A solar primer: how it works how it's made what it costs

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Buying a solar power system is not like buying a kitchen appliance or power tool. These, unlike a solar system, have published capacity and performance data that does not change with each hour of day or geographic location. In some respects, it may be like selecting a high end component stereo system which requires separately purchasing the speakers, an amplifier, a CD player, and tape deck. Each of these components must be

Roof-mounted solar PV array attached to house

selected for your specific needs, sound quality, and budget or you will not be pleased with the results.

Before deciding which components are right for your own solar energy system, it is important to understand that there are actually several different types of solar energy systems available, and each has very specific capabilities and limitations. Most solar photovoltaic systems will consist of one or more solar modules, one or more batteries, and a solar charge controller. If the system will be used to supply AC loads, you will also need an inverter to convert the DC voltage output of the solar array or stored in the battery bank to standard 60 cycle 120-volt AC power.

Solar array

A solar module is a glass sheet, enclosing either individual single-crystal or poly-crystal solar cells, sandwiched between the glass and a waterproof backing material, and edged with an aluminum mounting frame. Some solar modules are constructed using a non-glass glazing, over a metal back with no frame.

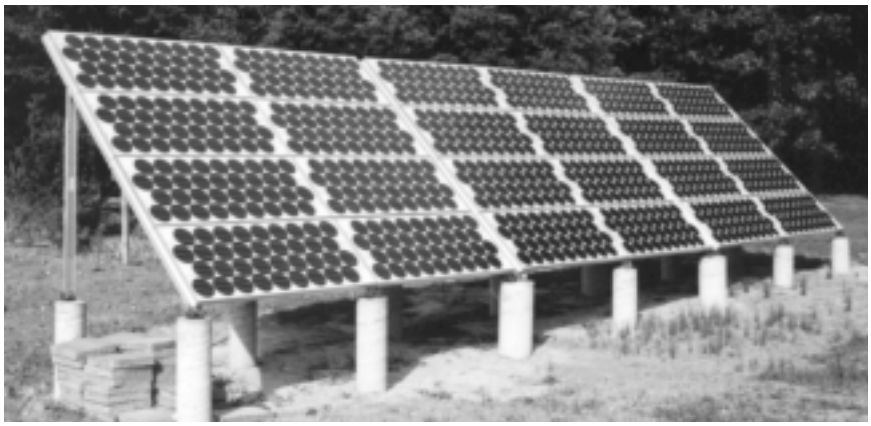
Due to the high cost of assembling and wiring individual silicon solar cells into a complete module, some manufacturers are now "plating" the silicon material directly onto the back of the glass in a continuous sheet, with this sheet divided into individual cells after assembly using a laser. This type of solar module is called "amorphous" and it has a lower energy efficiency than the individual silicon cell modules; however, most modules are priced on a similar "cost per watt" basis. This means you will probably pay about the same price for a given watt output array regardless of which module type is used, although the overall roof area covered and the number of individual modules required can vary widely to achieve the same wattage due to different module efficiency.

If you have a limited roof area, the more efficient and larger individual modules will actually reduce mounting hardware costs and require fewer electrical connections. When more than one solar module is used, they are interconnected to create a solar "photovoltaic array." Solar arrays can be ground-mounted on a tilted rack near your home, mounted on the roof of your home or garage, or pole-mounted in a nearby field.

Pole-mounted arrays can be attached to a fixed position frame on the top of the pole, or the frame can include a mechanism that rotates so the array faces the sun throughout the day. A tracking array will significantly improve solar performance during the summer, but will only sightly improve winter performance. Tracking array mounts are usually not used for residential solar power applications having rooftop arrays due to structural and appearance considerations. The tracking mechanisms also introduce an additional level of complexity and maintenance to an otherwise simple system.

Solar arrays should face south as closely as possible in Northern Hemisphere. However, facing 15 degrees east or west of south will only marginally reduce overall system performance since this is shifting the start and end time the array faces the sun. The tilt mounting angle as referenced to ground can vary from below 30 degrees in southern states to above 60 degrees in northern states. A steeper tilt will improve solar performance during winter months and a

Pole-mounted solar PV array on motorized tracking mount



Ground-mounted solar PV array attached to aluminum frame and concrete piers

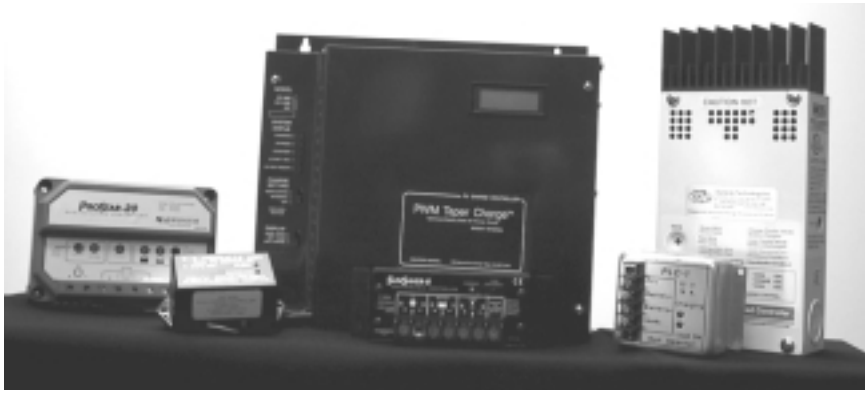
shallow tilt will improve summer performance. For a good overall yearly average performance, most installers try to make the tilt angle equal to the site latitude if your electrical loads are fairly constant throughout the year. If you have at least 250 square feet of existing unobstructed south facing roof area, you should be able to install up to 1,500 watts of solar array. Keep in mind that even a small shadow from nearby trees, chimney, or antenna can substantially reduce array output, so select an area free of shadows from 9 a.m. to 3 p.m. which is the period of maximum energy collection for most applications.

Electrically speaking, different brands and sizes of solar modules can be interconnected in the same system; however, you will have a much more attractive array and fewer interconnect wiring problems if you standardize on a specific module and stay with it. This includes future system expansions.

You will also find that buying individual modules in the larger 75 to 100-watt size range will reduce the number of total modules and interconnect wiring needed. Modules in the smaller 20 to 50-watt size range are more expensive on a dollar-per-watt-basis than the larger modules, so your comparison shopping should be based on dollar-per-watt produced, not dollar per module.

Charge controller

All solar power systems regardless of size will have a solar charge controller to serve as a voltage regulator to control battery charging by the solar array. This device provides several safety features including the prevention of overcharging the battery bank during peak sun output, and discharging the battery bank through the solar array at night.



Collection of the most popular brands of solar charge controllers having from 4 to 60 amp charge capacity

Solar systems intended for supplying solar power directly into the utility grid have their voltage control function built into the inverter and will not have a separate charge controller device. A low cost charge controller is usually a relay device that opens and closes the charging circuit to the battery based on a fixed voltage setpoint on an all or nothing basis. More expensive charge controllers have complex algorithms stored on computer chips to provide a more efficient incremental battery charging cycle. These devices produce constantly changing or pulsed voltage and amperage output to maximize every minute of solar energy collection. Obviously, if you plan to invest several thousand dollars in a solar array, the extra expense for a quality charge controller will more than return its higher cost in more solar energy harvested.

Battery bank

Everyone asks how many batteries do I need and should they be 12, 24, or 48-volt? First, there are some solar power systems that do not use any batteries. Although some inverters can take power from the grid for the purpose of recharging a battery bank, other inverters are designed to only sell back electricity to the utility grid. These systems are less expensive to install since they do not need batteries or a battery storage area, and they do not require battery maintenance or replacement. These systems have inverters that directly convert all of the DC voltage output from the solar array into 120 or 240-volt AC power that is back fed through the electric meter directly into the utility line. In reality, the utility grid becomes the "battery" for these systems and the utility company will require a power

Very popular "SunnyBoy" brand grid-tied inverter for direct grid connect solar arrays

meter that can read power flows in both directions so they can calculate a net bill.

Some states still do not require their utilities to offer this "net" billing, so check before buying this type of solar power system. The downside of a non-battery based grid-tied solar array is this system cannot power any of your electrical loads during a utility power outage, brownout, or rolling blackout. This can be somewhat embarrassing for you with your neighbors who think all solar systems can operate without the electric utility and that your home should have power when their's do not. Using an inverter designed to only transfer solar-generated power back into the utility grid reduces your total yearly electric cost, but does not provide any backup power function. Some months your electric bill may be a cost and some months it may be a credit.

Any solar power system intended to serve as an emergency backup system or designed to provide all electrical power needs for an off-grid home will have a battery bank. The battery bank will consist of one or more individual batteries wired together to match the voltage rating of the inverter and the solar array. Do not even think of using car batteries as these will last only a few weeks under the daily heavy charge/discharge cycle found with all solar systems.

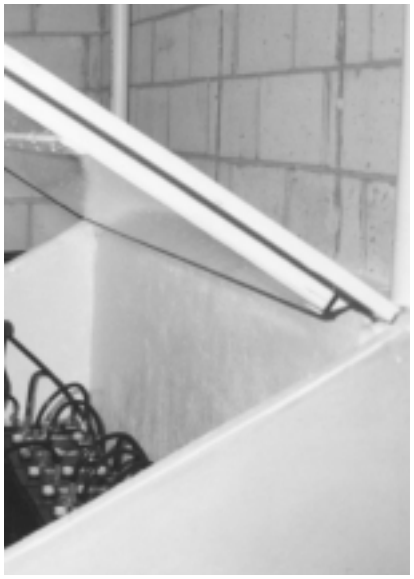
A favorite low cost minimum acceptable battery is the lead acid 6-volt golf cart battery. Its thick lead plates will withstand this heavy duty cycling, but its lower cost construction rarely lasts over three to four years in this type of service. If you are on a tight initial budget, golf cart batteries will get you started, and they can be replaced when they reach their useful life with heavier batteries like the popular "L-16" size electromotive battery. This battery is the same length and width as a golf cart battery, but it is much taller and heavier. These are very popular for use with larger solar power systems since their high amp hour storage capacity will reduce the number of total batteries you will need, along with fewer battery interconnects and terminals to keep clean.

If your solar-powered home or remote cabin will not be connected to the utility grid, your battery bank needs to be large enough to power your electrical loads for three to four days of cloudy weather. This could require a fairly large number of batteries for most applications. By adding a propane or diesel fueled generator to your system, you can get by with a much smaller battery bank. The generator can be started after one or two sunless days to quickly recharge the batteries which can substantially reduce the space and cost for a large battery bank. If you must locate your batteries in the same space where you will be living, you must either enclose the batteries in a vapor proof enclosure that has exterior vent pipes, or purchase gel cell lead batteries that do not vent gases during charging.

Any liquid electrolyte lead acid battery generates hydrogen gas during charging when it reaches its maximum charging voltage, but will not vent gases while being discharged. Unfortunately, gel cell batteries cost as much as 40 percent more than the same size liquid electrolyte lead acid battery without providing any additional energy storage capacity. You may find it less expensive to site-build a battery box and use the less expensive liquid electrolyte batteries which are fully recyclable. When planning the location of a battery bank, remember that all batteries are very heavy and should not be exposed to freezing winter temperatures or high summer temperatures. Published battery ratings are always given for 77 degrees F, and all battery capacities will be significantly less when exposed to below 40 degrees F. temperatures.

Inverters

If all of your electrical appliances and lighting will operate directly from a 12-volt battery, you will not need an inverter. However, if you want to use the lower cost and easier to find 120-volt AC lighting and appliances, your system will need an AC inverter. Even if you are on a tight budget, do not skimp on the inverter. To reduce total system costs you can always later add more solar modules and batteries to increase the capacity of your system, but if you initially buy a low cost or undersized inverter, you will soon find it will



Site-built insulated battery box. Note the gasketed lid and rear PVC pipe vent to outside.

Statpower brand modified sine wave inverter for smaller remote cabin and RV applications

need to be replaced with a larger unit. Inverters designed for the marine and RV industry like the Heart Interface and Statpower lines can be used for small off-grid solar powered cabins, but may be too small and lack many features that are desirable for a typical larger residential or farm application.

Most of the smaller and lower cost inverters are "modified square wave" design, meaning their 120-volt AC output voltage only approximates the utility grid's smooth 60 cycle sine wave by rapidly increasing and decreasing the output voltage in small "steps." Most power tools, computers, lights, and household appliances will operate satisfactorily on a modified sine wave inverter. However, most laser printers, photocopiers, and light dimmers not only will not work on a modified sine wave inverter, but can be permanently damaged when connected to these lower cost inverters, and a microwave oven will operate at substantially lower heating capacity. Modified sine wave inverters are typically sold in 400, 800, 1000, 1200, 1500, 1800, and 2500-watt capacity depending on price and manufacturer. These smaller wattage capacity models are available to operate from 12-volt batteries.

Dual 4 kW Trace sine wave inverters to provide 120 and 240-volt AC power from a 48-volt DC battery bank

If you want to power a microwave oven, well pump, or larger household appliances like clothes washers and refrigerators, while at the same time power room lighting, you need to consider a larger capacity sine wave type inverter like the Trace SW series. These inverters are usually available in 1800, 2500, 3600, 4000, and 5500-watt capacity depending on price and manufacturer. These larger units are not normally designed to operate from a 12-volt battery bank due to the extremely high DC currents and large wire sizes that would be required for capacities above 2500 watts. Most of these larger inverters also include a built-in high capacity battery charger that can recharge the batteries from the utility grid or a generator.

You will need a solar array and battery bank designed to operate at 24-volt or 48-volt DC to use these larger inverters, which keeps wire sizes and costs down but makes it difficult if you want to also use some DC rated lighting or appliances since most are not made for these higher battery voltages. A high quality inverter in the 4,000-watt range will meet the needs of most small residential applications assuming all space heating and air conditioning equipment, clothes dryer, domestic hot water heater, and cook stove are natural gas or propane-fueled and not connected to the inverter.

Since almost all residential inverters are designed to provide 120-volt AC output, you will not be able to power a standard 240-volt AC well pump without a step-up transformer or a second inverter. Your best bet if you have a well system is to replace your pump with a very high quality "soft start" 120-volt AC well pump and use a large expansion tank to reduce how often the pump cycles on and off. A well pump is a very difficult load for any inverter to power due to the very high starting currents, so do not expect a low cost 1000-watt modified sine wave inverter to power a 2 hp well pump, even if all other lights and appliances are turned off.

Safety and metering

You would be surprised to see how many Internet sites will sell you a very expensive inverter for your self-designed solar power system without indicating that it does not include any safety fuses or circuit breakers that will be needed to connect it to your battery bank, and many buyers may not realize that it is critical to also install these safety devices. In addition, these fuses and circuit breakers must be DC rated which are much more expensive and heavier duty than their 120-volt AC counterparts. An overloaded AC fuse or AC circuit breaker in a DC battery circuit may "trip" when overloaded, but the DC current can easily arc across the lighter duty AC contacts and keep on flowing, which could be a dangerous

situation. This is no place to save money.

System sizing

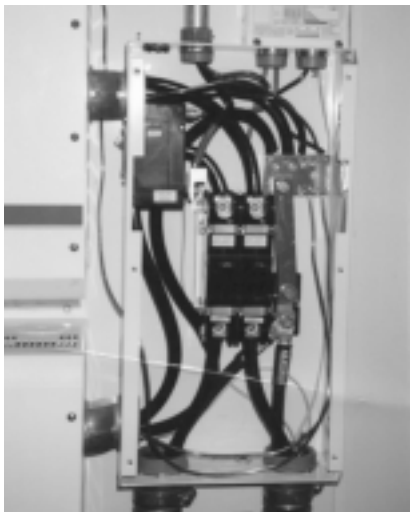
A typical single family residence buys an average of 1,000 kWh hours per month (34 kWh/day) from the local utility company. A solar array in most parts of the United States will collect energy about 5.2 hours per day in the summer, and 4 hours in the winter. Unless you first reduce your electric loads by converting to compact fluorescent lighting and high efficiency appliances to reduce this daily load, you would need a 6 to 7 kW array to power all of these existing loads. (5.5 hrs x 6kW = 33kWh.) When you start shopping for a solar system in this size range, expect to pay over $25,000 for the complete installation.

For homes already connected to the utility grid, most homeowners do not have the budget to spend this much money for what is essentially a backup power system, since the home will still be connected to the utility gird. A much more practical approach is to buy a solar system in the 2 to 3 kW size range, then reconnect all electrical circuits to a main and a backup circuit breaker panel. Have the solar system matched to the critical backup power loads it can safely power, and do without those other non-critical loads during power outages unless they are powered by a generator.

Do it yourself system

If you have the skills and experience to wire a room circuit to your existing circuit breaker panel without burning down your house or electrocuting yourself, and are willing to research the books and articles describing how these systems are safely wired, then head for the Internet or phone book and shop for the individual solar components you need.

You will find very good pricing for some brands of solar components at these Internet sites, but beware! These mail order distributors rarely offer system design assistance or have order takers that know which individual parts are best for your needs. You may end up with boxes of mismatched components and wiring connectors that require lots of additional time and expense to resolve. Also remember that the wiring of a solar electric system is covered by specific sections in the National Electric Code and these systems must be installed and wired to satisfy your local building inspector.



DC circuit breaker box (cover removed) showing much larger components and wire required to protect inverter (on left) and charge controller (on top)

Even if your system is so far out in the woods that nobody will ever know you are there, these electrical codes are based on years of system safety experience and should be followed even if the system will not be inspected. Most homeowners should hire their local electrician to complete all electrical connections.

In addition, many sine wave inverters and solar charge controllers have an extensive list of adjustable setpoints or system programming that are used to “fine tune” the equipment for your specific application. Do not assume all factory default settings will be correct for your system, and do not assume you will be able to maximize these settings just by reading a manual.

Working with a licensed installer

If you feel the system layout and wiring I have described is beyond

your capability or you just do not have the time, then consider hiring a licensed solar system installer. If you have the budget, their design assistance to match your specific needs to a specific system design will avoid another situation when you say to yourself, "If I had only known..." Since there are only a handful of quality solar equipment brands for each major component, many solar installers represent similar lines of solar power products, but may possess drastically different levels of design expertise and installation knowledge.

It is absolutely critical that you ask for recent installation references and actually call these homeowners. Since the installers will pass along all manufacturer's equipment warranties for the solar modules, inverters, charge controllers, and batteries, your main concern is to work with a solar installer who will still be around for years if you do have a system problem later.

Be forewarned: most experienced solar installers will not touch a problem system that was either poorly installed by a low budget "solar expert" or was purchased mail order by a homeowner who thought they could save lots of money installing the system on their own. All experienced solar installers have had their share of very bad (and costly!) experiences trying to help a stranded homeowner who took this low cost route.

Once you have selected your installer, be sure you are given a detailed written proposal that allows selection of several different array sizes and options to match your budget without sacrificing component quality. You can always add additional solar modules and batteries later to reduce initial system costs, but do not sacrifice system long-term reliability by buying undersized or low quality solar modules or inverters.

When reviewing a proposal for a turnkey solar power system from a solar system installer, be sure the following items are addressed since each item is needed for both safety and operating reliability.

- Evidence that all electrical work will be preformed by individuals licensed and insured to work on electrical systems.
- Safety devices are included in the system design like a DC rated circuit breaker wired between an inverter and battery bank, and between the charge controller and the battery and solar array.
- A catastrophic DC rated fuse installed at any large battery bank if the battery is located at a distance or in a different room from the inverter, even if the inverter has a circuit breaker.
- If your solar array will be mounted on the roof of your home, the National Electric Code requires a DC rated ground fault disconnect in the wiring connecting the solar array to the battery bank and charge controller. This is not required by code on ground or pole-mounted solar arrays.
- Any exposed wiring used to interconnect solar modules must be rated for high temperature, moisture resistance, and sunlight resistance. Module wiring technique must prevent rain water from entering into the module junction boxes.
- Although designed to carry high currents, standard welding cable is not approved for battery interconnects and inverter cables at this time, and some local building inspectors have been known to reject these cables. Do not make your own cables.
- Without some form of digital display on your charge controller or a digital amp hour meter for your battery bank, you will not be able to determine if your system is working if it is still connected to the utility grid, and you will not be able to tell how much energy your system has collected. Include some metering equipment.

Final notes

Most solar modules are extremely reliable and 20 to 25-year manufacturer warranties are not unusual; however, geographic location, array mounting, inverter efficiency losses, battery charging efficiency losses, and constantly changing local weather conditions will always reduce total system yearly performance. Solar

module wattage ratings are listed at a "standard sun" value that would be difficult to achieve unless you were in a desert facing the sun at high noon. Do not be surprised if actual solar energy harvested is only 65% to 75% of the nameplate ratings of the solar modules for any system you install, so be skeptical of unreasonable performance estimates.

Understand that the solar industry is still going through "growing pains" and some installers and equipment manufacturers have far less experience than others. Some of the newer grid-tied inverters that do not require a battery bank have had some reliability and performance problems that are currently being resolved.

If you are waiting for solar prices to drop before buying you may have a very long wait. Quality solar modules are made of the same glass, aluminum, copper, and other raw materials found throughout the construction industry and these materials are not getting cheaper. There are, however, some states and utility companies offering "buy down" rebates or tax credits that can offset some of the cost for the solar modules. These rebates or tax credits may help to reduce your total system cost, but do not buy a solar power system just to get these credits. This sad lesson was learned by many homeowner's buying low quality and poorly installed solar hot water heaters during the 1970s and 1980s just to quickly take advantage of the federal solar tax credits.

Take your time, decide what system size you can afford, and adjust your appliance or lighting loads to meet this maximum system capacity. It does not make sense to spend thousands of dollars for a few hundred watts of solar power, and then waste it to power low efficiency incandescent lighting or low efficiency appliances. Keep your list of solar powered electrical loads reasonable and as efficient as possible.

(Jeff Yago, author of the book *Achieving Energy Independence—One Step At a Time*, designs and installs turnkey independent energy systems. The book includes easy to apply system design information and includes wiring diagrams for most solar system types. It is available on line at www.pvforyou.com or by calling 804-784-0063 or from *BHM* [see pg. 92]). Δ