment needed to operate the system. The photo on the right shows a battery system and charge controller.



right

Photo credit: DOE

Batteries

Batteries for solar systems are known as secondary batteries because they can be recharged by reversing the chemical reaction. In contrast, a primary battery is non-rechargeable battery such as a dry-cell alkaline battery. The most common types of batteries for residential installations are Lead-Acid and Lithium-Ion batteries.

Lead-Acid Batteries

Lead-Acid batteries are the most common type of rechargeable battery and have been used in storage applications for decades. They are economical to purchase and can tolerate a wide range of operating conditions. One of the most common uses of lead-acid batteries is for starting, lighting, and ignition (SLI) loads in automobiles.

Lead-Acid batteries can produce either high currents or low currents over a wide range of temperatures and they have a good shelf life. They are heavy, and most are flooded cell units, which require regular maintenance.

The traditional lead-acid battery is known as a *flooded cell* and the lead plates are immersed in a solution of electrolyte. Flooded cell batteries vent gases during the discharge process and water must be added periodically to make up for lost electrolyte. Some of the newer flooded cell batteries, known as low maintenance batteries, come with enough extra electrolyte to make up for the electrolyte that will be lost during the life of the battery.

During the operation of a Lead-Acid battery oxygen is released at the positive electrode and hydrogen gas is released at the negative electrode. The loss of hydrogen molecules and oxygen molecules results in a loss of water in the electrolyte. Flooded cell units must be vented to allow these gases to escape and the area surrounding the battery must have adequate ventilation.

A newer design of lead-acid battery is known as a sealed-lead battery. In sealed-lead batteries the oxygen recombines with the lead and hydrogen to recreate water in the electrolyte. The separator in a sealed lead battery is a fibrous glass mat that is wetted with electrolyte. The design allows the gas by-products of the discharge cycle to recombine within the battery and thereby preventing the loss of electrolyte. Sealed-lead batteries must have a safety vent to prevent dangerous pressure buildups that might occur during overzealous recharging. Sealed Lead-Acid batteries are called *Absorbed Glass Mat* (AGM) batteries and the electrolyte is absorbed in a glass mat. They tend to have low self-discharge characteristics, but they generally have a shorter lifespan than traditional flooded cell batteries.

Lead-acid batteries are usually classified for SLI, deep cycle, or standby applications. SLI is starting, lighting, and ignition applications that require short, high current applications such as supplying an automobile starter. Deep-cycle batteries are designed for prolonged discharges such as solar power batteries.

Standby batteries are designed to sit idle for long periods of time and then deliver high currents when needed. Standby batteries are used in uninterruptible power supplies and emergency lighting. This is also known as “float service” since the battery is continuously connected across a charging source that is used to supply both the charging current and the load current.

The plates in a lead-acid battery are made up of a grid and a paste. The grid is a lead or lead alloy and the paste is the active material that holds the charge. The density and porosity of the paste and the physical dimensions of the plate determine the capacity and discharge rate of the battery plate. For instance, high discharge rates require plates with a thin, porous paste whereas; high capacity batteries require thicker, denser plates. Deep discharge batteries for solar power systems require thick plates with a denser paste to tolerate deeper discharge cycles.

Batteries require a separator to isolate the negative and positive plates. Separators in lead-acid batteries must be resistant to sulfuric acid, have low electrical resistance, have good wet-ability, and have a low specific density.

Lead-acid batteries suffer significant loss of life at high temperatures. Batteries are rated at 15C; at 35C a lead-acid battery may only have half its normal life.

Deep cycle batteries are designed to be discharged and re-charged many times. A deep cycle battery is charged, removed from its charging source, and then nearly totally discharged before recharging. Deep discharging creates large stresses in the plates, which causes the active material on the plates to pull away from the plates and fall to the bottom of the battery. Therefore, a deep cycle battery must be designed to account for the potential pull away of the

active material from the plates. To minimize pull away the plate separators are thicker, the plates are thicker and there are fewer plates than an SLI battery, and the battery has room below the plates to accommodate waste material that pulls away from the plates and settles in the bottom of the battery case.

The life of a battery is dependent on the number of charge-discharge cycles and the degree of the discharge as a percent of the battery's capacity. For a deep discharge, flooded cell, lead acid battery, the graph in Figure 9 shows the relationship between the number of available charge-discharge cycles compared to the percent discharge.

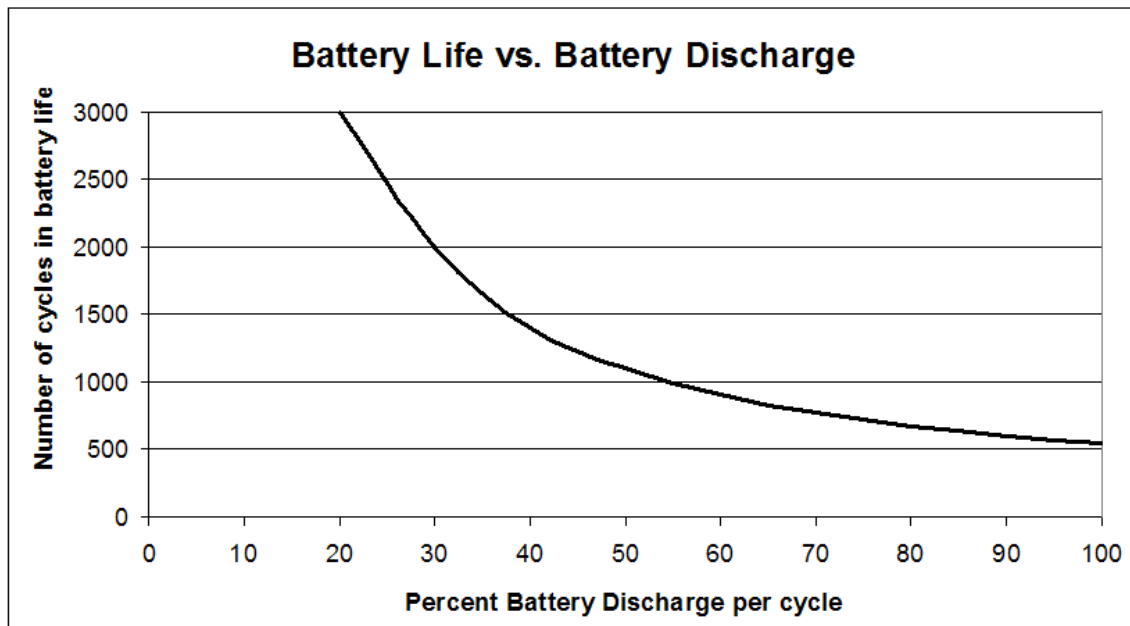


Figure 9

From Figure 9 we see that a battery that is routinely discharged to 100% of its capacity will only have 500 charge-discharge cycles. In comparison, a battery that is only discharged to 20% of its capacity will have 3,000 cycles.

To charge a Lead-Acid battery a current is forced into the battery and the voltage is allowed to rise to whatever level is necessary to deliver the current to the battery. At about 70% of a full charge the battery will begin gassing and the gassing will increase rapidly to the point of damaging the battery. Battery gassing is the process of converting water into hydrogen and oxygen gas. Gassing stirs the electrolyte and will cause the active material on the plates to shed. If the charging process is stopped at the initiation of gassing the battery will not reach a full charge. Repeatedly stopping charging at the first sign of gassing will ultimately damage the plates. To overcome the gassing problem, constant current chargers will usually drop back to a lower charging rate when gassing occurs and finish the charging at the lower rate. The switchover point from the high current to the low current charge is usually based on some

During discharge, lithium ions carry the current within the battery from the negative to the positive electrode, through the non-aqueous electrolyte and separator diaphragm.

During charging, the charging circuit applies an over-voltage, forcing a charging current to flow within the battery from the positive to the negative electrode, i.e. in the reverse direction of a discharge current under normal conditions. The lithium ions then migrate from the positive to the negative electrode, where they become embedded in the porous electrode material in a process known as *intercalation*.

Most types of Li-ion batteries are charged in three stages: constant current phase, balance phase, and constant voltage phase. During the *constant current* phase, the charger applies a constant current to the battery at a steadily increasing voltage, until the voltage limit per cell is reached. During the *balance phase*, the charger reduces the charging current (or cycles the charging on and off to reduce the average current) while the state of charge of individual cells is brought to the same level by a balancing circuit, until the battery is balanced. During the *constant voltage* phase, the charger applies a voltage equal to the maximum cell voltage times the number of cells in series to the battery, as the current gradually declines towards zero, until the current is below a set threshold of about 3% of initial constant charge current. A periodic topping charge is required about once per 500 hours. Top charging is recommended to be initiated when voltage goes below 4.05 volts per cell.

Li-ion rechargeable batteries have a self-discharge rate typically stated by manufacturers to be 1.5-2% per month. The rate increases with temperature and state of charge. Most cycling conditions self-discharge is primarily time-dependent; however, after several months of open circuit or float charge, state-of-charge dependent losses are significant. The self-discharge rate does not increase monotonically with state-of-charge but drops somewhat at intermediate states of charge. Self-discharge rates may increase as batteries age.

Li-ion battery life is typically defined as the number of full charge-discharge cycles before significant capacity loss. On average, lifetimes consist of 1,000 cycles at which point they will have lost 30% of their capacity. A cycle is considered a full discharge and re-charge, so a battery that is only depleted to 50% of its capacity before recharging has only used one-half of a charge cycle.

Charge Controllers

A charge controller regulates the flow of electricity from the solar panels to the system batteries. The charge controller monitors the status of the battery's charge to make sure the battery

receives charging current when needed, but doesn't allow the batteries to be overcharged, which may damage the batteries.

Charge controllers for solar systems face unique challenges compared to typical battery chargers. A charge controller interfaces between a power source, the sun, that is intermittent and variable and the battery. The batteries are usually deeply discharged between uses and must be recharged at least daily, and the battery loads can vary significantly during the day.

A key attribute of a solar charge controller is that it must be able to recharge the battery quickly when the power source is present while minimizing heating and battery gassing. It must also be able to regulate the battery voltage all day during both high and low solar resource periods and regulate the battery during long periods with no load applied.

The charge process usually consists of three stages. The charging process begins with a *bulk charge* that is a high current rate charge. Next comes the *acceptance charge* (sometimes called the absorption charge) where the charge current decreases as the voltage approaches the battery voltage rating. Once the battery is fully charged a *float charge* is applied to maintain the battery in a fully charged state. In addition, a controlled overcharge, also known as an *equalization charge*, is used to condition the battery.

The simplest charge controllers are "on/off" devices that allow current to flow until a specific voltage is reached and the unit is shut off. When the on/off controller reaches its voltage set-point and shuts off, much of the solar energy that is available during the day for charging is not utilized. These crude devices do not allow the batteries to reach their full capacity and some studies have shown that simple on/off chargers only allow the batteries to maintain about 60% state of charge, which causes reduced battery efficiency.

Most modern charge controllers use pulse width modulated (PWM) control using field effect transistors (FET's). PWM is a process where a square wave's duty cycle is modulated to vary the average value of the waveform, which will control the amount of power sent to the load. Most PWM charge controllers have a feature known as maximum power point tracking (MPPT) which will maximize the amount of current the battery receives during the charging cycle. PWM controllers respond well to variable duty cycles and will reduce charging current as necessary to maintain a constant voltage at the battery.

Using PWM controllers helps to break down lead sulfate on the battery plates and overcome the resistance that forms between the battery plates and the active material in the paste on the plates. The charge pulses with a PWM controller are also short enough in duration to reduce the possibility of gas bubbles forming in the battery.

Since high battery temperatures will increase the resistivity of the electrolyte and cause gassing, the charge controller should have a method to compensate for battery temperatures to prolong battery life.

Another useful feature of some charge controllers is the ability to disconnect the battery to prevent deep discharges. An automatic low-voltage load disconnect device (LVD) is an optional component on many charge controllers but is essential for long battery life.

Batteries require some amount of overcharge to reverse normal sulfation and to reach a full charge. This equalization charge is best accomplished using a PWM charge controller.

Inverters

An inverter is used to convert the DC voltage generated by the solar panels to a standard AC voltage. In its simplest form the DC power is fed into a pair of switching transistors. The transistors are rapidly turned on and off in sequence, which generates a square wave that crudely resembles a sine wave and therefore acts like an AC voltage.

Early inverters were purely square wave generators, which generates a very poor form of AC voltage. The waveform can be improved by more refined switching and filtering. The more the waveform is processed the better the waveform becomes. Just about all inverters made today either generate a modified sine wave or a sine waveform. Figure 10 shows each of the three types of inverter waveforms: square wave, modified square wave, and sine wave.

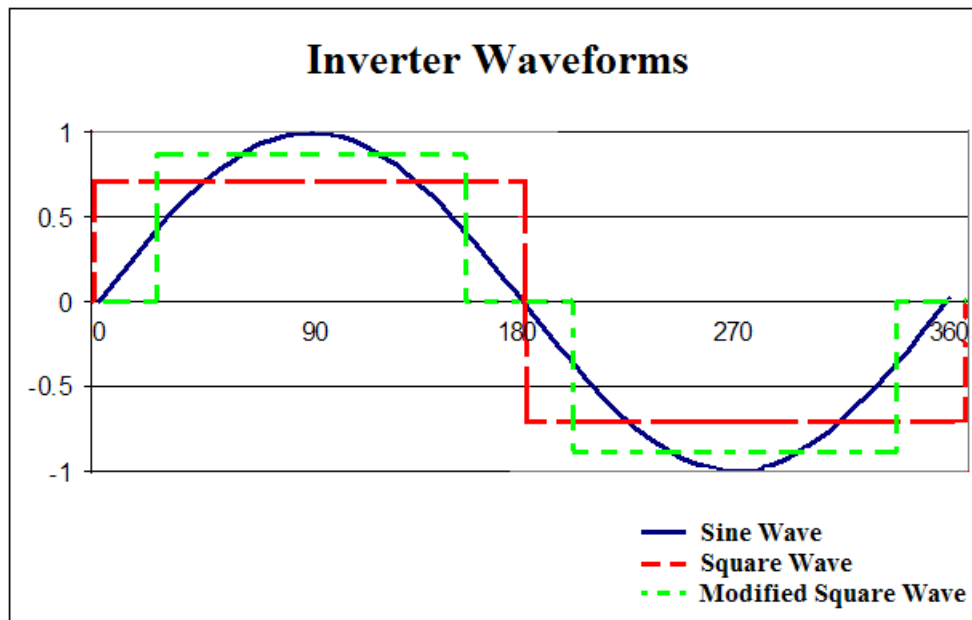


Figure 10

Manufacturers will often claim their unit is a modified sine wave inverter, but a more accurate description is that the waveform is a modified square wave. *Modified square wave* inverters work reasonably well for most appliances and they are very efficient at converting DC to AC, but they will cause problems for devices that have electronic timers, speed controllers, and some electronic sensing circuits. Specifically, small tool battery chargers, microwaves, laser printers, and even washing machine timers will likely not operate correctly with a modified square wave. Some devices, especially laser printers and small hand tool battery chargers can be damaged with the use of modified square wave inverters. Modified square wave inverters may have a very poor total harmonic distortion (THD) and may be 40% or greater.

With advanced electronics, *pure sine waveform* inverters are economical and will run virtually any AC device. They can generate a sine wave that is as good, and sometimes better, than the utility supplied AC voltage. Pure sine waveform inverters are slightly more expensive than modified square wave inverters, but they tend to have waveforms that have a total harmonic distortion of 5% or less. For grid-interconnected systems, the utility will most likely require the unit to have a THD of less than 5%.

Most modern inverters have efficiencies of 85% or better. However, if a modified square wave inverter is used with motor loads the efficiency of the motor will be reduced by an additional 15% to 20%.

The capacity of inverters is rated in watts. An inverter is sized by summing all the loads connected to the system. Inverters have three load ratings: continuous, limited time, and surge rating. The *continuous load rating* is obviously the nominal rating of the system. The *limited-time rating* is a short overload rating typically for 10 to 20 minutes. The *surge rating* is a very short duration overload capability for motor starting loads.

Inverters are designed as either a low switching frequency unit or a high switching frequency unit. Low switching frequency units are more expensive than high switching frequency units, but they handle high surge capacity (4-6 times nominal) and are well suited for large motor loads. They generate more noise than high switching frequency units. High switching frequency units are lighter, less noisy, and cheaper than low switching frequency units, but the surge capacity is only about two times nominal.

Most inverters are rated for 115-VAC. For loads that require 230-VAC, the voltage can either be stepped up using a 115:230-volt transformer or some inverters can be stacked so that two 115-VAC units are used to generate 230-VAC.

Inverters will use some amount of power even when no load is being supplied. To increase the efficiency of the units, some inverters have a “sleep mode” where the inverter automatically

shuts off when no load is present and then immediately turns itself back on when load is sensed. This feature is also called “standby”, “autostart”, and “power saver” mode. Sleep mode can be a nuisance for some loads though and the manufacturers usually include an “always on” setting to bypass the sleep mode.

Both charge controllers and inverters are governed by UL 1741. Equipment that meets UL 1741 should be compliant with IEEE 1547, which is the standard most utility companies use for grid-interconnected equipment. Likewise, UL 1741 equipment should be satisfactory to meet the National Electric Code (NEC®) requirements.

Chapter 6 Installation Issues

This Chapter explains how to properly locate and position a photovoltaic system for optimum efficiency, how to size the system to meet the electrical requirements, and the relevant codes and standards that apply to photovoltaic systems.

Siting

It may sound obvious, but for maximize efficiency, a photovoltaic system must face the sun. Ideally, the solar panels should be normal (perpendicular) to the sun during every daylight hour during the year. The problem is that, in relation to the solar panel, the sun's position moves throughout the day. In North America, the sun rises in the southeastern sky and sets in the southwestern sky. At the more northern latitudes the sun will be in a more southern position in the sky. Also, the sun's height in the sky varies throughout the year. So, the only way to maintain a solar panel normal to the sun is to have a dual tracking array that will follow the sun through the sky. Tracking arrays are expensive though and may not be worth the cost for a small photovoltaic system. The good news is that a correctly positioned fixed system will yield satisfactory results in most cases.

There are two values that describe the sun's position. They are the azimuth and attitude of the sun. The *azimuth* is the position of the sun in relation to true south. *Altitude* is the height of the sun in the sky. Figure 11 shows the path of the sun on June 21st, when the sun is in its highest position and December 21st, when the sun is in its lowest position.

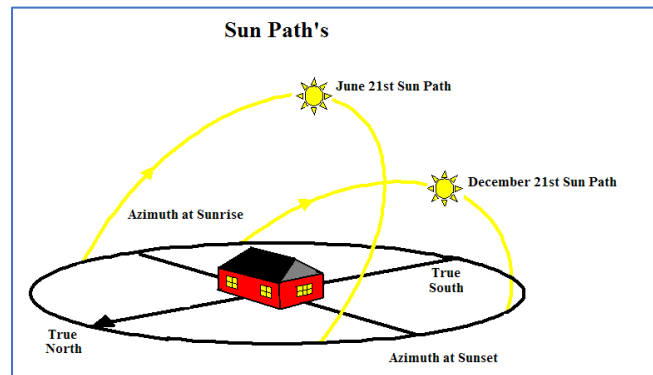


Figure 11

The azimuth is based on true south, which is the magnetic north south with the effects of magnetic variation considered. At some locations, such as Jackson, MS, true south and magnetic south are the same. But, as you move east or west, a compass will not read correctly due to the magnetic variation. For instance, in Orlando, FL, true south is five degrees less than what is observed on a compass. The magnetic variation changes over time and the United States Geological Survey generates magnetic declination tables that show the magnetic variation. Figure 12 is a magnetic declination chart. Any position east of the zero-variation line should be subtracted from the compass reading to obtain true south. West of the zero-variation line, the

variation should be added to the compass reading to correct for the variation. Looking at Figure 12, you can see that Denver, CO has a +10 variation, so ten degrees must be added to the compass reading to obtain true south.

Magnetic Declination

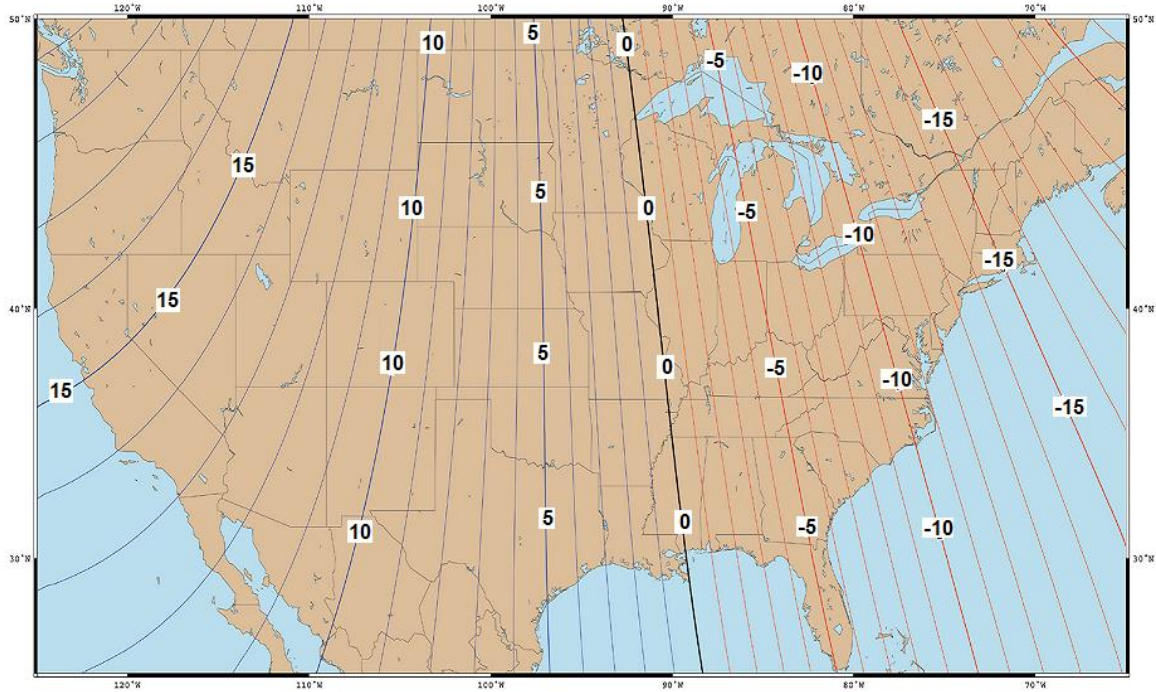


Figure 12

After true south is found the next concern is what angle to tilt the solar panel so that it will be perpendicular to the sun. During the summer the sun follows a very broad path through the sky and the path the sun takes varies with the latitude of the location because of the earth's tilt.

Figure 13 is a sun chart that describes the sun's path for a specific location. This chart was generated for 32 degrees west latitude and 85 degrees west longitude, which is approximately Columbus, GA. For a location of 32 degrees latitude and 85 degrees longitude the sun starts out at about 60 degrees east north at 5:00 AM and slowly rises from the horizon (zero elevation) to a height of over 80 degrees by noon (90 degrees is directly overhead) and then descends back to the horizon at around 7:00 PM setting at 300 degrees, or 60 degrees west of north. In the winter the path is much shorter rising at 7:00 AM at 120 degrees east of north and only rising to an elevation of 35 degrees before setting at 5:00 PM at 240 degrees.

The photovoltaic solar panel must have a clear view of the sun as it crosses the sky. This means that an area from the southeast to the southwest must be clear from the sun's lowest elevation during the year to its highest elevation. This area is known as the *solar window*. From a practical standpoint the area can be defined at the sun's position from 9:00 AM until 3:00 PM each day and from the December 21st position (winter solstice) to June 21st (summer solstice).

The time period between 9:00 AM and 3:00 PM is chosen because very little solar radiation is available when the sun is low on the horizon because of air pollutants and other atmospheric conditions.

In Figure 13, the solar window for Columbus, GA is shown in yellow. There should not be any obstructions such as trees, buildings, etc within the solar window.

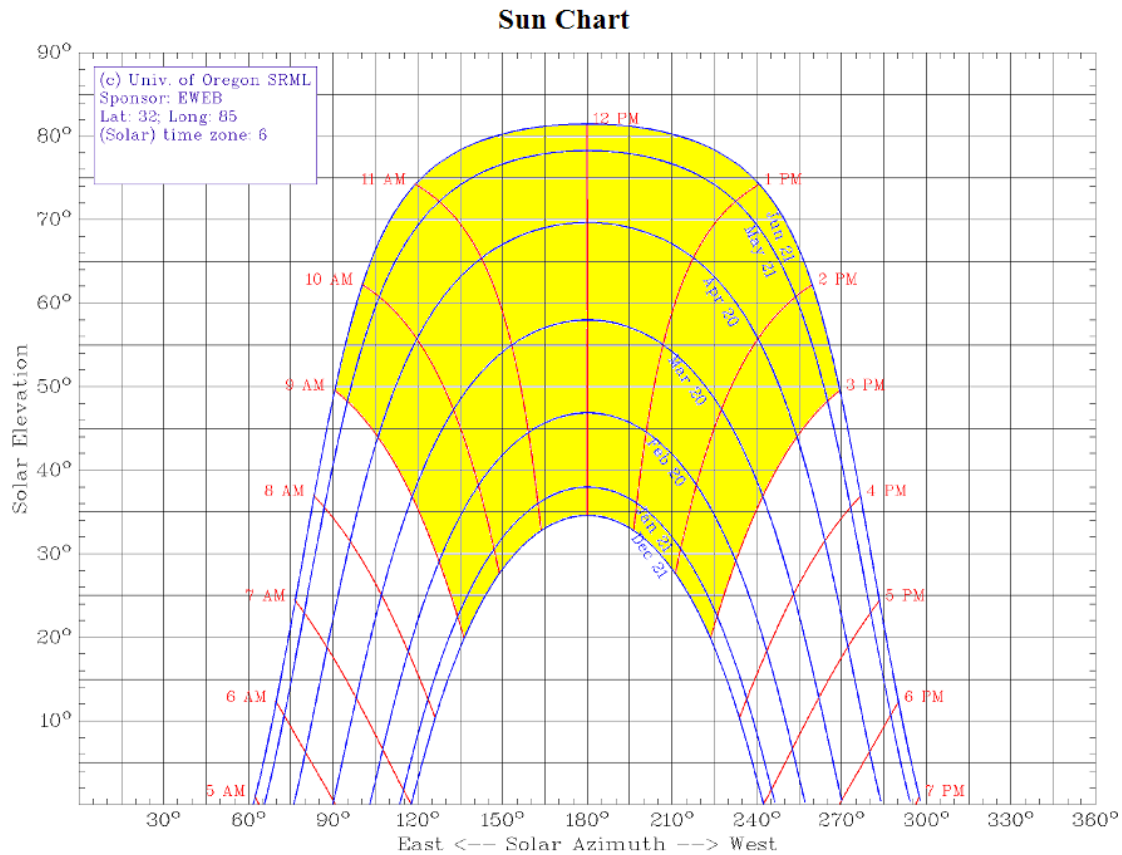


Figure 13

For fixed installations where the electricity will be needed on a year-round basis the solar panel should be tilted at an angle equal to the latitude of the location. At this angle the solar panel will be most efficient in the spring and fall and less efficient during the winter and summer, but this approach maximizes the annual solar energy collected. For applications where the electrical need is greater in the winter, the panel should be tilted at an angle equal to the latitude plus 15 degrees. If the summer electricity needs are greater, then an angle of the latitude minus 15 degrees is better. Another approach is to manually adjust the solar panel tilt as the seasons change. Look at Table 2 for the solar radiation for Atlanta, GA.

Table 2
Solar Radiation (kWh/m²/day)
Atlanta, GA

Tilt	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Lat - 15	3.4	4.2	5.1	6.0	6.2	6.3	6.1	5.9	5.3	4.9	3.8	3.2	5.0
Latitude	3.8	4.6	5.3	5.8	5.8	5.8	5.7	5.7	5.4	5.2	4.2	3.7	5.1
Lat +15	4.1	4.7	5.1	5.4	5.2	5.1	5.0	5.2	5.1	5.3	4.5	3.9	4.9

The average solar radiation for either -15 or +15 degrees is slightly less than the average solar radiation with a tilt angle equal to the latitude. But, for the winter months of December through March, the average daily solar radiation at +15 degrees is more than the values for a tilt angle equal to the latitude.

Sizing

To properly size a photovoltaic system, we must know the electrical load and the hours of operation of the load. Table 3 has the electrical load and typical energy consumption of many common electrical devices. The energy consumption of a load is based on the capacity of the unit in watts times the amount of time, in hours, that the load is energized.

Some loads, like a refrigerator, are always connected to the electric system, but a refrigerator does not run 24 hours per day, seven days per week. A refrigerator will run for a short time until the thermostat is satisfied and will then shut off until additional refrigeration is needed. From table 3, we see that a 12 cubic foot refrigerator has an electrical load of 575 watts. To find the energy consumption we must multiply the wattage by the number of hours in a month (730) times the load factor of the appliance and divide by 1,000 to obtain the monthly kilowatt-hour energy consumption. The *load factor* is a number that describes the percent of time the load is applied in a given month. For instance, the load factor for the 12 Cu. Ft. refrigerator is about 34%, so the energy consumption is,

$$\text{Kwh/mo} = 575 * 730 * 0.34 / 1,000 = 143 \text{ kWh/mo.}$$

Table 3, which is on the next page, has the load factor already factored in for various appliances to yield the energy consumption in kWh/month. From Table 3 we can find the electrical load in watts by summing all the appliances that are connected to the photovoltaic system. Likewise, we can sum the energy consumption (kWh/mo.) for the appliances to find the total energy consumption.

Table 3
Power Consumption Characteristics
Typical Appliances

Appliance	Watts	Hours/Month	kWh/mo.
Refrigerator//Freezer,12 cu. ft.	575	248	143
Refrigerator/Freezer, 16 cu. ft.	690	275	190
Refrigerator/Freezer, 21 cu. ft.	795	281	223
Freezer, 12 cu. ft.	440	333	147
Freezer, 16 cu. ft.	575	335	193
Freezer, 21 cu. ft.	495	340	168
Clothes Dryer	4,500	18	81
Iron	1,000	12	12
Washing Machine	600	12	7
Water Heater - 40 gallon	4,500	90	405
Water Heater - 60 gallon	5,000	88	440
Room AC 5,000 BTU's / 10 EER	500	360	180
Room AC 12,500 BTU's / 10 EER	1,250	360	450
Space Heater 1,500 Watts	1,500	360	540
Electric Blanket	177	69	12
Dehumidifier	600	210	126
Ceiling Fan	100	240	24
Attic Fan (house)	400	240	96
Humidifier	177	72	13
Gas Furnace fan motor	600	240	144
Wood Furnace fan motor	250	360	90
Toaster Oven/Broiler	1,350	6	8
Coffee Maker	800	10	8
Dishwasher	1,200	22	26
Microwave Oven	1,300	11	14

Range w/self-cleaning oven	12,200	12	146
AM/FM/CD Radio	71	100	7
TV – color	200	180	36
VCR	35	60	2
Telephone	3	730	2
Miscellaneous lights (small home) ¹	1,000	150	150
Miscellaneous lights (large home) ¹	2,000	150	300
Hot Tub	5,000	45	225
Hair Dryer	1,500	30	45
Water Pump (1H.P.)	750	96	72
Pool Pump	1,300	360	468
Personal Computer & Monitor	140	180	25
Note: 1. For fluorescent lamps divide the lighting figures by 4.			

Let’s consider the following example to illustrate the proper sizing of a photovoltaic power system. Assume that we have a small summer cabin in a remote area near Atlanta, GA where it is not practical to make a connection to the local electric utility. First, as much load as possible should be served by propane to minimize the electrical load. The loads are summarized below,

Table 4 Load Analysis for Small remote seasonal use cabin					
Qty	Appliance Characteristic			Total	
	Item	Per Device		Power watts	Energy kWh/Mo
		Power watts	Energy kWh/Mo		
1	Refrigerator/Freezer, 12 Cu Ft	575	143	575	143
1	Fluorescent Lights	250	37.5	250	37.5
1	Water heater	<i>Propane Gas unit</i>			0
1	Space heater	<i>Propane Gas unit</i>			0
1	Television	200	36	200	36

1	Radio	71	7	71	7
1	VCR	35	2	35	2
2	Ceiling fan	100	24	200	48
1	Well pump	750	72	750	72
1	Miscellaneous (outlets)	500	67	300	35
		Totals		2,331	381

Our cabin will have the potential to *demand* 2,331 watts of power from the electric system at any given time. Based on the expected usage patterns, the *energy* consumption should average about 381 kWh per month. It is important to understand the difference between *demand* and *energy*. Demand is the instantaneous need for power and is the sum of all electrical loads operating at any given time. Energy is the power consumed by loads over a period of time. The maximum demand will likely not occur in every hour - but it could – so the system must be able to supply adequate power for this anticipated demand.

Before going any further we need to consider the electrical losses that are likely to be present in the system. A standard photovoltaic module's output is generally rated at +/-5% of the nameplate rating, so to be safe we need to assume that the rating is only 95% of the nameplate rating. The nameplate rating must be reduced for increased temperatures that the unit may experience. A typical value is 89% of nameplate to account for the effects of increased temperature. As a unit ages, dust and dirt on the panel will degrade performance to about 93% of nameplate. Module mismatch and wiring losses will also decrease the output of a solar panel and a multiplier of 95% is generally used to account for wiring losses. The inverter to convert the output of the solar panel from DC to AC will add another loss factor of about 10% so the nameplate is again reduced to 90% of its nominal value. Summarizing the losses,

Panel variance 95%
 Temperature 89%
 Contamination 93%
 Wiring losses 95%
 Inverter losses 90%

The system *loss factor* is the product of all the potential losses in the system,

$$\text{Loss Factor} = 0.95 * 0.89 * 0.93 * 0.95 * 0.90 = 0.67$$

Therefore, only about 67% of a solar panel's capacity is available to serve load and the panels must be oversized accordingly.

In our example, the energy consumption is 381 kWh/month. To convert this monthly value to a daily value we need to multiply the energy consumption by 1,000 and divide by 30 days,

$$\text{Daily load} = 381 * 1,000 / 30 = 12,700 \text{ Wh/day.}$$

To size the solar panels, we must account for losses,

$$\text{Compensated daily load} = 12,700 / 0.67 = 18,955 \text{ Wh/day.}$$

Therefore, the system must be sized for a daily energy consumption of 18,955 Wh/day.

From Table 2 we see the average daily solar radiation in the summer in Atlanta, GA is 6.1 kWh/m²/day if the panels are tilted at the latitude minus 15 degrees. The number of solar panels needed is,

$$\text{Panel Requirements} = 18,955 / (6.1 * 1,000) = 3.1 \text{ m}^2.$$

This site needs 3.1 m² of solar panels to meet the energy needs presented. Panasonic makes a 325-watt solar panel which has 1.67 m² of area, so the total number of panels needed is,

$$\text{Panels} = 3.1 / 1.67 = 1.85, \text{ or } 2 \text{ panels.}$$

Based on this analysis, two 325-watt panels will meet the *energy* needs of the site, but this will not be adequate for the peak demands of the site. The peak demand may be met using either batteries or extra panels to meet the required demand of 2,331 watts (see Table 2). To meet this demand will require,

$$\text{Capacity} = 2,331/325 = 7.17 \text{ panels, or } 8 \text{ panels.}$$

Instead of using more panels, batteries can be used to meet the peak power requirements of the cabin. Let's look at how to size batteries to supply the peak load.

Remember that the daily load is 12,700 Wh/day which is 529 WH/hour. If 24-volt batteries are used the battery load is,

$$\text{Battery load} = 529 \text{ Wh/h} / 24 \text{ v} = 22 \text{ Amp-hours per hour.}$$

For the cabin we will need at least 22 AH/hour of battery capacity and we should plan on having 48 hours of battery capacity to account for cloudy days. Since it is not wise to completely

discharge the batteries, we should plan on an addition 20% of capacity as a reserve. The battery capacity requirement is then,

$$\text{Battery capacity} = 22 * 48 / 0.8 = 1,320 \text{ AH.}$$

Using 24-volt, 100 AH batteries, the system will need about 13 batteries to provide adequate capacity. Of course, the battery charge controller will need to be sized to service 13-100AH, 24-volt batteries.

The inverter will need to be able to supply the maximum instantaneous load plus a 15% margin. The inverter size should be,

$$\text{Inverter} = 2,331 / 0.15 = 2,742 \text{ watts.}$$

A solar system of this size - including solar panels, batteries, and inverter - will cost (2019 dollars) about \$4.00 per solar watt or \$7,000. This is certainly not cheap, but if the cabin is a mile from the existing power grid it may cost over \$50,000 to extend power lines to the site.

This example is for a small, isolated cabin. Most solar installations operate in parallel with the electric grid and these *grid-interactive systems* are usually designed to just meet the energy consumption needs of the facility and depend on the utility to supply the capacity needs.

Metering

Practically all utilities allow grid-interactive photovoltaic system interconnections and will purchase the excess solar power that is supplied into the grid. The utility will purchase the power using a net billing or a net metering arrangement. See Figure 14 for a graphical view of net billing and net metering.

With a *net billing* arrangement, there are two meters, or two-meter registers in one meter, where one-meter measures the power that is purchased by the customer and the other meter measures the power that is sold by the customer to the utility. See Figure 14.

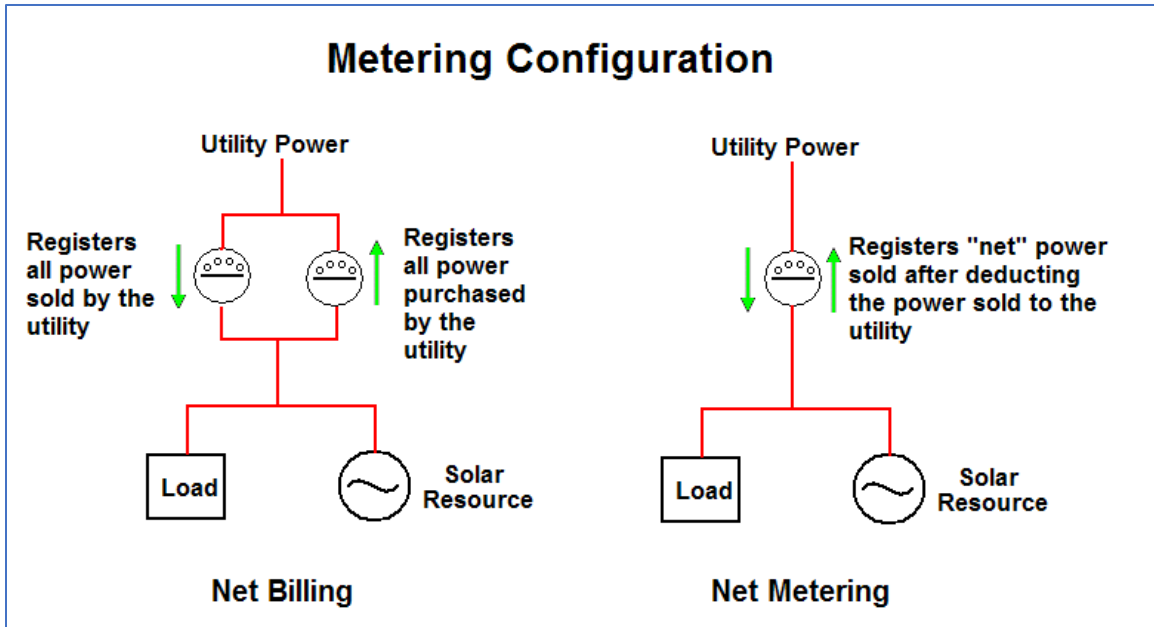


Figure 14

A utility’s cost structure includes capital costs for generators, transmission lines, distribution lines, and service lines as well as variable costs such as fuel, and other operating expenses. By using net billing, the utility recovers its fixed costs through the purchased power meter whereas the second meter gives the customer credit for the costs that he offsets, which is the variable costs such as fuel.

With the *net metering* arrangement, the customer can run the meter backwards when supplying power to the grid which means the customer only pays the utility for the “net” amount of power used. From a customers’ prospective, net metering allows the customer to “bank” excess solar generation for later use. However net metering unfairly shifts costs to other customers since the utility’s fixed capital costs must still be recovered. Nevertheless, many utilities are offering net metering arrangements as a social benefit to encourage the development of renewables.

Standards and Codes

The National Electric Code (NEC®), the Underwriters Laboratory (UL), and the Institute for Electrical and Electronic Engineers (IEEE) all have standards or codes that are applicable to photovoltaic systems.

The purpose of the NEC® is to ensure electrical equipment is installed and operated in a manner that will protect the public and not create a fire hazard. Article 690 of the NEC® covers photovoltaic systems and provides direction on how a system should be installed. It covers disconnect means, wiring, overcurrent protection, markings, and approved equipment. In addition to Article 690 of the Code, there are several other sections that are relevant to

photovoltaic systems. These include Article 230 - Disconnect means, Article 240 - Overcurrent protection, Article 250 - Grounding, and Article 300 – Wiring methods.

UL 1741, “Standard for Safety Inverters, Converters, and Controllers for Use in Independent Power Systems” is a standard that addresses charge controllers and inverters. Most jurisdictions will require that equipment be “listed” per the NEC® and UL 1741 compliant devices are considered as listed devices.

Each electric utility is free to determine its own interconnection requirements, but many State Public Utility Commissions require their jurisdictional utilities to comply with IEEE 1547, “Standard for Interconnecting Distribution Resources with Electric Power Systems”. IEEE 1547 lists the requirements for interconnecting a photovoltaic system to the utility. The purpose of IEEE 1547 is to ensure that the photovoltaic system does not interfere with the proper operation of the electric power system. Recent changes to IEEE 1547 allow for photovoltaic systems to ride-through system disturbances and to operate in a stand-alone or “islanded” mode.

Summary

Photovoltaic systems are not cheap. Even small systems are expensive. The price of photovoltaic systems has fallen dramatically in the past thirty years and as more units enter the mainstream energy markets, prices should continue to fall. These systems are already being widely used in certain high-cost markets.

The balance-of-system equipment associated with solar cells is increasing in sophistication and capability. With the technology available today, photovoltaic power systems can generate power that is equal to, and sometime, better, than the local power company can supply.

Photovoltaic power systems are just one of technologies that can be used to reduce the demand for coal and natural gas fired power plants. Along with other renewable power production technologies such as wind farms, geothermal, hydroelectric, and biomass systems, it has the potential to reduce to help reduce carbon emissions in this country.

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