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Stand Alone Photovoltaic (PV) Systems: A Description & Function of System Components

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Introduction

Solar photovoltaic (PV) energy systems provide electrical energy from the sun. The simplest systems match a solar PV cell or module to a direct current (DC) load such as a water pump or a ventilation fan. These electrical loads operate when the sun is shining. To operate an electrical load such as a direct current (DC) light during evening hours requires an energy storage device such as a battery. A flashlight is an example of a direct current (DC) load (lamp) operating on batteries. The lamp will shine if the batteries produce a charge. When the batteries lose their energy, the lamp begins to fade and will eventually cease to shine. A solar cell connected to the batteries of the flashlight could re-charge the batteries during daylight, so energy is once again provided to the lamp. For the circuit to operate, the size of the cell must match the size of the battery. Larger electrical systems with voltages higher than 1.5-volt batteries require a component to regulate the flow of electric current from the PV module to the battery and monitor the state of charge (SOC) of the battery and protect the battery from being drained by the electrical load. Examples of solar PV circuits with batteries include solar-charged calculators, wrist watches, flashlights, and lanterns. Our garden pathway lights are solar-powered as well as wall-mounted outdoor spotlights. They are simpler to install because they are not wired to our house circuits and are gaining popularity with homeowners. This publication is intended to guide homeowners with an interest in stand-alone solar PV systems.

Examples of Stand-Alone Solar PV Systems

Many of our traffic control systems we see as we drive down the street are examples of stand-alone solar photovoltaic (PV) systems. Speed monitoring devices equipped with a flashing light, and a radar projecting your driving speed are equipped with a battery sized to provide energy to operate the lights and the radar and the message board from dusk to dawn. The solar module is used to re-charge the battery during daylight hours. Railroad crossing guards in rural areas must always operate and rely on batteries for energy storage. Streetlights powered by solar photovoltaic modules are commonplace in rural communities. No longer is there a need for costly trenching and installation of cable for utility-connected power. Communication towers requiring power for lights or radios and illuminated highway billboard signs are more examples of battery-based or stand-alone PV systems.

Reasons to consider adopting a stand-alone or off-grid system vary. In rural areas, the cost to install an electrical connection to a utility-line may be prohibitive. For some folks the desire to "live off grid" is a personal thing. They want to reduce their carbon footprint, embrace the concept of using renewable energy, and desire more control of their lives. For other folks, it is a matter of economics. An opportunity to live in wide-open spaces without the cost associated with investing in a utility connection.

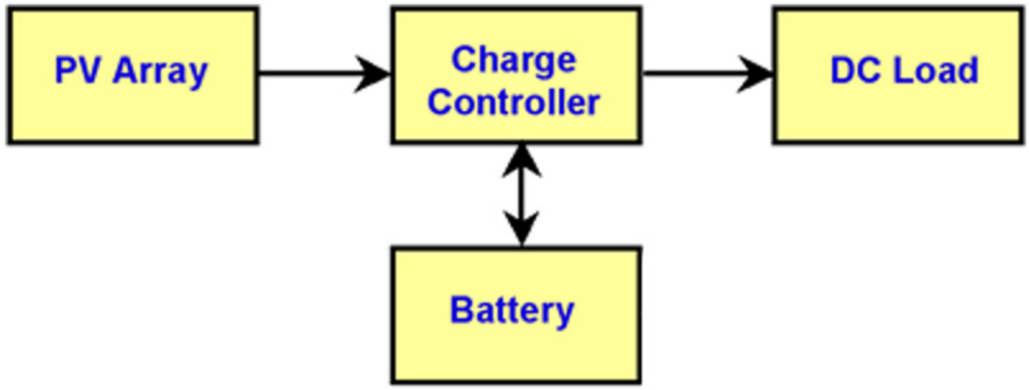

Figure 1. A block diagram of stand-alone solar PV system with DC load depicting the direction of electricity flow. Source: Florida Energy Center

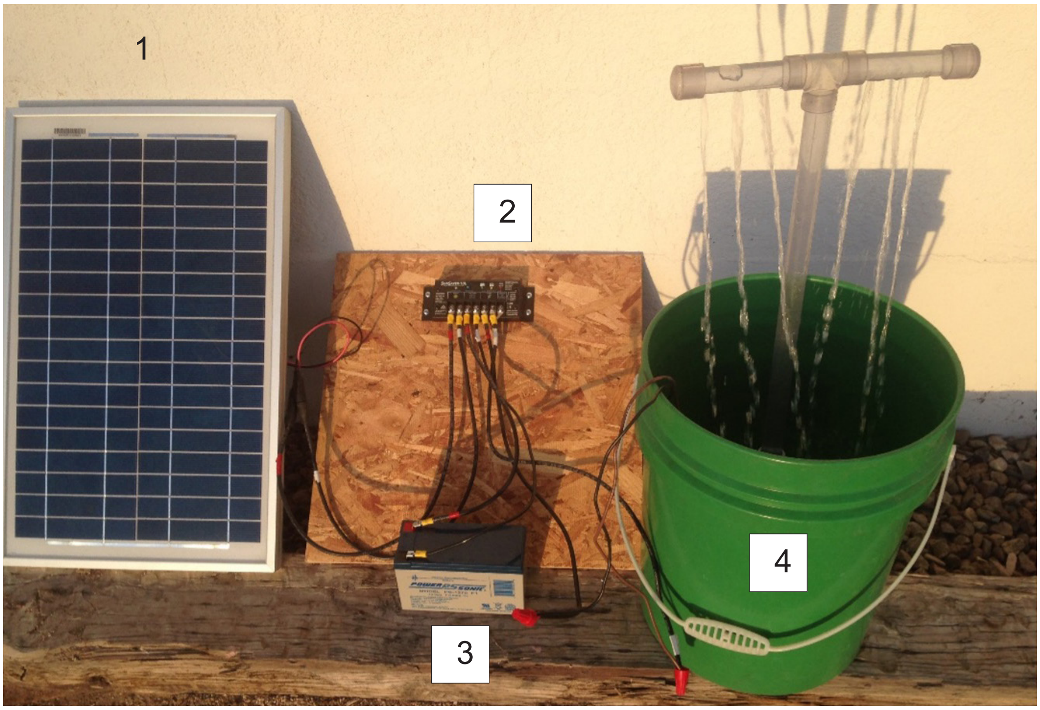

Figure 2. An example of a simple stand-alone solar PV system operating a DC load. The simple system includes a solar PV module (1), a WPM charge controller (2), a 12V battery (3), and a DC load (4). The DC load is a submersible sump pump used as a water fountain. Source: Author.

System Components

What sets apart a stand-alone solar PV system from other types of solar PV systems? Stand-alone solar photovoltaic (PV) systems provide energy for a load operating any time of the day regardless of available sunlight, regardless of location. A "stand-alone" system is not connected to the utility grid and operates independently. The basic components of a stand-alone system include the solar cell or module (1) the battery, a direct-current (DC) load, (2) charge controller, a (3) DC load, and (4) a battery. The following diagram illustrates the relationship of the DC system components.

This simple system produces electricity (PV array,) monitors the electricity (Charge Controller) from (and to) components, utilizes the electricity (DC Load), and both stores and draws the electricity (Battery). The load is dependent upon the battery (or battery-bank) for its source of energy. Figure 2 depicts an example of a stand-alone solar PV system. A PV solar module is wired to a charge controller. A submersible DC pump in the five-gallon bucket of water is the load and is connected to the charge controller. A 12-volt solar battery stores electricity and provides power for the pump in the bucket and is also connected to the charge controller.

Solar Module

Silicon crystalline-based solar modules are available in 36-cells, 60-cells, and 72-cells. A 36-cell module is a 12-volt module and is used for charging 12-volt battery systems. The 60-cell module produces 30-volts and is also used for 12-volt battery systems. The larger 72-cell modules, typically found in residential PV systems, produces 36-volts, and can be used for 24-volt and 48-volt battery systems. Strings of modules are assembled in series to create a desired system voltage. A series string is two or modules wired together connecting the positive (+) lead of one module to the negative (-) lead of another module. This results in the voltage of each module added together. This practice is used to build PV systems. Wiring ten 36-volt modules in a series string creates a system capable of producing 360 volts.

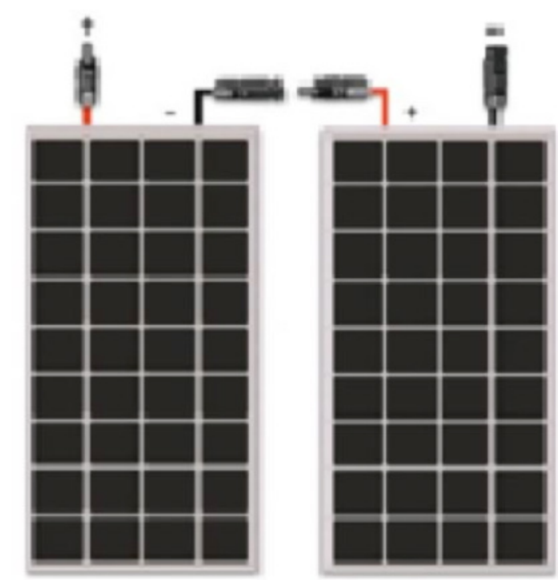

Figure 3. A series connection of two solar modules increases the voltage of the array. Source: renology.org

Figure 4. Two 17-volt modules wired in series produces 34-volts of electricity to increase the electrical power to the DC load. Source: Author

Temperature and Solar PV Voltage

Temperature has an inverse effect on solar cell output. Higher ambient temperatures with direct sunlight result in drop offs in solar PV voltage productivity. This can result in a loss of battery system charging if the solar modules are not rated for higher output voltages (Vmp). Many solar PV modules have a temperature coefficient of -0.3% /°C to -0.5% / °C (eco-greenenergy.com, 2021). Under Standard Test Conditions (STC), a solar cell is rated to produce the voltage and current at a temperature of 25 degrees Centigrade (25°C). A temperature coefficient is used to calculate the change of voltage for each degree of change in solar cell temperature. A typical temperature coefficient is 0.03% change in voltage for each degree change of 25o°C. For example, a Canadian Solar PV solar module (CSP-230) rated at 36.8 Voc has a Temperature Coefficient (for Voc) of (-0.34%/C°). For every one-degree Celsius above 25 degrees Celsius, the open-circuit voltage (Voc) of the solar module declines by 0.34 percent. On a sunny summer day, how much voltage can we expect to lose from the production of the array depends on the temperature of the solar cells. A noncontact thermometer aimed at the backside of the module can be used to obtain a temperature reading. If the reading taken on a module in Tucson, AZ on a sunny afternoon is 140-degree Fahrenheit (60 degree Celsius), the difference in temperature (from 25 degree Celsius (Standard Test Conditions) is 35 degrees (60 degrees minus 25 degrees). A 0.03% drop for every degree

Charge Controllers

The role of the solar module is to re-charge the battery. However, a solar battery cannot monitor the amount of current flowing into it from the solar module. The charge controller monitors the level of charge of the battery and prevents overcharging and undercharging of a battery. When battery charge level is low, the charge controller allows current from the PV module to flow into the battery. A direct current (DC) load (such as a light, fan, or water pump) is also connected to the charge controller. When the DC load draws down the current from the battery, the charge controller monitors the state of charge (SOC) of the battery and disconnects the load until the battery is re-charged. This prevents the energized load from depleting the battery. There are multiple types of charger controllers available. Two most popular types are *Pulse Width Modulation (PWM) and Multi Power Point Tracking (MPPT). The P*WM charge controller is an economical model. The PWM charge controller's nominal voltage of the solar panel must match the nominal voltage of the battery bank. A 12-volt battery bank must be matched with 12-volt solar modules. The charge controller selected must match the voltage range of the battery bank.

Sizing a PWM Charge Controller

Sizing a PWM charge controller is performed by selecting the short-circuit (Isc) current from the module string and the nominal voltage. A 12-volt battery bank requires a 12-volt module or solar array. If the stand-alone system is using a 24-volt battery bank, a 24-volt solar module or array is needed for the source. The PWM charge controller is rated by the maximum amount of current it can receive from the solar module or array. A solar module has two current ratings. One current rating is the current max power (Imp) value. This is the maximum current produced under load. The second current rating is short-circuit current (or Isc). This current value is higher than the current max power. The short-circuit current (Isc) is a value measured with a multimeter when there is no load connected to the solar module. The max power current value is rated under standard test conditions (STC) when the solar irradiance is measured at 1,000W/m^{2}. However, there are environmental conditions and times of the

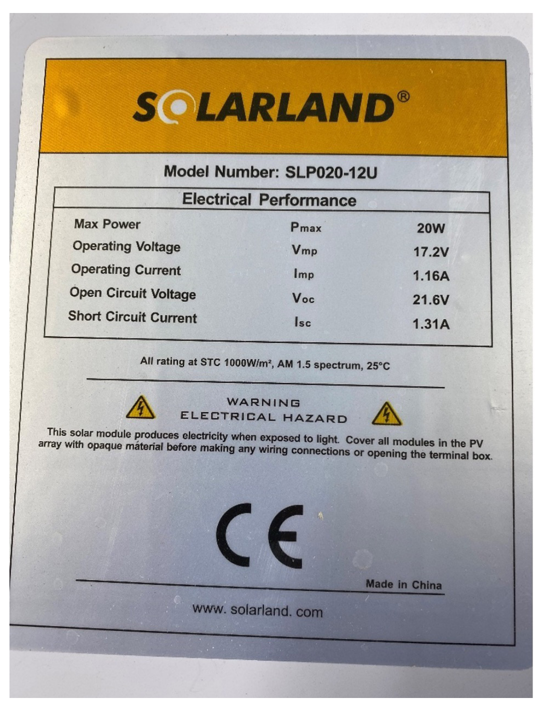

Figure 5. The short-circuit current (Isc) on this module is rated at 1.31A and the operating current (Imp) is rated ate 1.16A

Figure 6. Example of 6A, 12V PWM charge controller. Source: SunSaver.

when this value (1,000W/m^2) is higher. For example, when the sunlight is peaking from the edge of a cloud, the solar irradiance measured can spike. This would result in the solar module producing a higher amount of current. Since the short-circuit current (Isc) value of a solar module is always higher than the operating current (Imp) value, the Isc current value is selected. For an example of the current values located on a solar module, see figure 5 below.

The National Electric Code (NEC) is the "benchmark for safe electrical design (including solar systems), installation, and inspection to protect people and property from electrical hazards." (NFPA, 2020, pg. 1). The NEC manual recommends using the short-circuit current (Isc) value found on the solar module and multiplying the value by 1.25 as a safety factor. When the sun is shining brighter than Standard Rest Conditions (STC), especially on occurrences here in the southwest, we will add another 25% to the short-circuit current (Isc) value. Let's use the solar module in figure 5 as an example.

The 20W 12V solar module has an Isc of 1.31A, and the equation of 1.31A x 1.25 = 1.64A. We can use the 6A, 12V charge controller by Sun Saver for our solar module, and a 12V battery. For this make of charge controller, 6A is the smallest-size charge controller available. This unit would be sufficient for a smaller electrical load such as a light, a smaller pump, or a fan, and requiring energy storage.

What about a larger system with multiple solar modules wired together?

The module short-circuit current (Isc) value is multiplied by the number of parallel strings and the NEC safety value of 1.25. This value will indicate the size of the charger controller in amps. For example, a module Isc of 5 multiplied by a single parallel string (1) and multiplied by 1.25 equals 6.25 amps (5 amps x 1 x 1.25 = 6.25 amps). The next largest available model, a 10-amp charge controller can be selected.

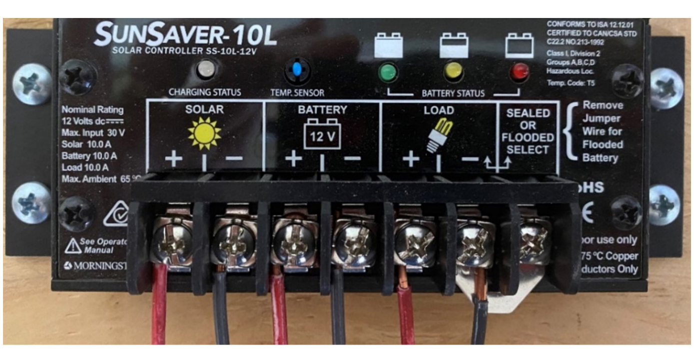

Figure 7. A 10-amp, 12-volt, PWM-type charge controller. Source: Author.

Figure 10. Float switch used in a low water cut off application in the mock well cistern Source: Author

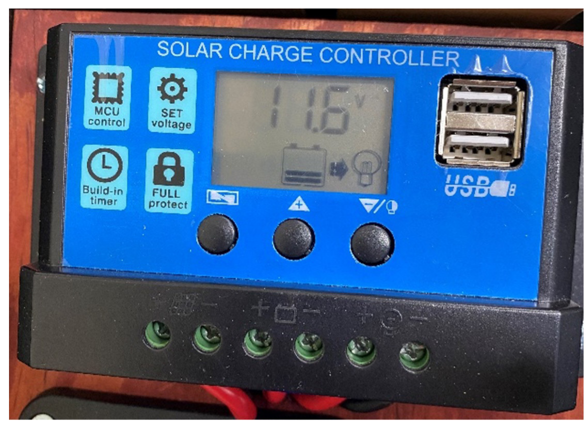

Figure 9. A 20-amp 12-volt PWM charge controller. Source: Author.Author

A MPPT charge controller is more expensive than a PWM charge controller. The advantage of the MPPT charge controller is that the higher voltage solar array can be used to charge a lower voltage battery bank without wasting or losing voltage. An array with higher voltage and lower current requires smaller diameter conductor wire. This is a saving to the owner of the system. Also, there are MPPT charge controllers that can take a lower voltage solar array and boost it. To size a MPPT charge controller for an array, take the total watts of the array and divide it by the voltage of the battery bank. An example, a solar array with 100-watt modules, with four modules wired in series, divided by a 12-volt battery bank multiplied by 1.25 (NEC requirement) equals 41.67A, (100 watts x 4 modules / 12-volts x 1.25 = 41.67 amps). A 50-amp MPPT charge controller can be selected. A review of the charger controller specifications will provide additional information about voltage requirements.

Figure 10. Examples of multi power point tracking (MPPT) charge controllers. Source: Author

Battery

Energy storage for use to power loads during early mornings and evenings is the purpose of the battery. Batteries designed for renewable energy systems (solar, wind, micro hydro) are of the deep-cycle rechargeable-type and are not the same as the primary battery found in our cars and pickups. These batteries are designed to be charged, discharged, and re-charged again. A deep cycle battery should not be discharged beyond 50% of its state of charge (SOC). There are multiple types of rechargeable renewable energy system batteries available to consumers. These include flooded lead-acid, (FLA), sealed batteries (AGM and Gel), and lithium-ion. Flooded lead-acid are more affordable, last longer than sealed batteries but require maintenance. Plus, their warranty is not if lithium-ion batteries. Lithium-ion batteries require no maintenance, can last 10 years but are the most expensive type of battery on the market. To protect the battery from overcharging a charge controller is connected between the solar module and the battery. Determine the size of the battery bank: 12, 24, or 48 volts. A guideline to consider is the size of system. Twelve-volt is used for systems whose load is less than 1 kWh/day, 24v for loads between 1 and 4 kWh/day, and 48v for loads larger than 4kWh/day. What is the size of the system you wish to operate, a small DC-system? A 2000-watt inverter may be available in 24-volt DC but a 6000-watt inverter will require 48-volts.

Figure 11. Example of an AGM-type lead-acid solar battery. Source: Author.

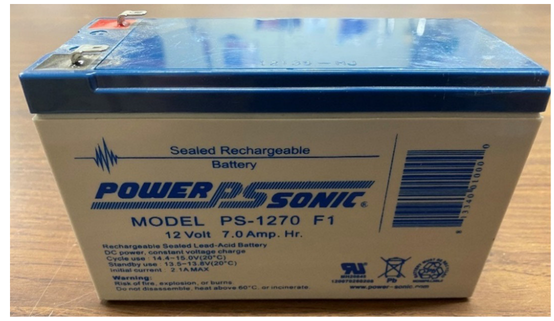

Figure 12. Example of a sealed lead-acid solar battery. Source: Author

Figure 13. Examples of Lithium batteries Source: Courtesy of Northern Arizona Wind & Sun


Figure 14. Example of 20 2-volt batteries wired in series produce a 24-volt battery bank. The positive terminal of each battery is connected to the negative terminal of the next battery. Source: Author.

Direct Current Load

Direct Current (DC) loads such as fans, lights, and water pumps can be connected to the charge controller. The bare ends of the positive (+) lead and negative (-) lead from the load are secured under the fasteners of the charge controller. The battery provides the energy for the DC loads.

Figure 15. Example of a direct current load: 12V LED lamp. Source: Author.

The following examples of direct current loads are connected to a system using a USB port cable or are plugged directly into a charge controller.

Figure 16. Example direct current load: 12V fan. Source: Author.

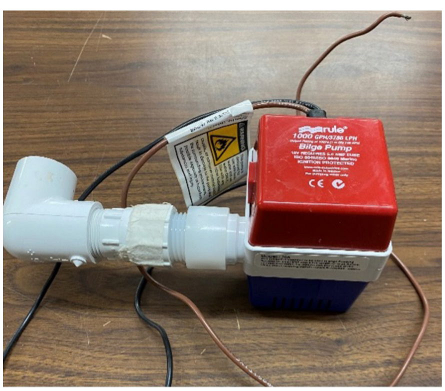

Figure 17. Example of a direct current load: 12V submersible bilge pump. Source: Author.

Fig 18. Example a direct current load: 12V light with USB connection. Source: Author.

Figure 19. Example of a direct current load: 12V solar-powered water fountain. Source: Author.

Systems with Both AC and DC Loads

Larger stand-alone systems such as off-grid cabins and residences, need to provide power for both direct current and alternating current loads. This diagram shows the components and the and the direction of travel of electrical current.

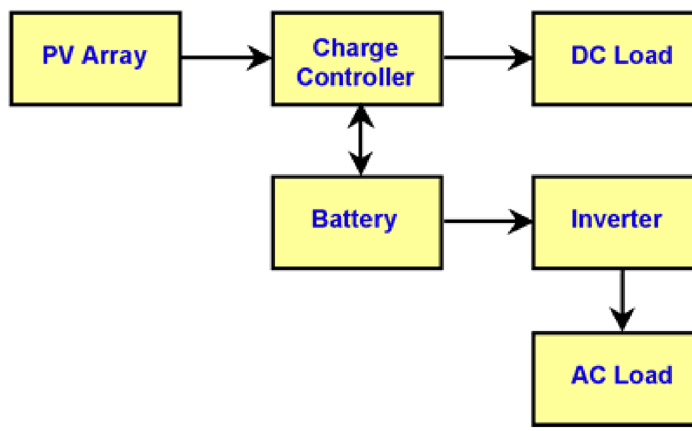

Figure 20. Diagram of stand-alone solar PV system both AC and DC loads and inverter. Source: Florida Energy Center

Inverters

What about alternating current (AC) loads as in a house? The current from the battery must be converted from direct current (DC) to alternating current (AC). An inverter designed for stand-alone PV systems is used. The inverter is connected to the battery and produces AC current. The inverter includes grounded outlets for plugs from AC loads and USB ports. Inverters are available in various wattages, input voltages from batteries, and sine wave frequencies.

The smaller direct current inverters plug into a 12v power socket and produces 100 watts. These are adequate for plugging in USB charging cords and smaller AC-powered tools or appliances such as a laptop, radio, lamp, or fan. Powering a cabin may require 24-volt input and require an inverter capable of producing 4,000 watts and an output voltage of

120/240AC. For a larger system, a 48-volt input (from the battery bank) can produce 4,400 watts and produce 120/240 VAC. Some inverters have the capacity to be "stacked" or connected for larger energy systems from 8,000 watts (8kW) up to 80,000 watts (80kW).

Larger pure sine-wave models are designed to handle the frequency signals of electronic devices such as laptop computers and communication radios with minimum distortion. Size in watts and unit cost are factors for consumers to determine.

Figure 21. Example of a smaller-sized DC inverter plugs into a 12V power socket. Source: Author.

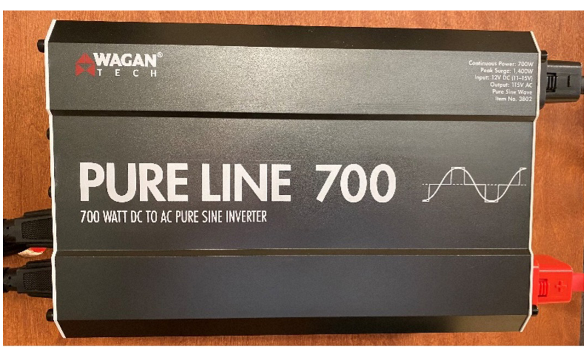

Figure 22. Example of a pure sine wave battery inverter with a 700-watt capacity. Source: Author.

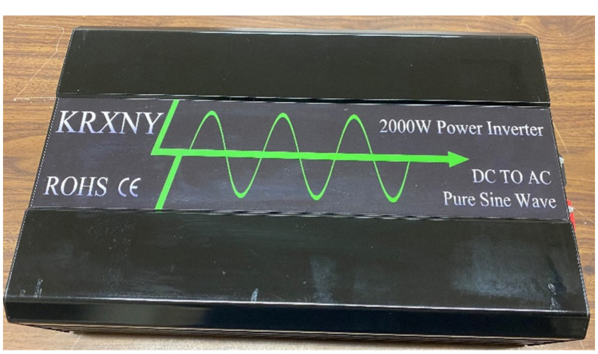

Figure 23. Example of a 2000-watt pure sine wave inverter for a stand-alone system. Source: Author.

Figure 24. A larger system inverter for off-grid systems. This unit is part of a system at an off-grid charter school in Northern Arizona. Source: Author.

Battery Monitor

These devices provide information for managing and protecting the battery bank. Units are relatively inexpensive and provide important data including charging status. It should be mounted in a visible location where a quick glance can inform the owner.

Figure 25. Battery monitor is used to show state of charge of battery bank. Source: Author.

Now that you are familiar with stand-alone solar PV systems and components, the next step is to design a system to fit your needs. The next solar factsheet focuses on the steps to designing your own stand-alone solar PV system

Backup Generator

A back-up power supply is important for charging a battery bank during periods of time when cloudy conditions during winter months and during monsoon seasons affect the power production of the solar PV energy system. An automatic starting generator fueled by propane can improve off-grid living.

Helpful Resources

Here is a brief list of renewable energy vendors and their website addresses. They are a source for individual system components, complete systems, and information about system design.

Backwoods Solar. www.backwoodssolar.com

Northern Arizona Wind & Sun. www.solar-electric.com

Wholesale Solar.www.wholesalesolar.com

AltE Store.www.altestore.com

Go Green Solar. www.gogreensolar.com

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