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A SunCam online continuing education course

Introduction to Solar Power Design for Small Structures 3rd Edition

by

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COURSE DESCRIPTION

The use of the sun's energy is nothing new and dates back to the beginning of time. In recent years, however, the focus on energy consumption worldwide has rapidly spurred growth in the research and development of "Green" alternative fuel sources including the sun, wind, hydro, wave, tidal, geothermal, hydrogen, and other forms. And today, because of that focus, the use of solar energy continues to expand exponentially… especially since sunlight remains free, unlimited, readily available, clean, reliable (still no reported failures to date), and "Green". A ***green*** sun, what a concept!

A small solar powered building

There are state and federal incentives available (see the Inflation Reduction Act of 2022) for residential and commercial solar PV (Photo Voltaic) and energy storage installations. Many power companies provide local net metering incentives for solar water heaters and solar electricity. These incentives, combined with the rising cost of electricity, brown-outs, and the huge demand of electrical power for data centers and EV charging, have prompted many owners to invest in solar systems even if they are located in urban areas. Frank Shuman (an engineer ahead of his time) stated in the early 1900s, that solar power, "... is the most rational source of power."

Part of a massive solar PV farm in Israel

Practically speaking, solar powered systems were originally developed as an energy source for satellites and the International Space Station... but what about today? How does one produce a design that is not only efficient, but practical for a small structure? In this course, we will look at common terminology, explanations of the system components and how they interact, designs using 12-volt, 24-volt, and 48-volt systems with the pros and cons of each, wiring considerations, emergency backups, realistic costs, expectations of performance, and the math… but no differential equations are involved, I promise.

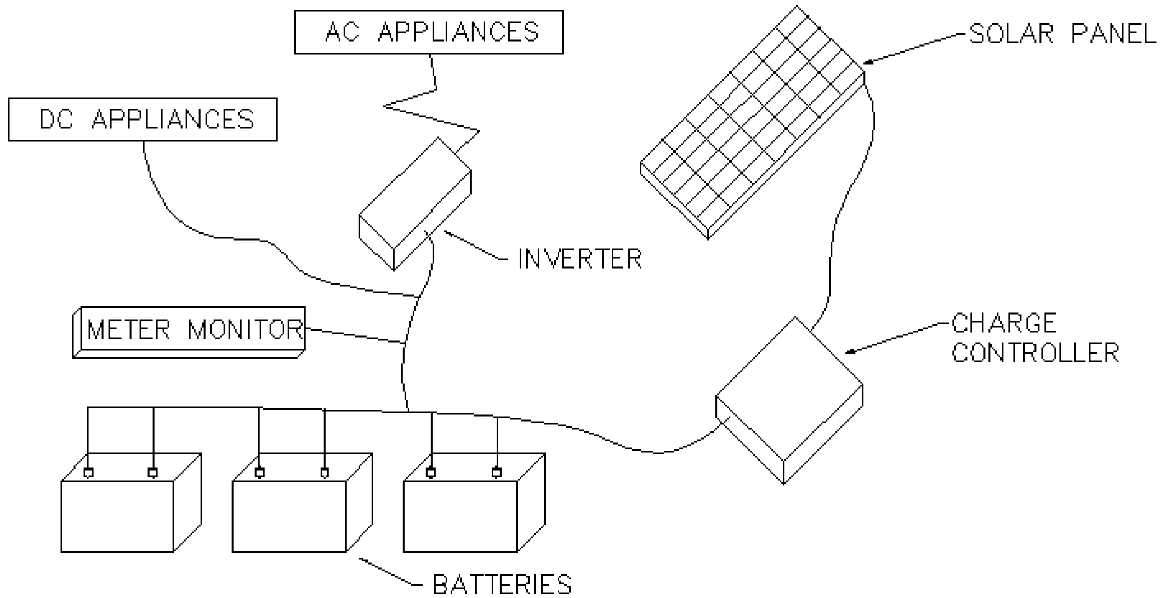
We will start “at the beginning” and then progress through the sequence of components… from the solar panels to the actual electrical appliances and the design involved in each of these components. This course is not intended to be all-inclusive in the design and installation of a solar electrical system, but it is intended to provide you with knowledge of how a basic PV system works, the components that make up the system, and the considerations involved in a solar PV system for a small structure. Obviously, these same principles apply to a system for a larger structure, but there are many more issues involved with larger PV systems. This is the first of five courses, and the four additional courses will delve into the installation, inspection, evaluation, and troubleshooting of systems for small structures.

Please realize that all costs mentioned in this course are subject to wild deviations due to the current worldwide tariffs and trade policies. So, that said… let's get started…

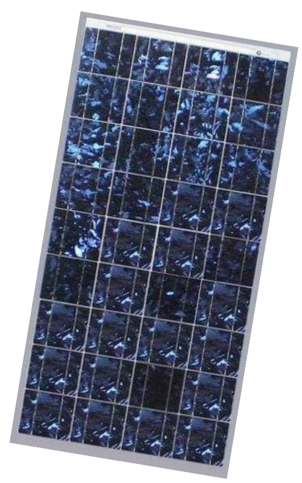
THE BASICS

A typical solar system is comprised of solar panels (a.k.a. photovoltaic or PV panels), a charge controller, batteries, a power inverter, a monitor meter, and the electrical distribution system (or the electrical wiring). Like many technologies, there are a multitude of manufacturers for each component offering different levels of quality, features, and of course… price. We will look at some of the different products as we design a simple solar system for a small structure in this course. There are also newer technologies available such as PERC cells, half-cut cells, bifacial panels, and others currently being developed which provide higher efficiency and improved performance in specific conditions, but this course will focus on the more common panels using monocrystalline, polycrystalline, and amorphous panels. Consequently, there has been about a 70% cost reduction since 2010.

Solar powered Rest Area in Michigan



SYSTEM COMPONENTS



A polycrystalline panel

Solar Panel – A manufactured photovoltaic panel is comprised of silicon crystals that are used to convert the sun's rays into electricity. They provide the electricity for charging batteries and/or for use by the appliances either directly or through an inverter. Multiple panels are used to produce more electricity than is consumed and then any excess energy that is produced may be stored in batteries for nighttime and cloudy/rainy weather use. The panels are available in different sizes, voltages, and amperages. They can be wired in series, in parallel, or both... depending on how the system is designed.

Charge Controller – The charge controller is the brains of the system. It monitors the electricity produced by the solar panels and then regulates the electricity to charge the batteries and prevent them from becoming overcharged. Proper charging is critical to prevent any damage to a battery and thereby increasing the battery's life and performance. Different technologies have replaced PWM (Pulse Width Modulation) controllers with MPPT (Maximum Power Point Tracking) charge controllers, and many are included with IoT (Internet of Things) capabilities for monitoring battery voltage, current, and panel status using a cloud platform or mobile app.

Batteries – The batteries are required to store the excess electrical power from the solar panels for later use. Without the batteries, you would only have power when the sun was shining. Additionally, the power would be interrupted each time a cloud passed overhead… which could become very frustrating very quickly. We all have become accustomed to, and even expect, a constant reliable source of electricity and so have our appliances. The batteries are available in different voltages and varying amp-hour ratings depending on the requirements of the system. Except for very small applications, lithium-ion technologies (LiFePO) batteries are being used due to their reduced maintenance, increased energy, long life cycle, and lower weight.

Inverter – The inverter converts the DC volts produced by the solar panels (or from the energy stored in the batteries) into AC volts. The inverter can also be used to charge the batteries by connecting to it a backup generator or an AC electrical source. Choosing the right inverter for the demand and power requirements of the system is critical for the components to function properly. Newer technologies have been introduced in the form of microinverters, hybrid inverters, and power optimizers depending on the setup and preferences. Because of current electronic device demands, the inverter **MUST** convert power to Pure Sine Wave AC.

Monitor meter – A monitor meter is used to monitor the condition of the batteries, the power being generated by the solar panels, and the user's current consumption rate. The various monitors available in the market today can provide detailed information on the system status. They can provide you with the information you need to protect the batteries, help you locate the source of any system problems when they occur, and allow you to reduce a generator's use by knowing when to shut it off (basically… when the batteries are approaching a full charge). As mentioned previously, many are using the IoT charge controllers to monitor their systems versus using a standalone fixed monitor box.

Generator – A gas powered generator is a good economical insurance policy to keep the batteries charged during those extended rainy/cloudy periods that can go on for days. Or it can provide the additional power needed for those temporary high-power demands. Without sunlight, a generator is the only thing that will keep the electricity available for your modern conveniences… unless you also happen to be connected to a power company's AC lines for backup during such times (commonly referred to as being "on-grid"). Additionally, the generator should output Pure Sine AC power. Generators are available for diesel, gas, and propane fuels.

On-Grid / Off-Grid / Grid-tie – These are terms used to identify whether a user is connected to a utility company providing AC power. An off-grid system would be a structure not connected to any external electrical service (normally provided by a power company). A grid-tie system means that you can use solar energy when it's available, and when that source is not available, it can have the system automatically switch to the on-grid electricity from a power company. In some cases, the power company will even buy back any extra electricity you have generated throughout the day. You can check your local regulations or with the power company for their policies and requirements.

SOLAR SYSTEM SIZING

Let's begin with your first two mistakes… "Huh, what? I haven't even started", you say? Well, you think you're designing a solar system, right? That's your first mistake. "Huh, isn't this supposed to be a course on solar design?" Yes, but thinking you're designing a solar system will get you into trouble. The correct answer is that you're designing a battery system. I'll explain why after your second mistake….

Your second mistake is skipping the first step. The first step has nothing to do with the system sizing yet everything to do with the system sizing. Yet omitting this step will cause you a lot of headaches, grief, and unhappy people. "So, what is this first step, you ask?" It is to consider the end user… for it is the end user who will ultimately be using the system on a regular basis. How well is this system going to function for them?

Now… to answer your first two whys...

So why am I designing a battery system? We live in an age of a seemingly endless supply of electricity for our modern conveniences… air conditioning, computers, stereos, lights, etc. Just think back to your last power outage and you'll remember the anguish of not having these conveniences available… when you wanted them. However, in a solar powered system, you do have an unlimited source of free energy… but it's available only for a limited amount of time each day. Once the sun sets, your supply ends. If it's cloudy or rainy, your solar generation is drastically reduced. The electricity you need is available only while you have sunlight or… enough energy stored in your batteries. Once the sun sets and your batteries are depleted, you have no electricity and then... Black-out!

So why must you consider the end user? Since the end user will likely not be you or an engineer, you must consider the way they will use electricity. They or their visitors may not be aware that there is a limited supply of energy for their use, or if they are aware, they may not understand the impact on the system when they add a new appliance or leave the air conditioner or heater running all night when they're not even in the building.

When you design a solar system, you must account for <u>every</u> demand the end user has for power. Every light bulb, radio, fan, air conditioner, computer, toaster, whatever…. Otherwise, the system will be expensively oversized or it will experience brown-outs or black-outs because it's undersized. While I've never seen one, you might want to consider posting a sign at the building entrance stating "You are entering a battery powered building. Please conserve our electricity." To the public, solar-powered implies "free & unlimited" while battery-powered implies "limited" … like a flashlight. The light is limited to the battery duration. For most small structures, a limited power supply is what you really have.

You are entering a
BATTERY POWERED
building. Please conserve
our electricity.

Step 1: Know your end users. Know what they will be using and how they will be using the electricity in the structure... now *and* in the future. Not knowing this information is setting your system up for failure, then unhappy clients, and then a bad reputation for you.

Step 2: For the reasons previously stated, you must quantify EVERY item that will require power. You will need to know the wattage of each appliance and the hours it will be used each day. This will provide you with the amp-hours you will use for the design.

Example project:

Appliance	Quantity		Watts		Hrs/day		Watt-Hrs
Lights	4	*	15	*	10	=	600
Lights	2	*	15	*	4	=	120
Ceiling Fans	2		19		6		228
Clock radio	1		5		8		40
Laptop cmptr	1		45		8		360
42" Television	1		80		6		480
Misc loads	?		?		?		5,172
							7,000 watt-hrs/day

You will continue this appliance list for every item you expect to be used and then provide an additional buffer based on your best estimate of the end users. People will ***ALWAYS*** use more electricity than they expect. Perhaps add a 20-25% addition for those "surprise" appliances that someone starts using… like a power table saw.

Again, consider the end user, the ones who will be in the building. For a small 4,000-watt-hr system, someone turning on a toaster oven for an hour that is rated at 1,500 watts that you have not accounted for has just used 37% of your precious power. Doing the same thing on a 10,000-watt-hr system has only impacted your system minimally. So your buffer needs to be tempered by your system size.

A rural home with a solar water heater and solar PV panel in Fiji

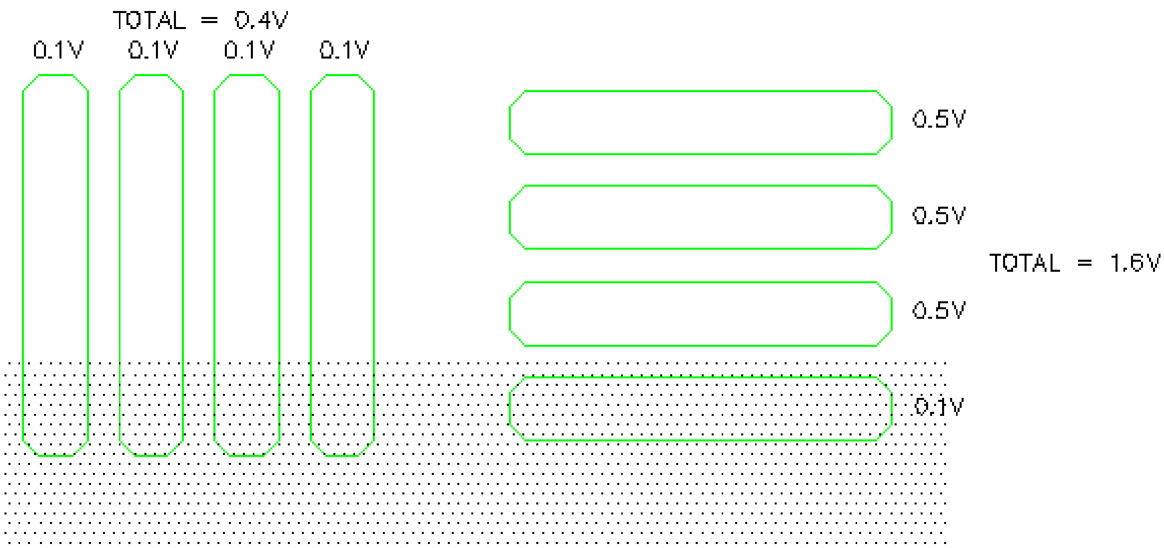
DISCUSSION ON SOLAR PANELS

Solar photovoltaic panels generate their sun power by converting sunlight into electricity and, amazingly, doing so with no moving parts, no harmful emissions, and virtually no maintenance. Most solar panels today are made up of many individual silicon cells manufactured into a single frame. As sunlight strikes the surface of the silicon cell, a small electrical current is produced. Each individual cell will produce almost 0.5 volts. A typical 12-volt solar panel will contain 36 cells wired in series to produce about 17 volts. A 24-volt solar panel is basically two 12-volt panels wired in series, so there are a total of 72 cells needed to produce the 24-volt panel.

Solar panel arrays are wired in parallel to increase the current capacity (or how much power will be available for use). The more panels, the more appliances you can use simultaneously. They will also be wired in series to increase the voltage… to 24, 48, or even higher voltage levels. The primary reason for using a higher voltage system is that smaller wire sizes can be used from the solar panels to the charge controller and to the batteries. With the high cost of copper these days, this can be a substantial cost savings… especially if the distance from the solar panels to the charge controller and to the batteries is significant.

Solar panels will vary in length and width depending on the manufacturer, but most are about 1 to 2 inches thick. And they can weigh up to 40-50 pounds or more, so the larger ones (up to 5' x 3') can be difficult to work with if mounting on a pole or on a roof. Framed solar panels are the industry standard, the most economical, and work great for most small structures.

An analysis of the type of shading where the panels are to be placed can make a big difference in the electrical output of the solar panel due to any partial shading of the panel. If the shading typically progresses vertically (from the ground upwards), then the panels should be mounted horizontally. However, if the shading typically progresses horizontally (from side to side), then place the panels vertically. The reason for this is the manner in which the panels are made. Since the crystals are generally long and narrow, partial shading of the fewest number of cells will allow the panel to perform at a higher output.

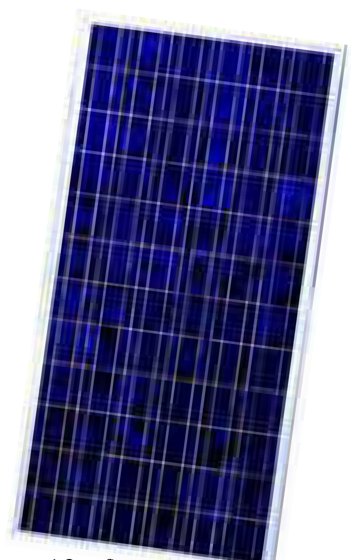


As you can see from the figure above, both have 4 individual cells with the same area of shading occurring horizontally on both, but the voltage output will differ significantly. If the shading were vertical (like would be present from the shadow cast by a pole), the results would reverse. Even partial shading will drastically reduce the power output by the cells impacted.

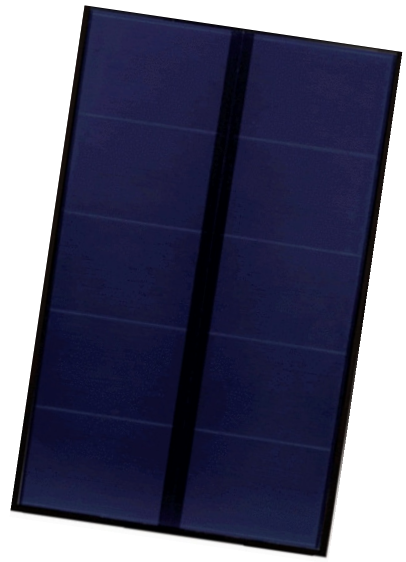
STC Ratings – Solar panels are rated under Standard Test Conditions (STC) by the manufacturers at 1000 watts per square meter of solar irradiance at 25° C. If the temperature is different than 25°C (77°F) or the sunlight intensity is different, then your panel will perform differently than the specifications stated.

Monocrystalline solar panels remain the most efficient panels and, therefore, the most expensive… with the most expensive being the PERC monocrystalline. These standard monocrystalline solar cells are made from very pure silicon and are manufactured through a complicated crystal growth process. The process involves growing silicon rods that are then cut into very thin slices, each one being approximately 0.2 to 0.4 mm thick. These slices are then manufactured into individual solar cells that are wired together to form a single solar panel. The advantage of *monocrystalline* panels is that because of their higher efficiency, they require less installation area for the same output.

Without getting too technical, the newer PERC (Passivated Emitter and Rear Contact) panels add an additional layer to the back side of the panel. This layer reflects unused light back into the solar panel to capture even more energy. These PERC cells are as thin as 0.15–0.18 mm which reduces material waste by 40% while being up to 12% more efficient than the standard panels. This increased efficiency further reduces the number of solar panels required for installation, reduces the total required area for power generation, and reduces the quantity of wiring and racks required. The PERC cells also reduce the energy losses due to excessive solar heating of the panels. Though the PERC cells are more efficient, they are more expensive than the conventional PV cells but could eventually pay for themselves over time. Incredibly, the PERC panels have a 30+ year lifespan with less than 0.5% annual degradation.



Polycrystalline solar panels (or *Multi-crystalline* solar panels) are made with *polycrystalline* cells which are less expensive, yet only slightly less efficient than are the *monocrystalline* cells. This is because the cells are not grown in a single crystal form but rather in a large block containing many of the crystals. Looking at them, they resemble a cracked plate glass (safety glass) door. Just like the *monocrystalline* cells, they are also cut into thin slices to produce the individual cells that make up the solar panel. These panels are still used today because they deliver only slightly less efficiency than the *monocrystalline* panels but at a more moderate price. Due to advances in monocrystalline technology and falling costs, polycrystalline modules are not normally used in new residential installations.



Amorphous solar panels are very different from the *monocrystalline* or *polycrystalline* cells because they're not really crystals. Instead, they are made from a thin layer of silicon deposited on a sheet such as metal or glass to create the solar panel. While the *amorphous* solar panels are much cheaper, they produce much less energy. The end result is that many more panels are required to produce the same amount of power than would be required by using *monocrystalline* or *polycrystalline* solar panels. However, one advantage of *amorphous* solar panels is that they can be made into long sheets of "roofing" material and can cover large areas of a roof. So, if you have a large area available for your panels, using *amorphous* solar panels can save you a considerable sum of cash.

Another negative associated with the use of amorphous solar panels is their shorter lifespan as compared to the monocrystalline or polycrystalline panels. However, they have an advantage in that the modules are far less sensitive to partial shading (as compared to monocrystalline or polycrystalline panels) so that in those areas where partial shading is unavoidable, they are worth considering since they can still produce a significant amount of power under those conditions.

Building-Integrated Photovoltaics (BIPV), sometimes referred to as Solar Roof Tiles or Solar Shingles, are designed to blend seamlessly into a building's architecture by acting as both the roofing material and the solar PV panels. Instead of mounting panels on top of an existing or new roof, these integrated tiles replace conventional shingles, providing a conventional low-profile appearance that are attractive to homeowners and homeowner associations concerned with architectural aesthetics. Modern BIPV tiles are made from durable materials and are engineered to withstand harsh weather conditions. As of 2025, advances in efficiency and manufacturing processes have made BIPV more available, with many new homes and re-roofing projects choosing these tiles.

Transparent Solar Panels are another new emerging technology that allows windows, skylights, and facades to generate electricity without blocking natural light or views.

These panels use advanced materials such as **transparent luminescent solar concentrators (TLSCs**) or **semi-transparent perovskite cells** to selectively absorb ultraviolet and infrared light while letting visible light pass through. Unfortunately, their current efficiency is lower than traditional PV panels (around 10%). A transparent PV is ideal for building applications concerned with aesthetics and daylighting. As this technology improves, transparent solar panels are expected to have a bigger impact on the buildings of tomorrow.

Considerations

Shadows, as we just stated, are a solar panel's enemy. Whether the shadows are cast by another building, terrain, vegetation, a piece of trash, or a leaf that has blown onto the panel, if the sunlight can't reach the solar panels, the system will either not produce electricity or will seriously reduce its output. Therefore, it is critical to minimize or eliminate any shadows that can impact the solar panel array… especially during ***peak*** sunlight hours (10am to 3pm). Not only will shading of the solar panels significantly reduce their output, but it could also damage them because of differential heating. So, avoid any rooftop vent stacks, antennas, satellite dishes, and chimneys—even small shadows can dramatically drop your solar panel's output. Shading is especially detrimental during the peak solar generation hours of 10 am to 3 pm. Some solar panel manufacturers will advertise that their panels can withstand shading, but many do so by using internal diodes which will also reduce the power generation slightly. Alternatively, you can use PERC panels or Half-cut panels to improve performance. As you can see, site selection is a very critical aspect in choosing the solar panel array location. You may need to change the location or trim/cut a few trees. However, trimming is only a temporary solution requiring regular maintenance because the trees will grow back.

Half-cut panels are often used to increase light capture and reduce the losses from shadows. Each cell produces approximately 0.5–0.6 volts, with current 24V modules typically featuring 60–72 cells wired in series to deliver a maximum power voltage (Vmp) of 30–38V, far exceeding nominal ratings for compatibility with some MPPT charge controllers. For example, a 24V panel may use 144 half-cut cells arranged in two parallel strings of 72 cells each, balancing voltage and current for higher yields in partial shade. This technology allows smaller and lighter panels to exceed the performance of older 12V/24V designs yet still comply with NEC 2023 rapid shutdown requirements.

Temperature is another issue that must be addressed. Solar panel efficiency decreases as temperature increases. So, the solar panels should be mounted in such a way as to allow for air flow around the individual solar panels to help with the panel's cooling. Again, you can use PERC, Half-cut, or micro-inverter panels to help minimize the panel temperatures due to their slightly increased efficiency.

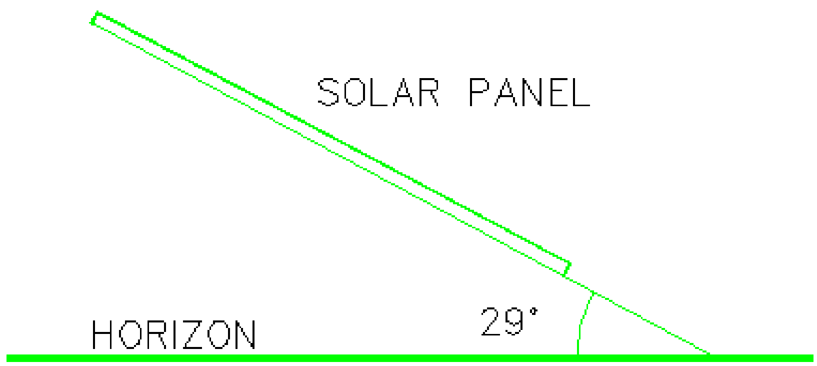
Wind is yet another issue that needs to be considered. Wind can aid in cooling the panels in the hot sun but too much wind… i.e. hurricanes, gales… can damage the panels with flying debris or actually ripping the panels from their mounts. Check the local codes to determine the requirements for securing solar panels to a building or a pole. Some building departments are also concerned about the panels causing damage to adjacent structures should the panels become separated from their mounts. Check the local building codes for the proper installation methods and mounting equipment to ensure panel safety, structural integrity, and protection against wind-induced damage to adjacent properties and structures.

Access to the panels must also be evaluated when considering where to install the solar panels. To maintain peak performance from the system, the panels will need to be checked on a regular basis. That inspection interval will vary from location to location because of site specific conditions. Are birds nesting in your panel array causing their nesting materials to shade portions of the solar panels? Are squirrels disturbing the electrical wiring of any of the panels? Have leaves adhered to the panels during the last rainfall event? Has a fungus started growing on the face of the panel? Plus any number of additional site issues will create the need to regularly inspect the panels for proper condition and operation. Modern monitoring systems make it easy to track performance remotely, alerting you to drops in output that may signal a need for cleaning or repairs. Ultimately, providing easy access for safe inspection and cleaning will help promote regular inspections by the user and keep the solar system operating at its best for years to come.

SOLAR PANEL MOUNTS

Solar panels should ideally face true south in the U.S. to obtain ***optimum*** performance. Solar panels can face in other directions but their performance numbers will suffer. And there is a difference between true south and magnetic south, and the magnetic variation changes slightly over time… which is why airports must also change their runway numbers. In some areas this can make a significant difference in alignment and in the power produced. Check the magnetic variation for the installation's location for proper alignment of the panels. Obviously, this is not as critical for tracking mounts as it is for fixed mounts.

The proper angle of inclination is another consideration to obtain maximum panel output. As a rule of thumb, the solar panel's angle of inclination (tilt) should be set equal to the installation's latitude. If your installation is at latitude 29 degrees North, then set the solar panels at 29 degrees of inclination. However, recent Department of Energy guidance suggests that slightly flatter angles-typically 3–5 degrees less than your latitude-can improve annual output in regions with frequent cloud cover or high summer sun. Online tools such as the NOAA Solar Calculator or PVWatts can help you calculate the optimal angle for your specific location, taking into account local conditions, roof pitch, and shading issues.



ANGLE OF INCLINATION

A practical schedule would be setting your panels equal to your latitude during Spring and Fall (around March and September). In Summer, reducing the angle by approximately 10 degrees less than latitude (for example, 19 degrees at latitude 29) improves production, while increasing the tilt angle by about 10 degrees above your latitude during the Winter months (around December) improves energy capture when the sun is lower in the sky. With these minor seasonal adjustments, the solar panel's maximal efficiency can be achieved throughout the year. Again, the ease of access to the panels will be a critical factor in making the decision to implement these seasonal adjustments.

Fixed solar panel mounts remain the simplest and least expensive way to mount solar panels. Typically, they will be attached to a building's roof which is convenient if the roof pitch is appropriate. Or the panels may be ground mounted on posts, frames, and supports. However, ground mounted panels are more susceptible to shading issues and impact damage. The biggest negative for both types of mounting is that a fixed mount will not allow adjustments for seasonal changes.

Adjustable solar panel mounts allow you to seasonally adjust the angle of inclination (tilt). For adjustable mounts, the angles are typically adjusted 4 times during the year to account for the seasonal angles of the sun. The rule of thumb is to increase your angle of inclination by 10 degrees in the winter and reduce it by 10 degrees in the summer. These mounts can increase the overall solar panel output by as much as 25% as compared to fixed mounts… which is sufficient to warrant an evaluation of the cost of adjustable mounts.

Tracking solar panel mounts allow the solar panels to track the path of the sun during the day which maximizes the direct solar light that the panels can receive. Two styles of trackers exist… a one-axis and a two-axis. A one-axis tracker will track the sun from east to west at a fixed angle of inclination. The two-axis tracker will track the sun's east to west movement as well as the seasonal declination movement of the sun. While a tracking type of solar panel mount is the most efficient type, they are considerably more expensive, require maintenance, and are subject to malfunctions. Many of the dual-axis trackers are advertised as providing up to 40-45 percent gain in output that the solar panels provide as compared to non-tracking mounts.

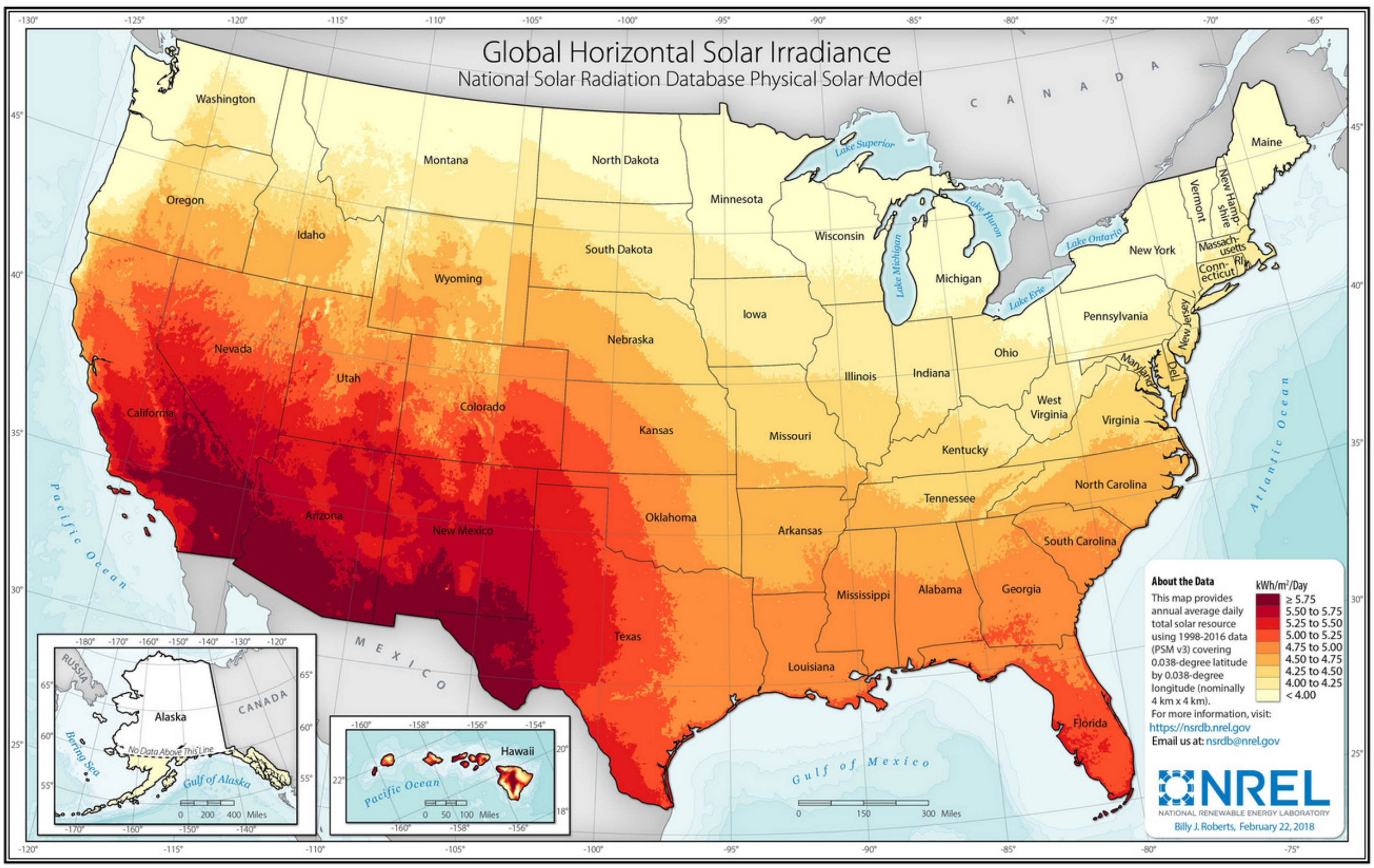
If space is available, an alternative to the tracking mounts is to consider purchasing additional panels instead. For the same cost of the tracker ($2,000-$3,000), purchasing additional panels will increase the power but with no mechanical failures to worry about. Even spending $2,000 on additional solar panels could buy at least 4 more panels and gain the system a year-round increase… provided you have the space to install them.

Costs – Since a solar system uses many solar panels and with the average cost of a panel being hundreds of dollars, the cost may seem to be expensive. However, when you factor in the energy savings over the lifespan of the panel (20-30 years) you begin to see the real cost savings. If a building's average electric bill is $200 per month and assuming the electric rates do not increase during the next 20 to 30 years (wishful thinking), you'd end up spending at least $48,000 to $72,000. That's a lot of solar panels! And by switching to the use of more efficient DC appliances and using them in exactly the same way as the AC appliances, the total energy used will decrease, which will provide an even greater savings in the purchase price. In 2010, the cost of solar panels was about $4-$5 per watt. By 2012, the cost had dropped to around $2-$3 per watt. So, in about 2 years, the cost of solar panels had dropped almost 50%. By 2022, the cost had dropped to around $0.30-$0.50 per watt. In 2025, the prices are in fluctuation due to competition, tariffs, trade issues, and technological improvements.

DISCUSSION ON SOLAR EXPOSURE

The yearly average of the approximate hours of daily sunshine in the Southeast U.S. is about 5 to 5.5 hours. The northern states average about 4 to 5 hours per day and the Southwest will see 5 to 6 hours per day. So, if you have an installation in the Southeast consisting of six 200-watt solar panels (in the 5.0-hour zone), you can figure 6 panels * 200 watts * 5 hours = 6,000 watt-hours per day or 6.0 Kilowatt-hours per day. Of course, this is an average, and you will get more power in the summer than in the winter and more on sunny days than on cloudy days. See the map below from the National Renewable Energy Laboratory Resource Assessment Program for the number of hours in your location or visit their website for more information at http://www.nrel.gov/gis/solar.html .

The solar exposure map is based on the average number of hours you can expect to receive the sun's rays for a particular location. The map does not take into account solar obstructions in the form of adjacent buildings, trees, terrain, signs, etc. When evaluating the placement of solar panels, check the location continuously from 9AM to 5PM for any shading that may occur during the day. Also, consider the changing inclination of the sun due to seasonal changes. Just because that tree doesn't cause problems in the summer, doesn't mean it won't be a problem in the winter months or vice versa.



Again, site selection is critical in determining your system design. Even if you live in sunny Florida, your particular site location may prevent you from having a viable solar system for the structure, or it may require a solar array 3 times the size of a better suited location. For example, if you have a tall building to the east of you and a line of trees to your west, your 5 hours of sunlight may now be reduced to only 3 hours. To put it another way, the number of solar panels required for 5 hours of sunlight may be 10 but the number required for 3 hours is 17. Consider that cost plus the additional area required for those 7 panels! So know your site and consider the options to improve your access to the sun's rays.

Step 3: Solar panel sizing is your next step. Let's calculate the number of panels you will need. Assuming our project is located in north Florida or south Georgia, we find we have 5-6 hours of sunlight available per day (see the map from the National Renewable Energy Laboratory Resource Assessment Program above). Knowing that our sample project needs 7,000 watt-hours and assuming that our site has 5 hours of sunlight available, we calculate that we need a supply of 800 watts per hour.

Watt-hrs / sunlight hrs avail = watts needed → 7,000 / 5 hrs = 1,400 watts

Now that we know our panel wattage requirements, we can start evaluating our solar panel options. Let's evaluate the following 200, 350, and 400 watt panels for our example project.

Watts req.		Panel watts		No. of Panels req.
1,400	/	200	=	7
1,400	/	350	=	4
1,400	/	400	=	3.5

It is generally better to stick with pairs of panels rather than an odd number of panels because of mounting and wiring simplicity… especially if you're working with panels in series to obtain higher voltages. We would not use 7 panels because we want them wired in pairs to provide 24 volts or 48 volts (I'll explain why later). Since any of these options work, we can select our panels based on the mounting area for the panels or on the price. For our calculations, we will use 4 of the 350-watt panels.

Step 4: Select solar system voltage. Selecting the most efficient voltage involves an evaluation of the distance from the panels to the charge controller and the costs of the voltage options available. Remember, increasing the voltage decreases the wire size required and that can be a significant cost savings in itself. For a 30-foot run with a 12-volt system versus a 24-volt system, the wire size changes from 2/0 AWG to 4 AWG. And 4 AWG wire would be much easier to work with and it's cheaper.

24-volt systems are the new standard for most small-to-medium installations, balancing cost, efficiency, and component availability. 48V Systems are gaining in popularity for larger systems (8kW+), with UL 1741-certified inverters and lithium batteries optimized for high-voltage efficiency.

Increasing the voltage to a 48-volt system will decrease the wire size even more but the selection of available 48-volt appliances is greatly reduced as well. If you need to use a 48-volt system and you use a lower voltage for the batteries, you may cause some unnecessary confusion as to which voltages are used where. In such cases, be very clear in your labeling of the various voltages. For small structures, it is best to choose a single voltage and use it throughout the system design for simplicity reasons… especially if the system is to be maintained by inexperienced people. Obviously, you could provide for a 48-volt design from the solar panels to the charge controller, then switch to 24 volts to the batteries, and then converting to 12 volts if needed for the appliances. But whoever is providing the system maintenance needs to understand where the different voltages occur. We will use a 24-volt system for our example.
For wire sizing, I recommend using NEC 2023 Table 310.16 for ampacity and use online calculators like WindyNation's DC Wire Sizer for precise voltage drop limits (≤2% panel-to-controller, ≤3% battery-to-load).

Step 5: Account for bad weather days. Now that we know our minimum system wattage requirements, we need to determine the number of days we need to provide electricity without sunlight since most places experience multiple days of clouds and rain. If you estimate you may have 3 days without sunlight, your battery bank must be capable of supplying 3 days of power without any recharge available from the solar panels. Since our example system is designed for 7,000 watt-hrs per day and you want to provide for 3 days of no-charging, your battery bank needs to be capable of providing 21,000 watt-hrs… or mathematically…

7,000 watt-hrs * 3 days = 21,000 watt-hrs

Or, if you need 5 days of backup, your battery bank needs to sized for 35,000 watt-hrs.

7,000 watt-hrs * 5 days = 35,000 watt-hrs

For our example project, we will use a 3-day backup which we just calculated as needing 21,000 watt-hrs.

Jumping to batteries… While the charge controller would be next in the normal wiring sequence of a solar powered system, we will jump to the batteries next. The reason is that we need to determine the most effective and efficient battery voltage before selecting our charge controller. Once we complete the battery design, we will return to the charge controllers.

DISCUSSION ON BATTERIES

Batteries provide the power for those times when there is no sunlight for the solar panels to function… whether it is nighttime or cloudy. RV or Marine type batteries are really not suitable for solar systems and should not be used. The reason is they really do not have the capacity for continuous service with many charge and discharge cycles. Car batteries (lead-acid) are the worst and should not be used at all because they cannot be safely discharged much more than 50% without causing internal damage. That said, some owners use them because they are cheap and readily available... but they must replace them frequently.

By contrast, the deep-cycle batteries used in solar systems are designed to be discharged by up to 50-80 percent. For all batteries, the expected battery lifetime depends on the charge and discharge cycles. The deeper the battery is discharged and the more frequently the battery is discharged the shorter the lifetime of the battery. Typically, 12 Volt batteries are generally preferred for off-grid systems though 4 or 6-volt solar batteries will work fine. They will simply require 2 or 3 times as many as the 12-volt batteries.

Flooded lead-acid batteries have the longest track record in solar electric use and are still used in small solar powered systems. Flooded type batteries are lead acid batteries that have removable caps to add water. However, the big negative with them is that they require regular maintenance in the form of maintaining proper water levels, equalizing charges, and keeping their caps and terminals clean. If the required maintenance is not going to be willingly provided by the end user, do not recommend a flooded lead-acid battery.

Many manufacturers make these types of batteries for solar energy use. Additional special care is required because flooded batteries release hydrogen gas when charging and should not be used indoors. If they are installed in an enclosure, a ventilation system must be used to vent out the gases which can be explosive. Always keep any batteries stored outdoors under lock and key or they will have a tendency to disappear. A flooded 12-volt 130 amp-hr battery will run about $200.

Sealed Gel type batteries are lead-acid batteries but are often recommended because they have no vents and will not release gas during the charging process like flooded batteries. And because they don't require venting, they can be used indoors. This provides two big advantages, which are 1) it allows the batteries to maintain a more constant temperature which helps them perform better and 2) because they're indoors, they are more secure. A sealed 12-volt 100 amp-hr battery will run about $230.

Absorbed Glass Mat (AGM) batteries are also lead-acid batteries but are somewhat better for solar power use and are only slightly more expensive than Sealed Gel batteries. They are manufactured with a woven glass mat between the plates to hold the electrolyte. They are leak proof, spill proof, and do not give off gases when charging. Basically, they have all the advantages of the sealed gel types plus they are of higher quality, maintain voltage better, and self discharge slower. An AGM 12-volt 105 amp-hr battery will run about $260.

Lithium-ion (LiFePO) are your "go-to" batteries of choice for solar PV systems. They are more expensive than the AGM batteries but are leak proof, spill proof, and do not give off gases when charging. What makes them particularly popular is that they can be discharged to as low as 0-10% without damage! This certainly beats the 50% limits placed on lead acid batteries! These lithium batteries are readily available in 12-volt, 24-volt, and 48-volt and will cost run between $400-5,000 depending on the manufacturer, amperage, and their specifications. However, **do not** mix brands or ages of the lithium batteries due to their specific design constraints. All lithium batteries are not the same and will not charge/discharge at the same rate in use.

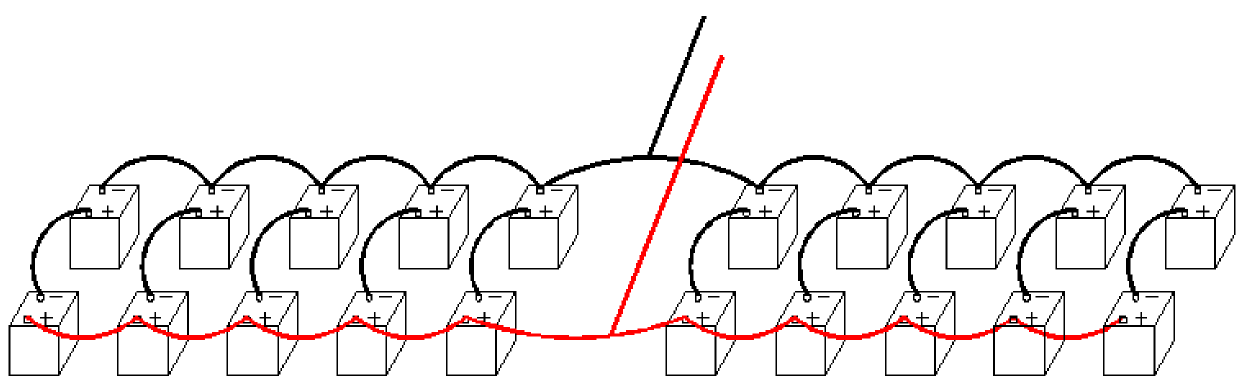
Step 6: Determine the battery bank size. Since you want to avoid damaging these expensive batteries, you never want to reduce your lead acid battery charge below 50% of their capacity. Some believe you shouldn't reduce their charge below 80% to extend their useful lifespan. However, in our example design, we will use lithium batteries with a usable depth of discharge of 90% and therefore we need to increase the watt-hrs from 21,000 to 23,333. Using 21,000 watt-hrs, we determine the required amp-hrs:

Efficiency Factor: 21,000 watt-hrs / 90% = **23,333 watt-hrs**

Using P = E * I we solve as: P / E = I

Battery Load: 23,333 watt-hrs / 12 v = **1,944 amp-hrs**

Using 100 amp-hr 12-volt lithium batteries, you will need 1,944 / 100 = 19.4 batteries. Since the batteries are being wired in pairs to provide 24 volts, you will need to specify 20 batteries. Two of these batteries would be connected *in series to make the 24-volts* that are being used in the system and *in parallel to provide the total power needed*. So, they would be wired as 10 banks of 2 batteries as shown below.



12V BATTERIES WIRED FOR 24V
SERIES & PARALLEL WIRING

DISCUSSION ON CHARGE CONTOLLERS

A charge controller is necessary to safely charge the batteries. The more direct the sunlight becomes, the more voltage the solar cells will produce and that excessive voltage could easily damage the batteries. Controllers can also include such options as blocking reverse current, preventing battery overcharge, preventing battery over-discharge, protecting from electrical overloads, and displaying the battery status and power rates. Basically, a charge controller is used to maintain the proper charging voltage on the batteries. Simply stated, as the input voltage from the solar panels increases, the charge controller adjusts the charge to the batteries to prevent any over-charging.

Preventing Overcharge Conditions. Once a battery reaches a state of full charge, it can no longer store any additional incoming energy. If the voltage supplied to the battery continued at the full rate, the battery voltage parameters would be exceeded. If that were to happen using conventional lead-acid batteries, the hydrogen in the battery water would begin to separate or "bubble out". This causes excessive water loss in the battery cell and a chance that any accumulating hydrogen gas could ignite... which is not a good thing… hence the need for ventilation.

Preventing an overcharge condition is easily addressed by reducing the charge to the battery when the battery reaches a set voltage. When the voltage drops due to a lower sunlight intensity or an increase in electrical usage occurs, the charge controller will increase the charge to the maximum allowable by the battery.

The voltage parameters that the controller uses for switching the charge rates are called set points. Some charge controllers will allow the user to adjust the set points based on the user's normal consumption patterns, the type of battery, or the operational preferences the user may have.

Set Points and Temperature. It is important to note that the ideal voltages for controlling the charge to a battery will change with the battery's temperature. Some controllers can compensate for the battery's temperature by changing the set points. When it detects a low battery temperature, it will slightly raise the set point voltages. Otherwise, when the battery is cold, it would reduce the charge too soon. For batteries that will experience temperature swings greater than about 25-30 degrees F, compensation is much more important. For this reason, many battery banks are installed indoors using sealed gel / AGM batteries or lithium batteries.

Some charge controllers also include an internal temperature sensor. If it does, the charge controller must be mounted in a place where the temperature is close to that of the batteries, or it must have an optional remote temperature probe. The probe is then attached directly to a battery which reports the temperature to the charge controller.

Set Points and Battery Type. The type of battery will determine the set points for the charge controller. Sealed gel and AGM batteries need to be regulated to a slightly lower voltage than flooded cell batteries, or they may be damaged. Most charge controllers have a switch to select the type of battery as being conventional, AGM, or Lithium. Always ensure that the selected controller is intended for type of batteries being used in the system.

Overload Protection. Any overloaded circuit can cause damage or a fire. The overload could be caused by a short circuit in the wiring or by a faulty appliance. Some charge controllers that are available today include overload protection and can be reset by a push-button or switch.

Any controller that includes overload protection is helpful, but most systems will also require the use of additional circuit breakers. The controller's overload protection is typically for the system and not for separate circuits within the system or the structure. Regardless, always follow the manufacturer's requirements, the National Electrical Code, and the local code requirements.

Monitors and Meters. The charge controllers available on the market today include a variety of possible displays, ranging from a simple red light to digital meters for voltage and current. For complete and accurate monitoring however, purchase a quality charge controller with the monitoring meter included for the system. If you use a separate system monitor, then it is not necessary for the charge controller to have a digital meter.

Some older multi-stage charge controllers are **Pulse Width Modulation (PWM)** types and many have what is known as a 3-stage charge cycle consisting of *Bulk, Absorption*, and *Float*. During the Bulk phase of the charge cycle, the voltage gradually rises to about 14.5 volts during which time the batteries draw maximum current. Once the Bulk level voltage is reached the Absorption phase begins.

During the *Absorption* phase the voltage is maintained at the *Bulk* voltage level (14.5 volts) for a specified time (usually about an hour) during which time the current gradually decreases as the batteries' charge increases. After the *Absorption* time ends the voltage is reduced to the Float level (usually 13.4 to 13.7 volts) and the batteries will receive a small current for maintenance purposes until the next charge cycle begins. There are also two-stage PWM controllers that will hold the voltage more constant. Initially, it will hold the voltage at the *Absorption* rate for the battery to reach its full charge. Then, it will decrease to the *Float* level to maintain the charge.

Most systems now use the **Maximum Power Point Tracking (MPPT)** controllers and are preferred over the multi-stage charge controllers because they match the output power of the solar panels to the battery voltage to obtain the maximum charging amps in the shortest amount of time. The reason this is important is simply that just because a solar panel is rated for 200 watts, doesn't mean you will get the full 200 watts unless … the battery is already at optimum voltage. Mathematically speaking…

P = E * I (from Ohm's law) or Power = Voltage * Current

or think of it as Watts = Volts * Amps

With a *PWM charge controller*, if your battery voltage is low, for example 11.6 volts, then your 200 watt solar panel can only charge at 139 watts.

E * I = P

16.5 V * 12 A = 200 W *(what your solar panel is rated at)*

11.6 V ** 12 A = 139.2 W (what your PWM charging system will deliver with a low battery voltage)*

In essence, you will lose 30% of your 200-watt capacity when your battery charge is at 11.6 volts. However, the *MPPT Charge Controllers* will compensate for the lower battery voltage by delivering 17.24 amps to the battery which maintains the full power of the 200-watt solar panel to the batteries.

11.6 V * 17.24 A = 200 W

So you can see the value of using *MPPT Charge Controllers* and why they are well worth the extra money. *MPPT Charge Controllers* allow your solar panels to operate at their optimum power output voltage, improving their recharge performance by as much as 30%.

Regardless of the type chosen, the Charge Controller is always installed between the solar panels and the batteries. It takes the charge delivered from the solar panels and then automatically adjusts it to provide the proper charge to the batteries.

Step 7: Charge controller design. In our example design, we are choosing four 350-watt panels. So, we will evaluate the amps required by each selection to determine our charge controller design.

From the solar panel's specifications, we determine the following results:

(4) 350-watt   12-volt   29.17 amps = 2 banks at 58.34 amps

(4 panels / 2 = 2 banks * 29.17 amps = 58.34 amps)

Since the maximum amperage produced is approximately 58 amps, a single 60-amp charge controller is all that is required. However, a slightly larger one would allow for additional batteries or PV panels for future use. A good MPPT charge controller can be found for about $250. Speaking of charging the batteries, an Inverter can also be used to charge the batteries if needed and we will discuss that next...

Various charge controllers

DISCUSSION ON INVERTERS

Unless you plan on using DC power for everything, you will need a power Inverter. Since the majority of modern appliances run on 120 volts AC, an Inverter will be a necessity. It not only converts (or "inverts") the low voltage DC to the 120 volts AC that is required for most appliances, but the inverter can also be used to charge the batteries as we mentioned previously. To be able to charge the batteries, it must be connected to an on-grid power supply or to a fuel powered AC Generator. An inverter may look like a boring non-descript box with one or two switches on it, but inside it is anything but boring. An inverter must handle a wide range of loads, from a small light bulb to the big surge required to run a shop motor and everything in between. Through all of these loads, the inverter must regulate the power output within very tight parameters and… especially for solar systems with… a minimum of power loss.

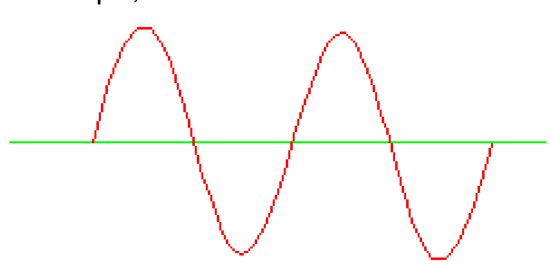
Over the years the 24-volt, 36-volt, and 48-volt systems became the standard because the higher voltages reduce wire sizes (which reduce costs) and the smaller wire sizes are easier to work with. Consequently, many DC appliances are now more easily obtained in these higher voltages than in their previous 12-volt rating.

Selection Considerations. When checking the specifications of an inverter you are considering, check its specifications with the following to ensure good performance: *Total harmonic distortion (THD)* should be less than 6 percent for most installations and less than 3 percent is excellent.

RMS voltage regulation should be +/- 5 percent or less.

Peak voltage (Vp) should be +/- 10 percent or less.

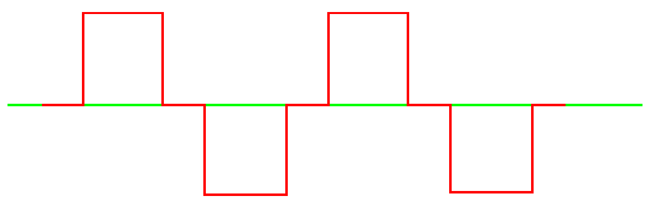
A **Pure Sine** wave is what is provided by the power company to your home and business. On an oscilloscope, the wave looks like the following:



PURE SINE WAVE

Ideally, we want our inverter to produce power that replicates this wave as close as possible for our use in the structure to avoid problems.

Avoid the **Square Sine Wave** inverters which are the least expensive and the ***least desirable*** type. The square wave it produces, besides being inefficient, can be harmful to many types of equipment. Square Wave units can be particularly harmful to some electronic equipment and especially equipment with transformers, timers, or motors. The square wave output has a high harmonic content which can cause some equipment to overheat. These inverters are usually fairly inexpensive. Using one of these types of power inverters is not recommended, and especially not recommended, if you are planning on using any sensitive electronics or motors. On an oscilloscope, the wave looks like the following:

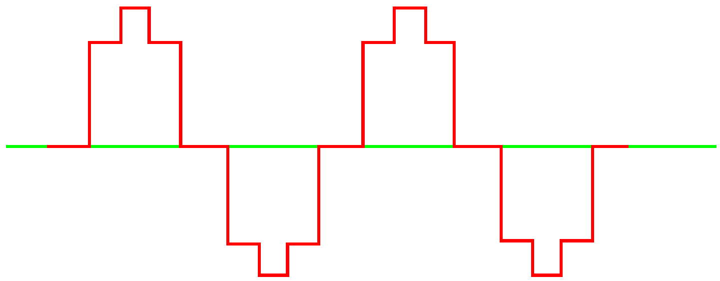


SQUARE SINE WAVE

Avoid the **Modified Sine Wave** inverters that were very popular prior to the development of the MPPT inverters. The power wave is not as clean as the electricity from the power company. It produces an AC waveform somewhere between a square wave and a pure sine wave. When viewed through an oscilloscope, it appears as a modified square wave. Modified Sine Wave inverters, also called Quasi-Sine Wave inverters, are not as expensive (somewhat less than the price of a True Sine Wave inverter) but may work in some situations. However, there are exceptions. Some appliances that use motor speed controls or timers may not work properly with a Modified Sine Wave inverter. Keep this in mind since many consumer products are using speed controls & timers.

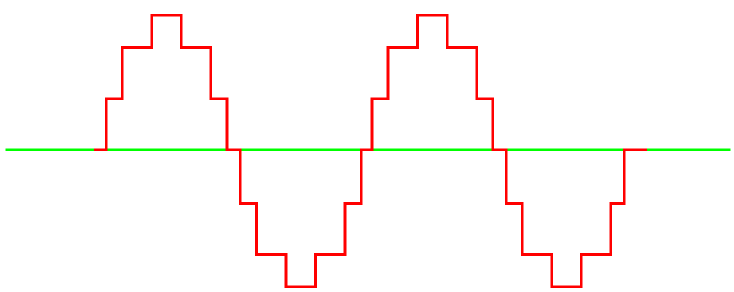
Many appliances won't work on modified sine wave power at all. Audio devices can give off an annoying buzz from the speakers and can also be heard from some fluorescent lights, ceiling fans, and transformers. Even microwave ovens will buzz and produce less heat. Electronic TVs and computer monitors will likely show rolling lines on the screen. And *surge protectors should be avoided* as they can overheat when using these inverters.

On an oscilloscope, the modified sine wave looks like the following:



MODIFIED SINE WAVE

True Sine Wave inverters produce the closest pure sine wave of all power inverters and in many cases can produce cleaner waves than the utility company itself. The number of steps produced is dependent on the manufacturer but will generally look like the one below, but with many more "steps". It will run any type of AC equipment and is, consequently, the most expensive. But for most installations, they are well worth the extra cost. Many True Sine Wave power inverters are electronically controlled and will automatically turn on and off as the AC loads appear. Some check every couple of seconds for anything that wants AC power and will then power up automatically. When the AC demand ends, the power inverter shuts down to conserve battery power.



TRUE SINE WAVE

As noted, while the price of a True Sine Wave inverter is more expensive, it is still recommended for most installations. Also, most appliances will run more efficiently and use less power… which is another good reason to use a True Sine Wave inverter.

Grid Tie Inverters are a relatively new breed of inverters that allow systems to connect with an on-grid system (the power company) to reduce your electric bill without being a totally independent system. With a Grid Tie Inverter, you may actually be able to sell any excess power produced by your solar array back to the power company. These systems are easy to install and, since the on-grid system is available, back-up batteries are not a requirement. However, a small battery bank may still be desired to cover any short-term power outages. In this case, **Hybrid Inverters** can do both… Grid Tie and battery backup.

If that is of interest, the first step is to contact the utility company to see if they will allow you to connect a solar system to their electrical grid. Note, that while there is a national law that requires **investor owned** utility companies to allow interconnection of a solar system, **rural electric cooperatives** are exempt from this law.

If you are allowed to connect to their grid, the next question is… will they buy the energy back at the retail or wholesale rate. Ideally, you want the utility company to buy any excess electricity produced at the same retail rate that you buy electricity from them. This is commonly referred to as "net metering" and is the simplest way to set up a grid-tie system. This way, you only have one electric meter and it can record whether you are buying or selling electricity. To find out if your state offers any incentives or "net metering", visit www.dsireusa.org.

Inverter Input Voltages. What should be used… a 12, 24, or 48-volt inverter? The main consideration in deciding on the voltage from the batteries to the inverter input is the distance between your solar panel array and your batteries. The higher the voltage, the lower the current… which means the smaller the electrical wiring can be. Remember, on small structures, the solar panels, the inverter, and the batteries should all use the same voltage to avoid confusion and costly mistakes. But that is not a requirement, only a recommendation.

Inverter Stacking is using multiple inverters to provide more power or higher voltage (i.e. 240 VAC). If two compatible inverters are stacked in series, you can double the output voltage. This would be the technique used to provide 240 VAC. On the other hand, if you configure them in parallel, you can double your amperage. Two 4000-watt inverters in parallel would give you 8000 watts (8KW) of electricity. Typically, a cable must be connected directly between the inverters to synchronize them, so they act as a single unit.

Step 8: Inverter design. Again, using our design calculation thus far, we have a solar system charging our battery bank which is providing us with ~2,000 amp-hrs of power. Some of this will be used by DC circuits and the remainder will be with the AC circuits. Since the power supplied by the batteries and solar panels is provided as DC, we will need to convert it to AC power by using a DC to AC inverter. Sizing an off-grid inverter is relatively straight forward. It must be sized to be large enough to handle the total amount of AC watts *that you will be using simultaneously*.

Begin by reviewing your appliance listing you made previously in Step 2 of all of the appliances in your building and note those that require AC power. Then of those, note which ones will be used simultaneously and total their wattage. For example, if you will be using a 1000-watt microwave at the same time you will be running 1500 watts of air conditioning and also running other appliances (radio, tv, etc.) that will draw 300 watts of power, you will need an inverter that can handle at least 2800 watts (1000 + 1500 + 300). Once you have identified a minimum wattage, you will select an inverter that has the same nominal voltage as your battery bank, or in our case 24 VDC. And if you will be using sensitive electronic equipment or motors, choose an inverter that provides True Sine Wave outputs as we discussed previously.

So we would look for a minimum 3,000 watt 24-volt True Sine Wave inverter and specify something like an Outback VFX3524 (3,500 watt 24-volt). The 2,000 to 5,000-watt inverters will run about $1,000 to $3,500.

Low Voltage Disconnects

As mentioned earlier, the deep-cycle batteries used in solar systems are designed to be discharged up to about 80 percent. If they become completely discharged they will be damaged. Every time this happens, the life of the battery and its capacity will be reduced by a certain amount. If the battery remains in a discharged state for days, it will become permanently damaged.

The only way to prevent over-discharge of the batteries when the solar system fails to provide the necessary charge is to disconnect the electrical loads. Then you can reconnect the loads to the system once the emergency generator or the solar system is once again providing the needed power for the loads and recharging the batteries. An over-discharge condition is reached when a 12-volt battery drops below 11 volts or a 24-volt battery drops below 22 volts. The typical Low Voltage Disconnects will reset at 13 volts on a 12-volt system or 26 volts on a 24-volt system.

Currently, all inverters have a Low Voltage Disconnect included. As such, the inverter will shut off as necessary to protect the inverter, the loads, and the batteries.

The DC loads should have a Low Voltage Disconnect as well. Some of the charge controllers on the market have one included. Even so, you can also add an independent Low Voltage Disconnect. Some of the newer Low Voltage Disconnects have a delayed switch with an alarm to allow a minimal amount of time to correct the problem or... to find a flashlight. Many allow the user to select the voltage settings for disconnect and reconnect levels.

DISCUSSION ON METERS AND MONITORS

Monitoring battery voltage and system performance is very important so we can determine the current state of the solar system. As we have discussed, preventing batteries from discharging below a certain level will greatly improve their performance and their life span. Monitoring the Voltage and Current readings in your system will tell you the batteries' current state and how fast they are charging or discharging. All this can be monitored with one or more meters. Many charge controllers display Amps, Watts, Volts, Amp-Hrs, and Total Amp-Hrs to provide easy monitoring of the system status. It is recommended that you select ones that do include this information or install an independent monitor. You should never use cheap panel meters that are not intended for use with solar systems because they are not designed for low voltage high amperages, and you really do not want to risk your high investment in batteries and solar panels on cheap meters.

Step 9: Meters & Monitors. Older PV solar systems generally did not include monitoring meters. However, newer systems have the monitoring built into the charge controllers/inverters. Many modern solar inverter systems come with monitoring software which can log performance and even notify owners of issues remotely.

DISCUSSION ON GENERATORS

Generators are best used for backup power during long periods of little or no sun. Ideally, when you need to run the generator, you want to run it just long enough to provide the batteries with both the Bulk stage charge and the first portion of the Absorption charging stage. Then shut it off! Once it is in the Absorption stage, the current will begin dropping as the batteries approach a full charge so most of the generators' power is not being used and is simply being wasted. Using a generator under these conditions is obviously very inefficient and wasteful of energy and fuel. Any time you're running the generator, then also run anything else with large electrical loads (like power tools, air conditioners,… anything that would normally put a real drain on your batteries).

If you charge the batteries up to about 85% to 90% capacity with a generator, not only will that prevent the batteries from becoming too deeply discharged, but then only a short period of sunlight is required to complete the battery charging.

Most solar inverters have a battery charger built in. This allows the generator to simultaneously charge the batteries while also providing power to the AC loads. This is a much more efficient use of the generator, and it minimizes the wear on the generator and the batteries.

Be careful when sizing a generator. Many inverters require the generator to be oversized because of their low power factor. Always check the specifications first before selecting a backup generator.

Step 10: Generators. For most small to medium sized structures, a 4,000 to 7,000 watt generator will work nicely and they are moderately priced. Generators can be found in the $350 to $1000 price range depending on brand & features. Modern backup generators often feature automatic start capabilities and advanced integration with hybrid inverters, which can provide efficient transitions between PV-generated electricity, battery-stored energy, and generator-supplied backup power. Additional features like flex-fuel, diesel, and propane fuel are available depending on user preferences. The newer inverter-generators are quieter, more efficient, and compatible with lithium battery charging requirements. In 2025, a 6500-watt generator can be purchased for under $600.

DISCUSSION ON WIRING

Step 11: DC System Wiring. Correct wire sizes are essential for wiring the various components of a Solar Energy System. The correct wire size ensures low energy loss and prevents overheating and damage. Below is a chart showing the required wire size for various wire lengths used to connect the solar panels to the Charge Controller using a 12-volt system. If you're using a 24-volt system, make sure you use a 24-volt wire size chart. Also note the allowable voltage drop when using the chart and be sure you account for the voltage drop in your design. Never use more than a 2% voltage drop when sizing wire from the solar panels to the charge controller. A 3% - 5% DC voltage drop may be allowable between the batteries and the appliances.

Incorrect wire sizing will result in excessive heat buildup and even fire due to the large currents found in solar systems. Using properly sized and types of wire will minimize the need for maintenance and/or replacement for years. And never use interior wiring for exterior uses. All exterior components, wires, and cables must be rated for UV exposure, or they will break down over time… and interior wiring is not provided with UV protection.

It is also important to note that when selecting circuit breakers, AC and DC breakers are NOT interchangeable. So be careful in the selection of breakers and only allow DC rated products on DC wiring. Note that fuses can be used, but I recommend using circuit breakers because they are easier to reset and rarely need replacing. Again, only use DC rated fuses on DC circuits.

Most building codes will not allow the use of AC plugs or outlets for DC circuits because of obvious safety reasons. Therefore, always require the use of DC type plugs and outlets for all DC circuits to ensure anyone wanting to use the outlet is not injured because they were unaware of the outlet's voltage.

See the wire sizing chart on the next page for the impacts of amps on various wire gauges for 12-volt and 24-volt wiring. The Voltage Loss chart values were calculated using Ohm's Law as shown:

From Ohm's Law, we can calculate: **E = IR**

where: E = Voltage Loss (volts)

I = Current (amps)

R = Resistance (ohms)

Therefore, using the manufacturer's specifications for the Resistance values of the different size wires, we can calculate the allowable wire lengths for various amperages.

Voltage Loss = 2 * I * R (per 1,000 ft) * Dist (per 1,000 ft)

Dist = (1000E) / 2(IR)

The results of the calculations for a 2% voltage drop are in the chart on the next page.

The top row represents the Wire gauge size, the left column is the maximum number of amps, and the chart cells show the distances in feet allowed for a 2% voltage drop. For all numbers, use the next higher value in choosing amps or distances.

For example: If you have 3 solar panels rated at 12 volts 6 amps each, mounted 30 feet from the Charge Controller, then you would move down the chart to 20 amps (3 panels * 6 amps and then round up), and across to 36 (closest to 30), and then up the chart to #2 ga. You would need at least #2 AWG gauge wire to move 18 amps 30 feet with a minimum voltage drop of 2% or less, which is an acceptable loss.

If you have 3 solar panels rated at 24 volts 6 amps each, mounted 30 feet from the Charge Controller, then you would move down the chart to 20 amps (3 panels * 6 amps and then round up), and across to 45 (closest to 30), and then up the chart to 4 ga. You would need at least #4 AWG gauge wire to move 18 amps 30 feet with a minimum voltage drop of 2% or less. I would much rather wire with #4 AWG than #2 AWG.

Remember, if you can't find the exact values, choose either a larger gauge wire (smaller number) or select a distance longer than your actual distance. Using a larger gauge wire will also reduce the voltage drop for the same length of run.

12 Volts - 2% voltage drop

	AWG Wire Gauge										
AMPS	18	16	14	12	10	8	6	4	2	1/0	2/0
1	17	28	45	71	114	181	288	457	730		
2	8	14	22	35	57	90	144	228	365	581	730
4	4	7	11	17	28	45	72	114	182	290	365
6	2	4	7	11	19	30	48	76	121	193	243
8	2	3	5	8	14	22	36	57	91	145	182
10		2	4	7	11	18	28	45	73	116	146
15		1	3	4	7	12	19	30	48	77	97
20			2	3	5	9	14	22	36	58	73
25			1	2	4	7	11	18	29	46	58
30				2	3	6	9	15	24	38	48
40				1	2	4	7	11	18	29	36
50					2	3	5	9	14	23	29
100						1	2	4	7	11	14
150							1	3	4	7	9
200								2	3	5	7

24 Volts - 2% voltage drop

	AWG Wire Gauge										
AMPS	18	16	14	12	10	8	6	4	2	1/0	2/0
1	35	56	90	143	228	363	577	915			
2	17	28	45	71	114	181	288	457	730		
4	8	14	22	35	57	90	144	228	365	581	730
6	5	9	15	23	38	60	96	152	243	387	487
8	4	7	11	17	28	45	72	114	182	290	365
10	3	5	9	14	22	36	57	91	146	232	292
15	2	3	6	9	15	24	38	61	97	155	194
20	1	2	4	7	11	18	28	45	73	116	146
25		2	3	5	9	14	23	36	58	93	116
30		1	3	4	7	12	19	30	48	77	97
40			2	3	5	9	14	22	36	58	73
50			1	2	4	7	11	18	29	46	58
100				1	2	3	5	9	14	23	29
150					1	2	3	6	9	15	19
200						1	2	4	7	11	14

Disclaimer:
The values listed above are approximate values only and intended to demonstrate the voltage drop for various wire gauges. Use of the values for actual wire sizing is at the sole risk of the user.

Solar Panels to the Charge Controller and Batteries

After selecting the proper wire size to connect the Solar Panels to the Charge Controller, use the same size wire to connect the Charge Controller to the batteries, since these wires will carry no more current than the solar panel wires ***as long as*** the distance to the batteries is less than the distance to the solar panels.

Batteries to the Inverter

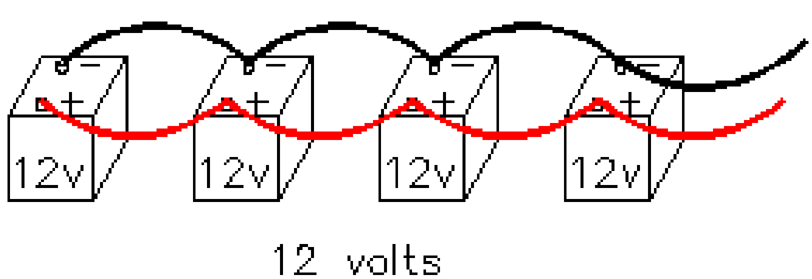
Both the Inverter and the Batteries require the largest wires in the system. During operation, the Power Inverter can draw a tremendous number of amps from the batteries to produce the AC required. These wires are like the large battery cables found in cars. An AC appliance drawing 10 amps (like a microwave) will require 100 amps at 12 volts DC.

Wiring the Batteries

As we mentioned, the batteries will require very large cables like the large battery cables in cars. Always connect the batteries with large high quality copper cables. See the Battery Wiring Diagrams below for examples of wiring different battery voltages.

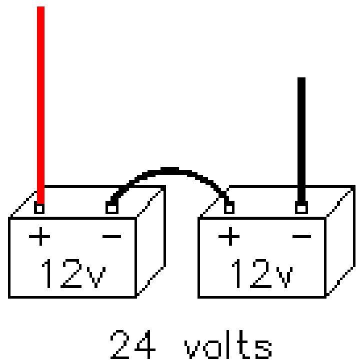
Step 12: Battery wiring

Parallel wiring to increase current is obtained by connecting the positive (+) terminals of multiple batteries together and then connecting the negative (-) terminals together. Connecting four 12-volt batteries in this manner provides four times the power but the voltage remains at 12 volts. Parallel wiring simply increases the current but the voltage remains unchanged.



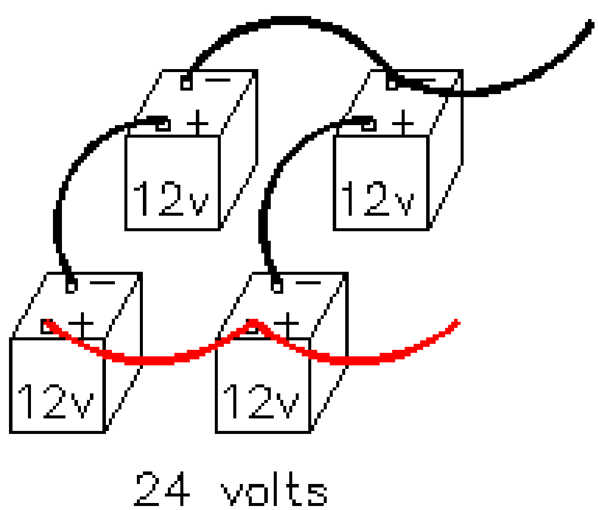
Remember: Parallel wiring → Voltage stays the same and the Current is additive.

Series wiring to increase voltage is obtained by connecting the positive (+) terminal of one battery to the negative terminal of another battery and connecting the negative terminal (-) to the positive terminal of another battery. Connecting two 12-volt batteries in this manner provides the same current but doubles the voltage to 24 volts. Series wiring simply increases the voltage, but the current remains the same.



Remember: Series wiring → Current stays the same and Voltage is additive.

Using series & parallel wiring in combination doubles the voltage and doubles the current. This method combines the batteries by using both wiring methods described above. Using four 12-volt batteries in this manner essentially provides two 24-volt batteries with double the current.



DISCUSSION ON PRE-WIRED POWER CENTERS

Pre-wired Power Centers can be used to provide an efficient method of managing your solar system wiring and space. A power center can contain inverters, low voltage disconnects, over-current protection devices, grounding, and charge controllers … all in a single mount using compatible components. These power centers can save a considerable amount of time on the installation labor and save floor space, too. Obviously, this comes at a price but it does simplify the installation process. Prices for these panels run about $4,000 to $8,000 for small to medium sized panels.

SUMMARY

As we have seen, there are six basic components found in every solar powered system. They are the solar panels, charge controllers, batteries, monitor meters, inverters, and the electrical wiring. Depending on the system size, additional items that the system may include are a generator, an AC power grid switch, additional charge controllers, and additional inverters.

And don't forget the appliances that will be using the generated electricity. They, too, are a critical part of the system and each one must be accounted for in the solar system design. For most of us, since we are connected to a seemingly endless source of electricity through an on-grid electrical supplier, we don't give much thought to the appliances we plug in… until we receive the electric bill.

While a solar system ***can*** use standard AC appliances, it is much more efficient to use DC powered appliances. Some commonly used powered appliances such as lights, fans, and air conditioners are also readily available in DC-wired models. These DC appliances can significantly reduce the size of the solar panel array and the number of batteries with no negative impact to the end user. Or, for a system that is struggling for power, switching from AC fixtures to DC appliances and LED lighting can make all the difference needed to make it an efficient functioning system again.

DC converters, also known as voltage reducers or voltage regulators can reduce a higher voltage DC (such as 24VDC or 48VDC) to 12VDC for those appliances that require the lower voltage. Most of these DC/DC voltage reducing converters are suitable for running some electronics. but not all. So, verify their limitations and get the right one for your application.

If you've recently completed a solar PV installation and would like to send me some photos with a short narrative on what & where, I may add it to the next edition of this course. Additionally, please leave a review of this course for other engineers.

Now… go have fun!

A plethora of solar heated water tanks and solar PV panels in Israel