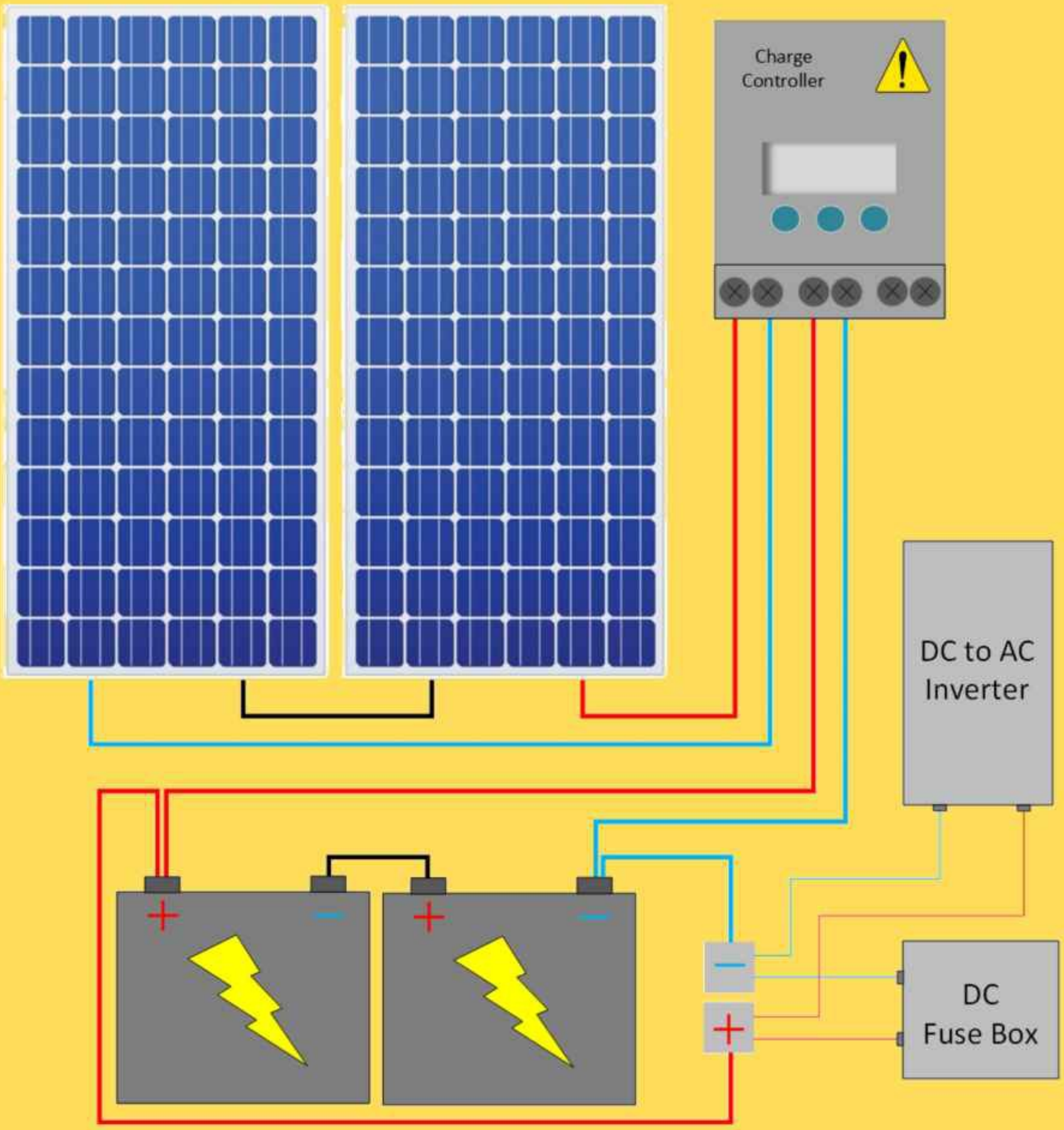
Off-Grid
Solar Power
Simplified

For RV's, Vans
Cabins, Boats, and Tiny Homes



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Off-Grid Solar Power Simplified

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Introduction

Among available renewable energy sources, solar photovoltaic (SPV) is the most practical, distributable, and mature of them.

With a demanding increase in grid-tied and off-grid PV systems, the need to provide a simple but yet technical reference for the design of these power sources is always increasing. A wide range of available options exist to size an off-grid solar power system and will depend upon the specific power and energy requirements of the user.

This book focuses on the pragmatic approach to design and install an off-grid solar power system with all the specific components, steps, and recommendations that you will need to size your PV system and install it in your Rv, van, cabin, boat, or tiny home.

Some of the important content you will find in this book refers to basic electrical principles, solar panel types, tools, and equipment used for the installation, inverter and battery types, charge controller specs, and types of PV systems.

Moreover, we will also discuss safety and precaution rules to install an off-grid system, steps to size, and wire up your solar array, as well as examples to give you a better idea about the schematics of a PV system.

The content in this guidebook will be explained in simple terms to give a clear idea to both technical and non-technical readers about all the requirements of an off-grid PV system.

This information will allow you to install your PV system without the need to require an electrician or a solar designer to complete the task.

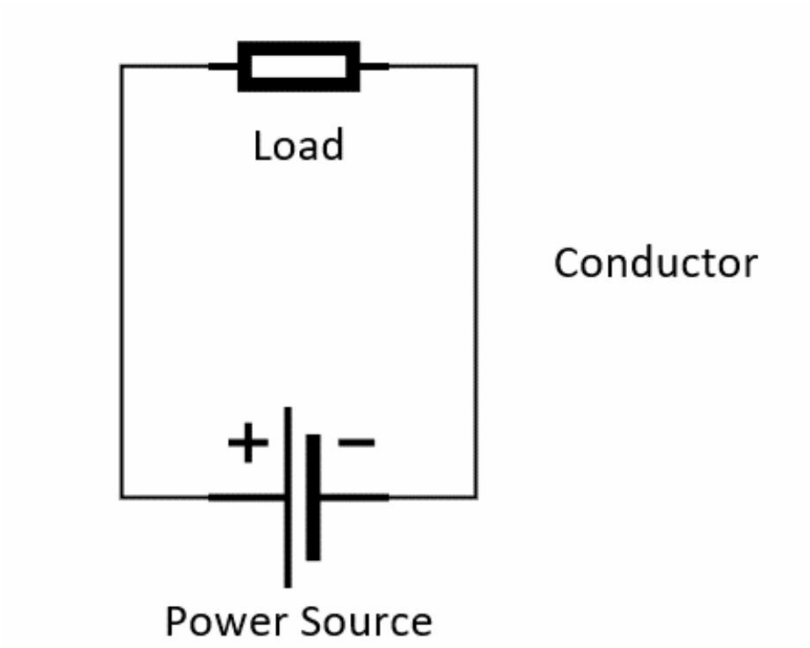
Electrical Units

Energy can be described in many ways, but basically, energy is referred to as the capacity of developing a specific work. Energy is presented in many ways in nature, and one of them is electricity, which can be described as the capacity to establish electrical work.

To understand how electricity works, some important concepts must be addressed.

First, you must understand that an electrical circuit can be described as the interconnection of electrical components where at least three basic elements will exist:

- Power source
- Conductor
- Load



Basic electrical circuit

The power source is referred to as the element that produces or stores electricity (a battery, a generator, or a solar panel).
The conductor is simply the element through which electricity flows.

The load is the element that receives electricity from performing some sort of work (a lamp generates light, a motor provides motion, and an electrical resistor generates heat).

Now, in order to understand the concepts that will be explained throughout this book, we need to describe some electrical terms first.

Voltage

Electricity is generated by the movement of electrical charges (electrons). In order to move an electron from one point to the other, it is necessary to perform electrical work.

This work is performed by an electromotive force (EMF) or voltage, which is generated by the power source. Voltage can be understood as the pressure required to move the electrons from one point (A) to a second point (B) within an electrical circuit. The greater the voltage, the greater the flow of electrons through an electrical conductor.

This movement is generated from the highest electrical potential point (A) to the lower electrical potential point (B), and voltage is referred to as the electrical potential difference between these two points.

Voltage is measured in Volts (V).

Current

The second important concept is the electrical current.

The electrical current can simply be understood as the intensity of the flow of electrons per second through a conductor.

This element is measured in Amps (A).

Resistance

The resistance is referred to the opposition of a specific material to the flow of electrical current. In other words, the resistance provides a reference of how easy or hard it is for the electrons to flow through any material (steel, aluminum, copper, etc.).

Every electrical load or conductor has an internal resistance, which is typically measured in ohms (Ω). For example, wood has a higher electrical resistance than copper.

Power

Power is one of the most important variables in electricity as it represents the combination of voltage and current in an electrical circuit.

In order for an electrical load to perform any type of work (illumination, motion, heat), this element demands an instantaneous equivalent work source, which is provided by power. Power acts as a reference to the rate at which electricity is delivered (power source) or consumed (load) and is the product between voltage and current. The unit of power is Watt (W).

Electrical Energy

As we mentioned before, power is referred to as the instantaneous rate at which electricity is provided or consumed. When we refer to energy, we are evaluating how electricity is being delivered or consumed over time.

In other words, electrical energy can be described as the power generated or consumed over time.

As a general convention, electrical energy is typically expressed in watt-hour (Wh), which represents the consumption of a specific number of watts in a single hour. This unit will generally be used to account for energy consumption of electrical loads in an off-grid solar power system.

Also, when consumption is bigger, it is generally expressed in kilowatt-hours (kWh), which is referred to as the consumption of 1,000 watts of power in a single hour. This unit will generally be used to account for electricity generation or consumption of an entire solar power system. You will be already familiar with the term Kilo Watt-hours, as it is listed on your electricity bill.

Amp-hour

Energy can also be expressed as consumption of the amount of current in a single hour and is referred to as amp-hour (Ah).

Amp-hours is used to describe the amount of energy a battery can store. The battery of a typical smartphone has a capacity of 3 Amp-hours or 3,000milli Amp-hours.

Ah is mainly used in off-grid solar power systems to indicate the amount of energy a battery can store.

Energy Measuring Equipment

Digital Meter

The digital meter (regularly known as a digital multimeter) is a test tool that is used to measure at least three variables:

- Voltage (AC and DC)
- Electrical current (DC)
- Resistance

A digital meter combines the capabilities of three tools into one: an analog voltmeter (measures volts), an analog ammeter (measures amps), and an analog ohmmeter (measures resistance).

Typical digital meter

Every digital meter should have:

- A display to show measured values.

- Button(s) to switch available mode options.
- A rotary switch to select the variable that will be measured.
- Input jacks for test leads.

The meter will have a range of unit scale measurements from millivolts (mV) to volts (V), from milliamps (mA) to Amps (A), and from milliohms(mΩ) to mega-ohms (MΩ).

You will need to know the range of the unit that you will be testing in order to select the right scale and obtain an accurate result.

Generally, for solar power applications, we will use the voltage, ohm scale, and sometimes amps.

Keep in mind that you will have test leads with insulated wires, which will be used to test electrical circuits. There will be a test lead for positive terminals (red), and a test lead for negative terminals (black). When measuring DC circuits, the colors (polarity) of the wires matter. It does not matter in AC because it is alternating. More on this later.

When you test voltage, you need to put the black lead in the 'COM' input and the red lead in the 'V' input. Then you need to select the 'V' variable on the rotary switch and place the positive and negative leads accordingly to obtain an accurate measurement. Otherwise, you will obtain a negative value.

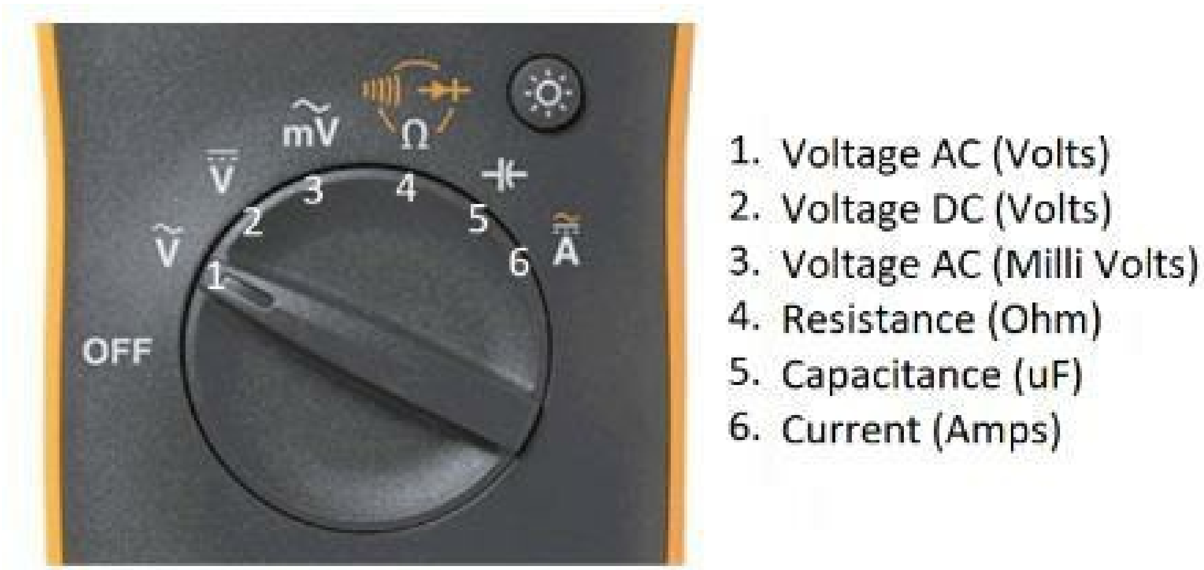
Input terminals of a multimeter (left: black, right: red)

The same concept applies to measuring resistance. The black lead will need to be put in the 'COM' input, and the red lead should be in the 'Ω' input, which is the same as the 'V' input. Select the Ω symbol on the rotary switch and measure the resistance of a device.

When you are testing voltage, you must measure it in an open circuit, which means measuring without load. For example, if you wish to measure the voltage that comes out of your power socket, you touch the positive and negative wire of both pins to the electrical wires.

If you want to measure resistance, you must measure it without any applied voltage. For example, if you want to check if a fuse is broken, you take out the fuse and measure at both ends of the fuse. If the display states a resistance of 1 or higher, the fuse is broken. Resistance is also measured in an open circuit.

Read the manual of the digital multimeter for further information on how to measure voltage, resistance, and current.
Although you could measure current using a digital meter, it's better to use an ammeter for this. This is because current will flow through your meter, which will potentially damage it or blow a fuse inside if there is no load applied. There is really no need to measure current because you can calculate it using the formulas discussed in the next chapter.



The layout of a Fluke digital multimeter

Ammeter or Clamp Meter

The digital ammeter or clamp meter is a device that combines the advantages of a digital multimeter with an additional feature.

Similar to the digital multimeter, the ammeter is able to measure voltage (DC and AC), resistance, continuity, AC current, and other variables as frequency, temperature, or capacitance.

The main difference with the multimeter is that the ammeter includes a clamp that allows you to measure the RMS (root mean square) value of the electrical current. You simply need to open the clamps and close it around a conductor through which an electrical current is flowing. You cannot measure a cable that has a positive and negative wire inside of it. It can only measure one wire at a time because they will cancel each other out. An ammeter is only able to measure AC current, which is not very useful for solar systems.

This is possible because the current creates an electromagnetic field that the clamp is able to sense and transform into an electrical current value.

This instrument becomes really useful to measure current in the wiring system located after the inverter.

Ammeter by Etekcity

Basic Formulas

To perform calculations related to sizing an off-grid PV system, you will need to use some basic formulas.

Ohms Law

$$V = I \times R$$

Where,

V = Voltage (Volts)
I = Electrical Current (Amps)
R = Resistance (Ohms)

Or,

$$I = \frac{V}{R}$$

Or,

$$R = \frac{V}{I}$$

Power

$$P = V \times I$$

Where,

P = Power (Watts)
V= Voltage (Voltage)
I = Electrical Current (Amps)
Or,

$$V = \frac{P}{I}$$

Or,

$$I = \frac{P}{V}$$

Energy or Watt-hours

$$E = P \times t$$

Where,

E = Energy (Watt-hours)
P = Power (Watts)
t = Time (hours)

This unit is used by your electrical company to bill your energy consumption. Watt-hour is a large number. Therefore, a kilowatt-hour is used. This means that 1,000 Watt-hours is equal to 1-kilowatt-hour or simply 1 kWh.

Running a heater with a power rating of 1,000 Watts for one hour will consume 1,000 Watt-hours of energy or 1 kWh.

$$E = 1{,}000 \text{ Watts} \times 1 \text{ hour} = 1{,}000 \text{ Watt hours or } 1 \text{ kWh}$$

Let's explore why voltage is an important factor when calculating Watt-hours.

Let's take two batteries for a better explanation.

- Battery one has a capacity of 2 Amp-hours at 12 Volts.
- Battery two has a capacity of 2 Amp-hours at 1.2 Volts.

It seems that these batteries have the same amount of stored energy because the amp-hours are the same. However, this is not true because the voltage is different. Let's calculate the number of watt-hours that is stored in each of these batteries.

$$2 \text{ Amp hours} \times 1.2 \text{ Volts} = 2.4 \text{ Watt hour}$$

$$2 \text{ Amp hours} \times 12 \text{ Volts} = 24 \text{ Watt hour}$$

From the calculation, we can clearly see that the stored energy in battery two is greater. That is why watt-hours must always be seen in context with the voltage of a battery.

Energy Cost

$$\text{Energy Cost} = \text{Energy in kWh} \times \text{Rate in cents per kWh}$$

Every state or country has different rates for electricity. To know how much you need to pay your electricity provider, you need to know your local electricity rate. The national average in the U.S. is $0.12 per kilowatt-hour. Note that the unit is per kilowatt-hour and not per watt-hour.

If you run a light that has a power rating of 20 Watts and run it for 8 hours each day for 30 days, this is how much you will need to pay your electrical provider:

$$\text{Energy in kWh} = \frac{20\ \text{Watts}}{1{,}000} \times (8\ \text{hours} \times 30\ \text{days}) = 4.8\text{kWh}$$

$$\text{Energy Cost} = 4.8\text{kWh} \times \$0.12 = \$0.576$$

Amp-hours

$$\text{Amp hours} = \text{Amps} \times \text{hours}$$

One Amp-hour is equivalent to one amp expended for one hour.

Amp-hours is not commonly used in standard electrical practice but is used for calculating the capacity of a battery bank.

For example, a simple AA battery has a capacity of 2,000mAh (milliamp hours) or 2Ah.

This means the battery can supply a load of two amps for the duration of one hour. It could also deliver one amp for two hours, and so on.

If you have a bigger battery that has 100Ah of capacity, you can draw 100 Amps for one hour or 10 Amps for 10 hours.

This is only in theory because different batteries have different depth of discharge (DOD) limits. For example a lead-acid battery can only use half of the battery capacity to keep it healthy. We will talk more about this in the battery chapter.

AC and DC

Difference Between AC and DC

In a solar power system, you will most likely have two source signals:

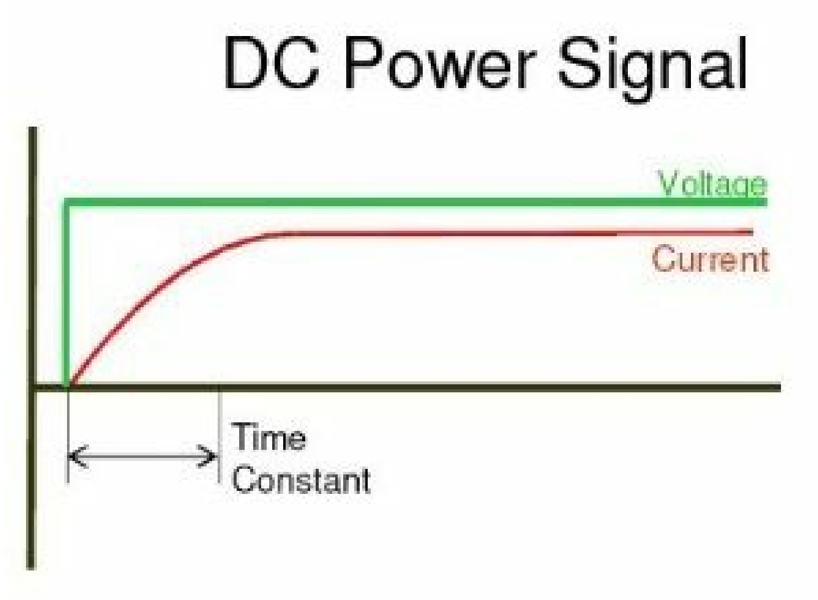
- DC – Direct current
- AC – Alternating current

Therefore, it is important that you understand the differences between these two signals in order to know which device you must use, where, and why.

Simply put, DC stands for Direct Current, and AC stands for Alternating Current. The direct current is an electrical signal that constantly flows in a single direction across the electrical circuit over time.

AC and DC symbols

In the following image, you can see a DC voltage signal, which is stable and always has a constant value. However, values in other cases may increase or decrease over time.



DC Voltage Signal
Source: LWClearning

The most important factor in qualifying as a DC signal is that the wave is either entirely positive or entirely negative (always above or below the X-axis).

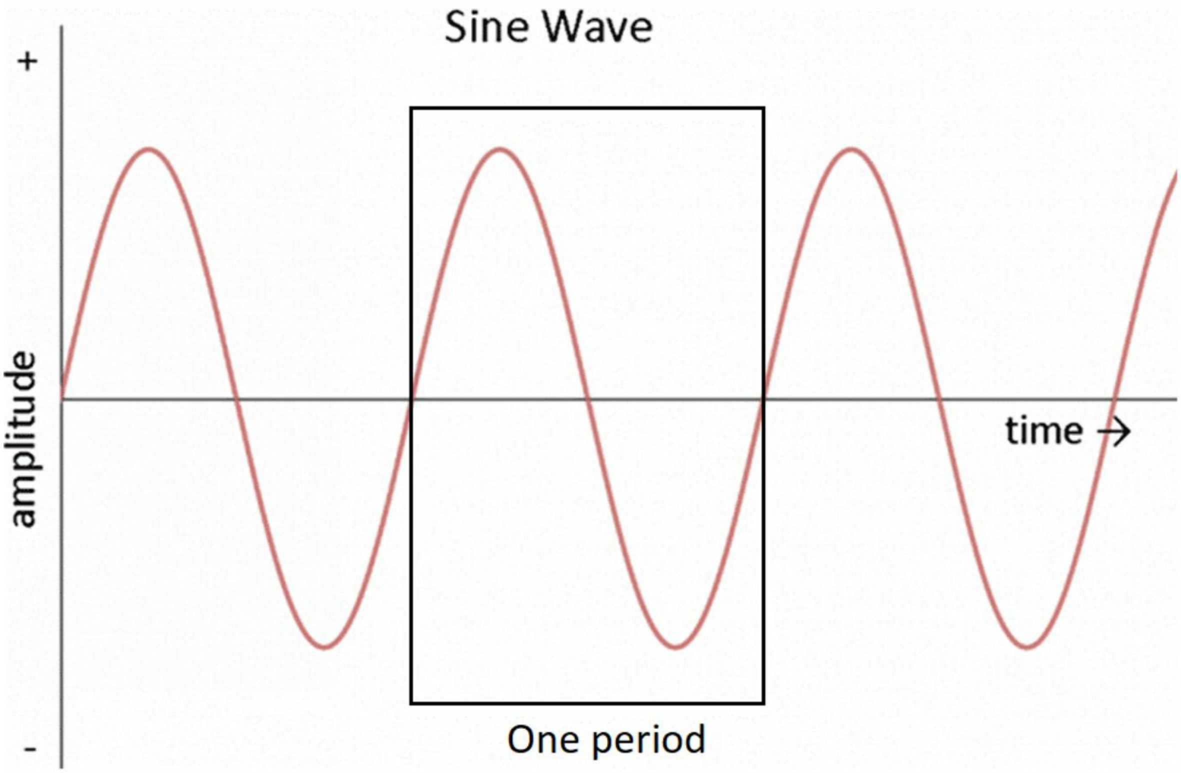
The best example for DC power source signals is a battery. Any battery generally provides a constant DC voltage (generally between 2V and 12V), while the electrical current may increase, decrease, or stay constant over time, depending on demand.

The solar panel is also a DC power source. When testing voltage and current for this component, you will need to use DC measurement instruments.

If you measure DC voltage with a digital meter, you will get a reading in positive (+) or negative (-). This way, you can figure out the polarity of a DC source. Try it with a battery and see if you can figure out the polarities without looking at the positive and negative signs.

On the other hand, AC is completely different.

In this case, the electrical signal fluctuates direction over time. The signal changes between positive and negative values periodically over time. This is what we call a sine wave.



AC power signal and one period

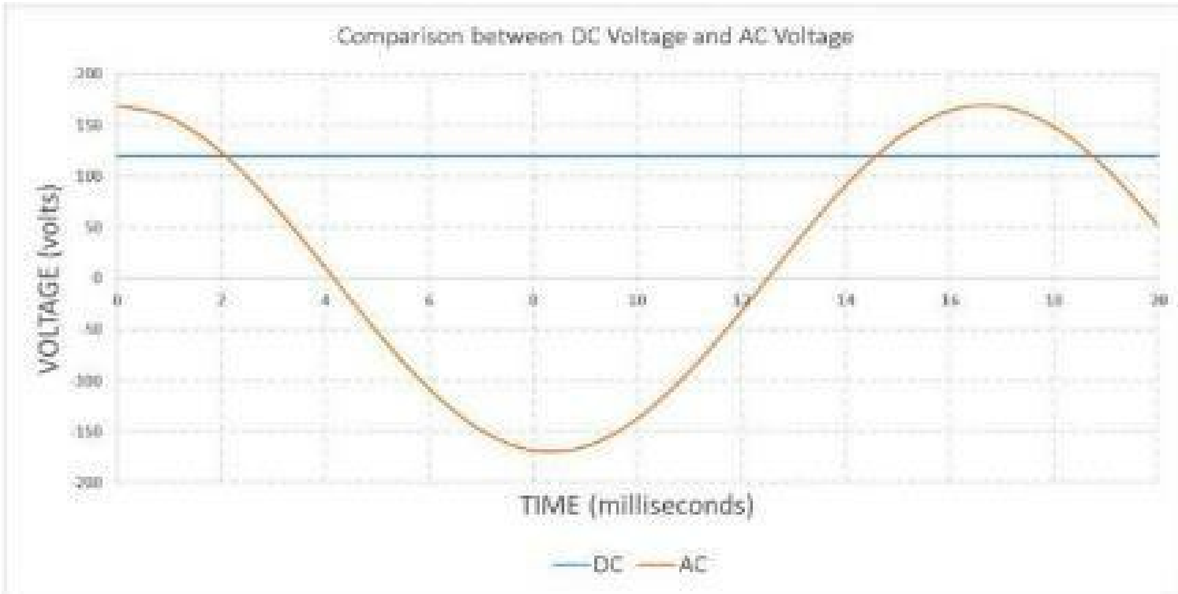
This alternating shape is created by a device called the synchronous generator, which uses mechanical energy (derived from the movement of a turbine driven by water or steam) and converts it into a periodical electrical signal output.

As this generator has a rotor that spins around its own axis in 360 mechanical degrees, the output signal always features 360 electrical degrees. These changes in the value of the AC signal are always referred to the period of the wave, which at the same time are referred to the frequency of the signal.

Another method of creating an AC signal from a DC source is to use electronics which we will be talking about in the chapter about inverters.

Most countries around the world use frequencies of 50 Hertz.
The U.S., Canada, and several other countries use 60 Hertz. This means that in the U.S., the electricity completes 60 periods in one second.

In the following image, you can see DC and AC voltage in the same graph.



DC and AC Voltage Curves
Source: Zoroad Electric

Now, you may be wondering how you can measure the value of the AC signal when it's constantly changing.

The measuring instruments for AC signals will always display a specific value called the Root Mean Square (RMS) value. If you measure with a digital meter, you will always measure the Root Mean Square.

The RMS is a constant value of the AC signal that is equal to the value of the direct current that would produce the same average dissipated power in a completely resistive load.

In the following figure, you can see the position of the RMS in an AC voltage signal.

V RMS value of a voltage signal
Source: Wikipedia

This means that the peak (maximum volts) of a sine wave in the U.S. measures 170 Volts AC, but you will see 120 Volts AC on your measuring device.

Or, Volts peak = $1.414 \times \mathrm{Vrms}$

The power grid works using an AC signal that reaches the residential, commercial, and industrial sectors under particular specs related to quality, voltages, and ancillary services.

At the residential level, there may be three possible types of RMS values for the AC voltage:

- 120V single phase
- 120/240V split phase
- 208V three-phase

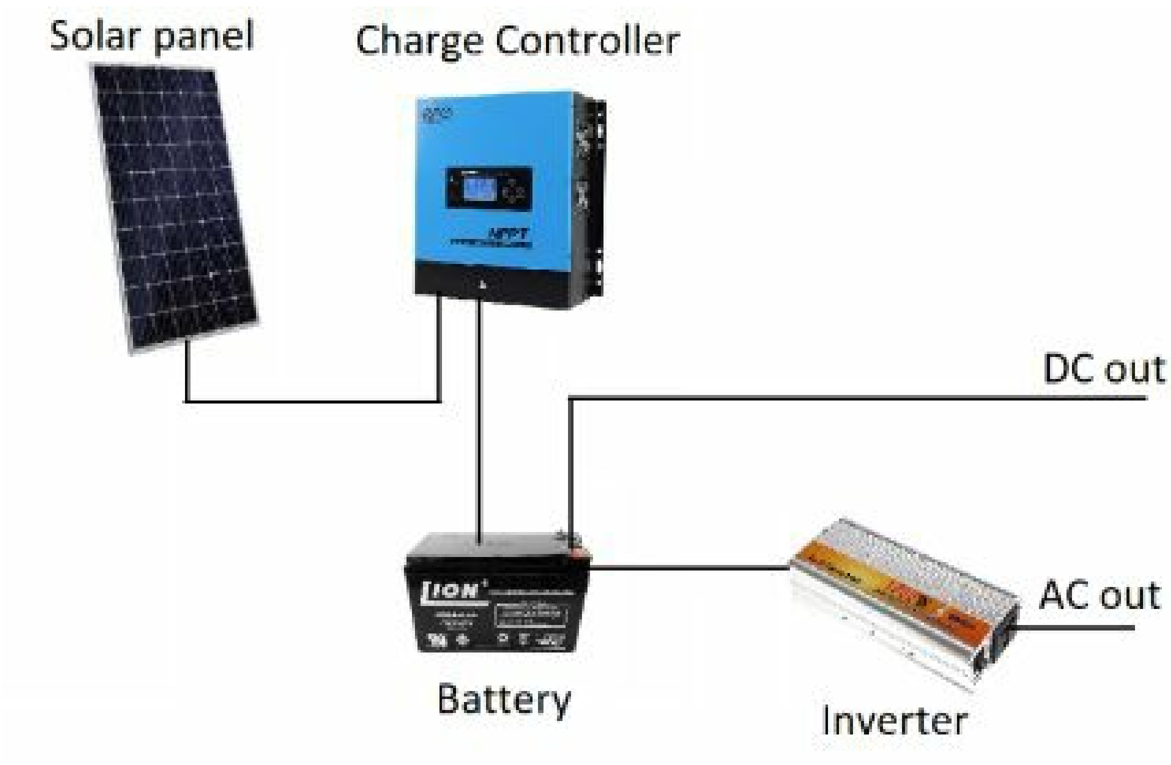
Most countries use different power grids. In Europe, for example, the power grid is different. You will find these values:

- 230V Single-phase
- 400V Three-phase
- 690V Three-phase

AC and DC in the System

In a solar power system, you will most likely have both AC and DC signals. The solar panels, the batteries, and the charge controller will always work in DC. The inverter will transform the DC signal coming from the battery into an AC signal to power specific loads.

Therefore, when you test voltage or current in any part of the electrical circuit located before the inverter, you will have to measure in DC, while if you test any variable in a section located after the inverter, you will measure in AC.



Basic outline of AC and DC in the solar PV system

Equipment

Among some of the topics that you must be aware of to install an effective off-grid solar power system is the basic equipment that is required. Here you can see a list of items you would need when building a solar system.

Wiring

There are many types of wiring you can use. I highly recommend getting stranded wire, which consists of multiple wires in one. This has the advantage of being very flexible, while solid cables are very hard to work with.

Stranded flexible wires

If you are going to buy wires in the store, you will have two options. Buying copper wire or aluminum wire. Copper wire is a better conductor than aluminum, but it is also more expensive.

Since copper is a better conductor of electricity than aluminum, you need to increase the diameter of your aluminum wires to account for this. More information about this in the wiring chapter.

The diameter of the wire depends on the amount of current the wire needs to transport. The higher the current, the thicker the wire needs to be. If the wire is too thin, it will heat up, which will reduce its efficiency, or in the worst case, catch fire. Using fuses to protect the wires is essential. We will talk about choosing the right fuses later.

Wire Lugs

The wire lugs are metal-based components that are required to make a solid connection between the connections to the batteries. Wire lugs are used for the parts in your system where the highest amount of current will be. You will find multiple options available from different manufacturers and materials.

Basically, you can use any of them as long as you consider that the size of the battery terminal lug fits the wire gauge and that the terminal lug is also suitable in diameter for the battery posts. You will need a special tool to crimp the wire lugs on to the wire, which we will discuss in the tools chapter.

You can buy battery interconnection cables that already have the terminal lugs included. This way, you don't need special tools to fit these bigger wire lugs. Remember that the thickness of the wire depends on the current that has to flow through the wire.

Example of an interconnection cable with wire lugs


Wire lugs for different AWG wire

Apart from the AWG size, you have two options when buying wire lugs. One is copper, and the other is tin-plated copper. Copper tends to corrode over time, while the tin-plated copper is not. I recommend using the tin-plated ones for your project.

Wire lugs are used for big cables only. For smaller cables, crimp connectors are used.

Crimp Connectors

Hopefully, you are convinced to use stranded wire for your solar system. The only downside to using stranded wire is that you need crimp connectors at both ends to connect your terminals to other devices.

The reason for using crimp connectors is that it gives a better point of contact to the device terminals, which reduces heat loss. It will eliminate the creation of corrosion at the exposed sides of the stranded wire.

There are several types of crimp connectors:

- Blade
- Ring
- Spade
- Ferrules
- Bullet

Several types of crimp connectors

Ferrules, rings, and spades are the most used in solar applications. Ferrules are used to connect to the terminals of the devices while ring and spades are used to connect to busbars.

Like most crimp connectors, they come in several colors. Each wire diameter has its own connector color. We will discuss which wiring diameter you need in the wiring chapter.

Different sized ferrule connectors

- AWG 10 (Green)
- AWG 12 (Gray)
- AWG 14 (Blue)
- AWG 16 (Black)
- AWG 18 (Red)
- AWG 20 (White)
- AWG 22 (Orange)
- AWG 22 (Yellow)

Color coding is not always standardized so they can differ.

Bullet connectors are used to fit MC4 connectors. These are used to transport the electricity from the solar panels to your combiner box. The plastic MC4 connectors protect the cable from moisture, dust, and rain.
They also function as a plug and play wiring method for combining solar panels in a string or array (series and parallel).

Several different MC4 combiners

After stripping the wire insulation with a wire stripper, you can place the crimp connector, which will then fit through the MC4 connector. Use a crimping tool to apply pressure on the crimp connector and secure a good wiring conductivity.


Inserting the stripped wire in the bullet connector

Crimping the wire inside the connector

Crimped wire inside the connector

Inserting the crimped connector in the MC4 housing
Source: Marine How-To

Next, you need to tighten the connector to the wire using an assembly tool, which will most likely be delivered together with the MC4 connectors.

MC4 Assembly tool

If you do not want to make these cables yourself, you can buy them already made. This is easier and will reduce the possibility of error. Search for ‘MC4 connector cables.’ Make sure you select the right gauge size for the current that flows through it.

Busbar

In electrical power distribution, there is an element that is crucial to consider in any installation: the busbar.

These are copper or aluminum strips that can typically be seen inside switchgear or panel boards that carry all the currents in any electrical system. They act as the collection or distribution of electrical currents through which there is a path from the generation source up to the loads. They are also called a central wiring terminal.

There are several uses for busbars:

- Positive busbar
- Neutral busbar
- Ground busbar

There are smaller busbars mainly intended for small, off-grid PV applications with just a few pins for interconnection between components (inverter, charge controller, and batteries). In smaller systems, you do not need any busbars.

Small 250A busbar

Busbars are also useful in combiner boxes, which we will talk about next.

Displays

One of the details that you will notice as we go ahead in the topics is that many of the components of the PV system will need to be placed into compartments where access may not be regular or easy.

In order to have a visual of the charging stage of your battery or the solar power output that is generated, you will need to have a display instrument. This device will constantly show the values of the variables related to voltage, current, and power that you can locate in any other place that has easy access.

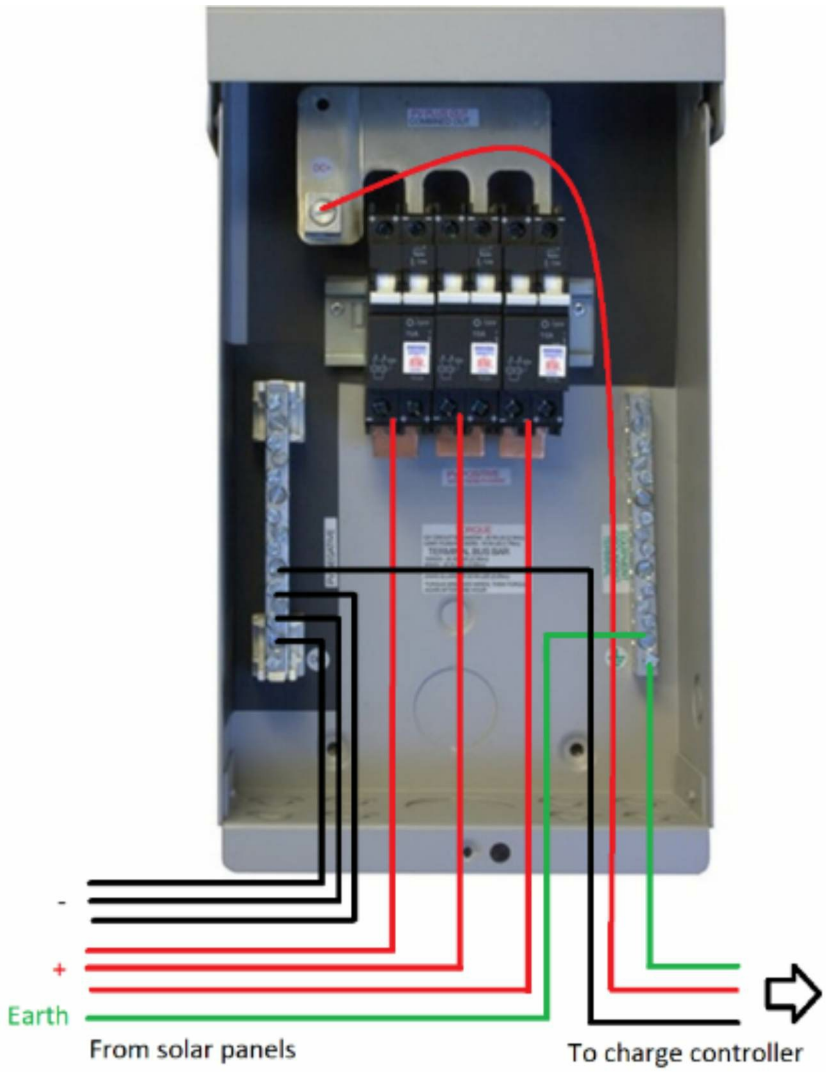
One example of such a case is the battery monitor of a battery bank. In the following image, you can see the voltage level of a lead-acid battery. There are many other displays available like the shunt, which we will talk about later in the book.

Battery voltage indicator

Combiner box

This component is a box that contains all the connections coming from every string of solar panels and joins them in a single wire. It is mostly used when connecting panels in parallel.

From this connection, two higher wire gauge output cables (one for positive terminal and one for negative terminal) contain all the generated DC electricity and transport it to the charge controller. The combiner box generally consists of a negative bus bar, a ground bus bar, a positive PV bus bar, circuit breakers or fuses, and an optional surge protection device.



Combiner Box Wiring scheme
Based on MidNite 20A combiner box

The combiner box is usually set as close as possible to the string of PV modules in order to reduce voltage drop or DC wiring ohmic losses. Therefore, in residential or commercial applications, they are typically placed outdoors on the roof or on the ground, depending on the type of PV system. Refer to the mounting instructions of the combiner box if you are going to use one.

When selecting a combiner box, you must be aware of several factors:

Encapsulating Rating

Typical encapsulating ratings are classified under the National Electrical Manufacturers Association (NEMA) standards. Typical encapsulating ratings for combiner boxes are type 3R and type 4X.

The type 3R rating enclosure is constructed for either indoor or outdoor use and protects the equipment inside against incoming solid particles (dirt) and the ingress of water as well (rain, sleet, or snow). It also provides protection for the equipment against the formation of ice on the exterior side.

Meanwhile, the type 4X enclosure rated combiner box protects all internal equipment from windblown dust and for the ingress of water (in the rain, sleet, snow, or splashing water). It also protects against corrosion and the formation of ice on the exterior side as well.

In order to make the box weatherproof, the feeding of the cables should be done by using a PV wire cord grip. This is a plug that takes several PV wires and makes the enclosure watertight.

PV wire cord grip

The output side, which goes to your charge controller, needs regular cord grips.

Maximum Voltage Capacity

The combiner box is also designed to withstand a specific voltage rating to provide insulation. Typical low voltage applications for off-grid purposes will be rated at 600VDC.

Fuse or Breaker Capacity

Also, the combiner box will generally have a specific rating for fuses and breakers in volts. The number of breakers/fuses that can be placed inside is also very important to consider, as this will indicate if the combiner box is able to connect all the PV strings.

Let’s talk about fuses and circuit breakers in the next chapter.

Fuses and Circuit Breakers

Fuses or circuit breakers which are put inline in your solar system are not intended to protect the device it is wired to.

Devices like the charge controller and the inverter have their own fuses. The reason why we put fuses or circuit breakers inline is to protect the wiring of the system from getting hot, melting, or even catching fire.

Therefore, the fuses or circuit breakers that are placed inline are calculated on the size of the actual wiring. This is to protect your system from catching fire if there is a higher current flowing through the wires at which they are rated for. This is how you determine fuse sizes:

1. Figure out the load.
2. Figure out the distance to the appliance (voltage drop).
3. Decide wiring thickness.
4. Decide fuse rating based on wire thickness.

There is an exception to wires that come directly from solar panels. The wiring coming from PV panels is bigger than it needs to be to minimize the voltage drop. The back of the solar panel will display the maximum allowed fuse size (more on this later).

An example of this is that you will be running wires that are rated for 30 Amps to minimize voltage drop, but the maximum fuse for the solar panels is only 10 Amps.

Technical data of a solar panel

Where to Place Fuses

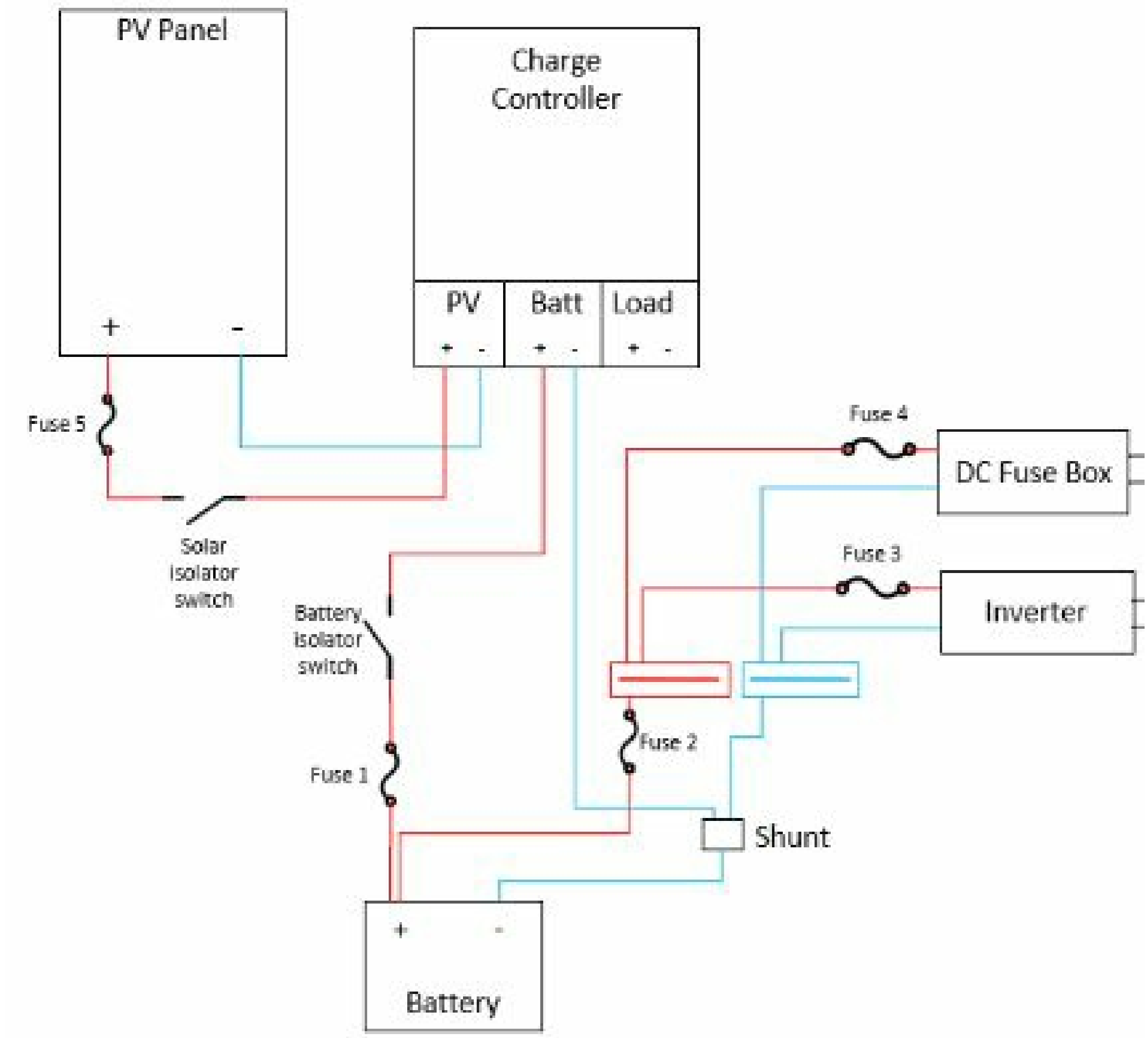
Fuses should be placed as close as possible to the energy source. If current flows from your battery to your inverter, place it as close to the battery as possible. If current flows from solar panels to the charge controller, place it as close as possible to the solar panels. Only place fuses on the positive (red) wire.

Fuses should be placed in the following locations:

- On the positive wire from your solar panel(s) to your charge controller (as close as possible to the panel itself). You can use an inline MC4 connector fuse for this. You can put a fuse in a combiner box if you wire in parallel.

Inline MC4 connector with fuse

- On the positive wire from the charge controller to the battery.
- On the positive wire from the battery to the busbar.
- One the positive wire from the busbar to the inverter.
- On the positive wire from the busbar to the DC loads.



Placement of fuses in your solar system

Fuses vs. Circuit Breakers

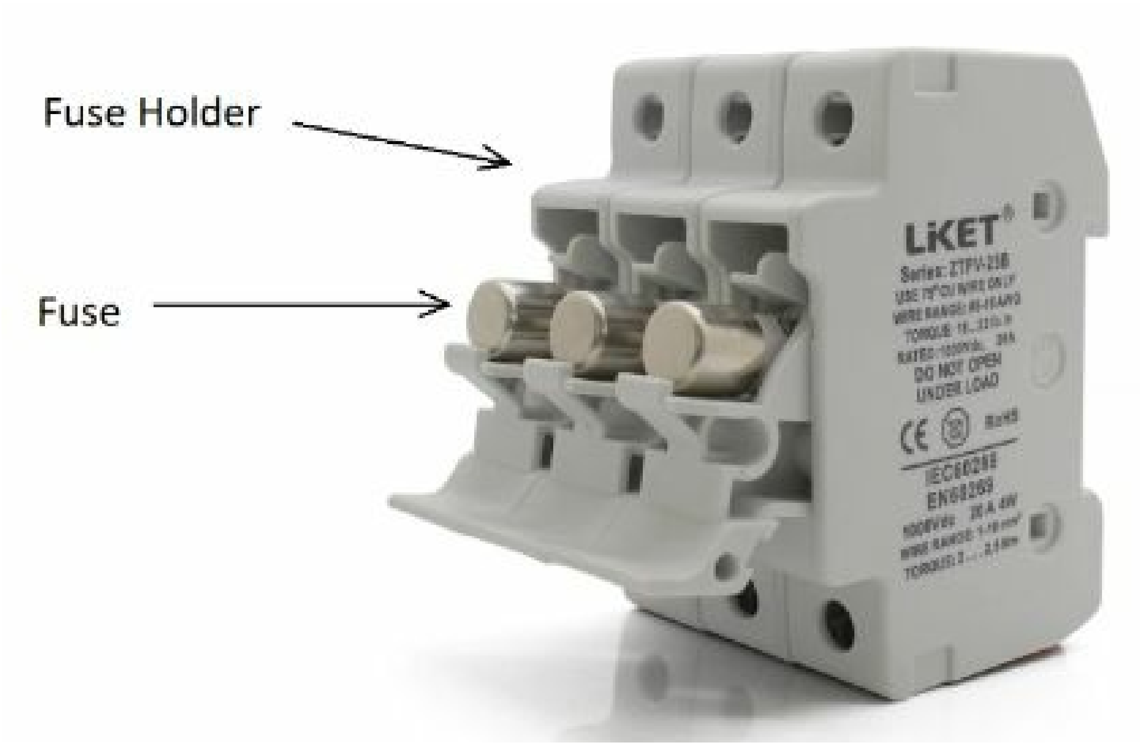
DC protection devices are essential to guarantee the safe and effective functioning and operation of any PV system.

For this purpose, there are two main types of DC protection devices: Fuses and circuit breakers.

Fuses are overcurrent protection devices that contain a filament inside that heats up as current flows through it. When a specific current located above the permissible limit passes through the filament, the filament heats up above its thermal capacity and melts. When the wire inside the fuse melts, the circuit gets opened.
An overcurrent can be produced by:

- An overload caused by excessive current demand from the electrical loads, above the design limit.

- A short-circuit caused by a fault that occurs in the circuit.



Fuse holder with removable fuses

On the other hand, the circuit breaker is another popular protection device intended for overcurrent protection as well.

A thermal protection mechanism is based on a bimetallic contact that heats and expands when an electric current located above the rated value is present. This protects the circuit against overload. A magnetic protection mechanism instantly responds to high fault currents that protect the electrical circuit against short-circuits or overcurrents.

Inside the DC breaker, two contacts split when an overcurrent passes through the protection device, automatically switching it to the OFF position.
The DC breaker needs to be put back in the ON position to allow electric current flow again through the circuit. There is no functional difference between fuses or circuit breakers. If a fault occurs with a fuse, you need to replace it. With a breaker, you flip the switch back in the on position. Fuses are cheaper than circuit breakers.

Keep in mind that for solar power applications, you must choose circuit breakers that work on DC to protect solar panels and batteries. Circuit breakers that work on AC are used to protect the AC loads.

DC breakers

Now, you may be asking yourself, which protective device should you use for each application?

I recommend using fuses for parts in your circuits that do not easily trip. This is the DC part of your solar system.

Circuit breakers can be reused each time that they trip, and they are more intended to protect multiple electrical circuits.
You will need to use fuses specifically for protecting the battery bank as higher currents flow through this circuit, and the protection speed of these devices will guarantee that the batteries will not suffer any damage.

Finally, for the main AC panel, it is more common to use circuit breakers to protect loads in residential-sized or off-grid PV systems.

Because of the high current in DC systems, it can get very expensive to use DC circuit breakers. Therefore, fuses are preferred.

Slow or Rapid-acting?

Fuses and circuit breakers can also be classified according to their response speed.

The acting speed is the time it takes for the fuse to open once a fault current or overload passes through the filament. This is dependent mainly on the material used for the fuse element.

Selecting the accurate fuse type also involves selecting the appropriate speed response for the particular application that you are using. Choosing a fuse that acts too fast may not allow normal current operations to run, while choosing a fuse that is too slow may not interrupt faulty currents quickly enough.

There are 3 main types of fuse speeds:

- Ultra-rapid
- Fast-acting
- Slow-acting

Ultra-rapid fuses are mainly used for semi-conductors' (electronics) protection.

Fast-acting fuses can be used to protect cabling and less sensitive components such as batteries and PV modules.

Finally, slow-acting fuses feature a built-in delay that temporarily allows the flow of inrush electrical currents in electrical motors.

When checking the datasheet of the fuse, you may find some of the following marks, as described in the following table:

Marking	Description
FF	Very Fast Acting Fuse
F	Fast Acting Fuse
M	Medium Acting Fuse
T	Slow Acting Fuse
TT	Very Slow Acting Fuse

Generally, for battery and solar panel protection, you will need FF, F, or M type fuse ratings. If you intend to protect a more specific load like a motor or pump, you might need to select a slow-acting fuse in order to allow normal inrush (starting) current to flow.

Electrical engineers use a detailed analysis of this aspect considering time vs. current graphs of the fuse to ensure that the protection device acts when it needs to.

Let's look at different fuses and circuit breakers.

Spade Fuses

A type of fuse that is widely being used in solar power applications are spade fuses, also called blade fuses. These can easily be found in the electrical fuse box of most cars. Their principle is the same as described before. You have to replace them once they trip.

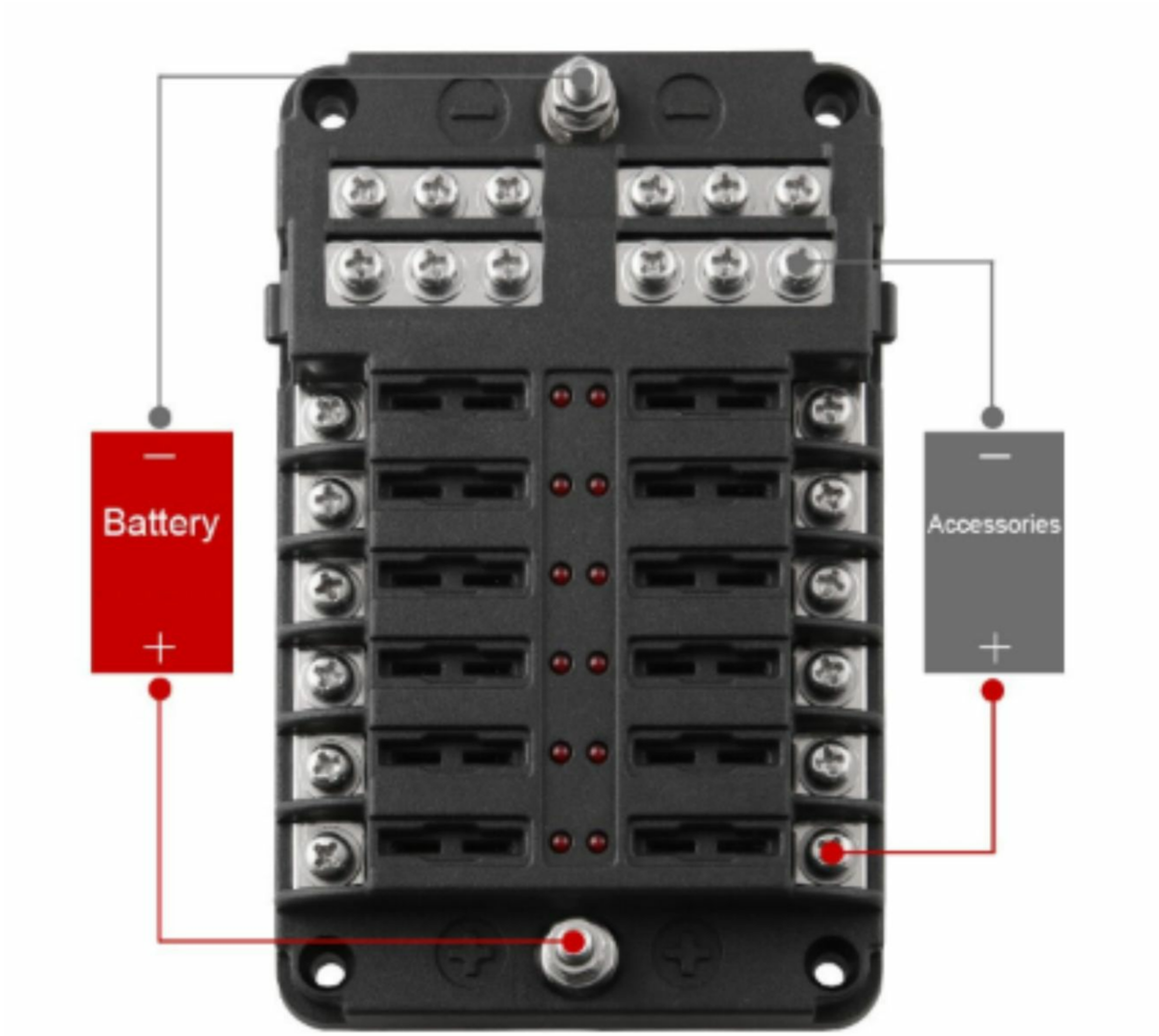
These can be used to act as overcurrent protection for multiple DC loads.

6 spade fuses

The color of the spade fuses indicates their current rating.

Color	Current
Dark blue	0.5 A
Black	1 A
Gray	2 A
Violet	3 A
Pink	4 A
Tan	5 A
Brown	7.5 A
Red	10 A
Blue	15 A
Yellow	20 A
Clear	25 A
Green	30 A
Blue-green	35 A
Orange	40 A
Red	50 A
Blue	60 A
Amber/tan	70 A
Clear	80 A
Violet	100 A
Purple	120 A

Spade fuses can be used in the part of your system where DC loads are attached. Using the following fuse box will give you a neatly organized DC load box for led lights or ceiling fans.



Fuse box for spade fuses

Wiring of a DC fuse box using spade fuses
Source: Blue Sea Systems

ANL Fuses

ANL fuses are especially used in off-grid applications, in RVs, or boats due to their simplicity and their integrated case box.

These fuses are used for high current applications, mainly as the fuse between:

- Battery and charge controller
- Battery and DC loads
- Battery and inverter

They typically go from 60A up to 500A and maybe more, depending on the manufacturer.
Just as with any other fuse, when an overcurrent exceeding the rating of the fuse passes through it, the fuse will instantly break.

Two metal prongs are available at the ends of the fuse to attach it to a specific case box that can later be mounted on any surface using screws.

ANL fuse with box

Circuit Breakers

Circuit breakers are mostly used in AC systems. Fuses are better suited for high current DC systems.

There are mainly three types of circuit breakers.

- Single pole
- Double pole
- Triple pole

Single-pole models are suitable for most circuitry. Simple loads such as fans, TVs, microwaves, coffee makers, home theater equipment, and any other load that works in 120VAC will need a single-pole one.

Other loads such as air conditioners, washing machines, dryers, and some motors work in split-phase configuration requiring nearly 240VAC. Therefore they need double-pole circuit breakers. Finally, some loads will need to work on three-phase systems at 208VAC. Therefore, they will need a triple pole circuit breakers.

Mainly large AC motors will be the ones using this type of breaker, which will not be generally used for small off-grid applications. Below, we can see samples of each type.

Single pole breaker

Double pole breaker

Triple pole breaker

No-name Safety Equipment

I recommend buying fuses and breakers from well-known brands. It only has to fail you once, and you are in trouble. Instead, opt for a brand that is known for many years in the solar industry and purchase your equipment from there.

AC or DC Equipment?

AC components are cheaper than DC components, mainly because of the scale of production.

Some people use AC equipment in their DC solar system. However, this is not a good idea because the DC equipment works differently and has other internal components than AC equipment. Therefore, it is not recommended to use AC safety equipment in DC circuits.

DC Isolator Switch

DC circuit or DC isolator switches are used to decouple parts of the solar system from each other. They are used when maintenance needs to be done to the components in the system.

DC isolator switches are placed in these locations:

- Decoupling solar panels from the charge controller.
- Decoupling batteries from the system.

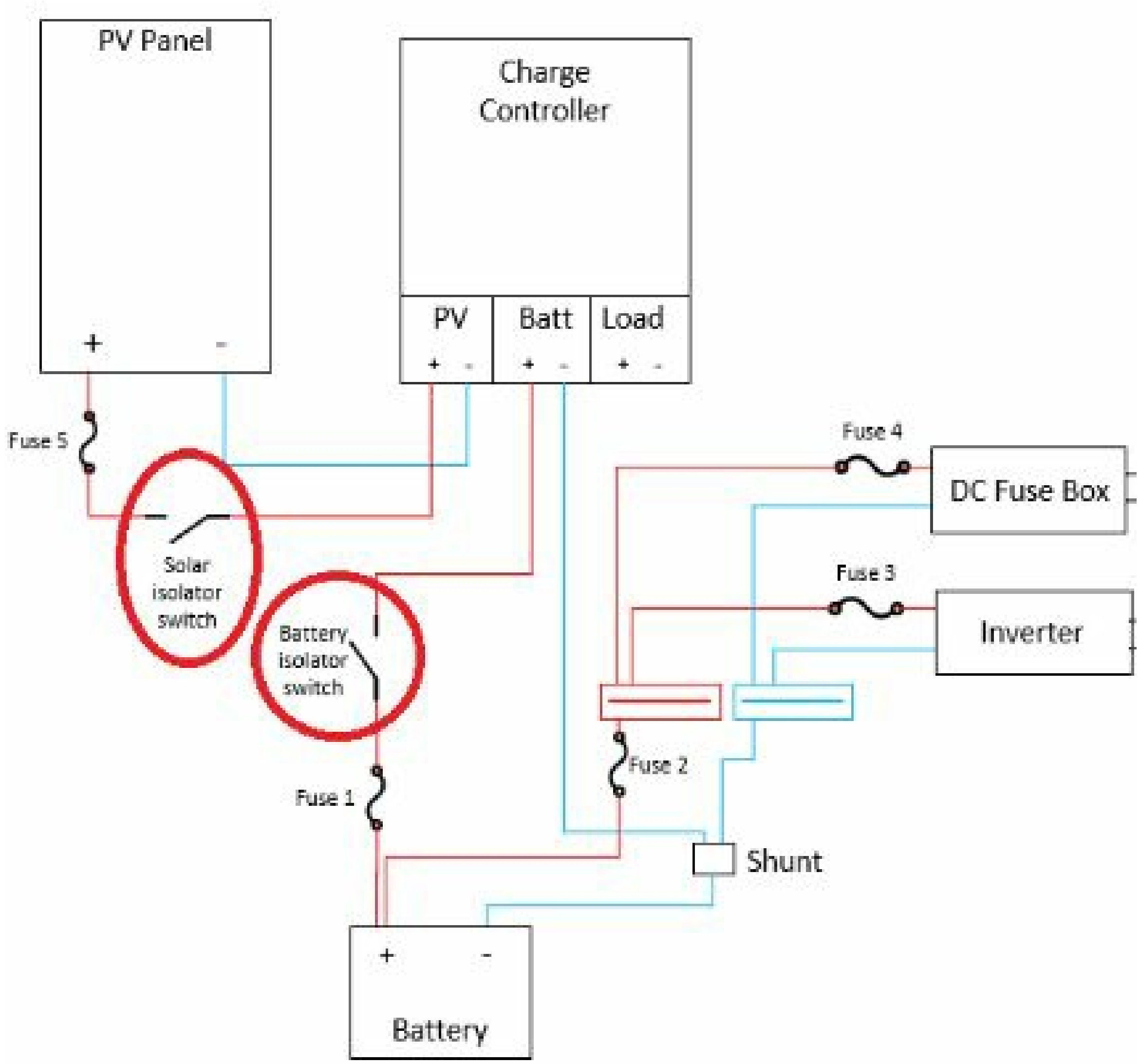
Before you buy a DC isolator switch, make sure it complies with the system’s current and voltage. For example, the DC isolator switch (solar disconnect switch) that is coming from your solar panels has lower current but higher voltage while the isolator switch from the battery requires higher current but lower voltage (depending on the voltage of your battery bank).

48 Volts DC, 300 Amp battery isolator switch

800 Volts DC, 25 Amp solar disconnect switch

I do not recommend using regular circuit breakers as a disconnect switch because they are not built for switching under load that often.

Always buy an isolator switch that has a higher voltage and current at a specific point in your system.



Where to place isolator switches

Tools

Wire Stripper

A wire stripper is a multi-use tool that is necessary for any electrical installation (including solar photovoltaic). It allows you to strip and cut any wire with gauges between 10-24AWG. The tool will allow you to easily cut either copper or aluminum wires with precision and without damaging the metal part of the electrical wire. Moreover, an integrated swivel knob can adjust the precision of the two jaws effectively to modify the power as needed.

Wire stripper

Cable Stripper

A cable stripper is also needed to strip cables from #5AWG to 4/0AWG, something that a wire stripper wouldn’t be capable of doing. The cable stripper is capable of cutting PVC, rubber, foamed polyethylene (PE), along with other insulating materials.

The interesting and more useful fact about this tool is that you can make longitudinal, circular, spiral, and mid-span cuts to the end of stripping to remove the jacket of the cable. The tool includes a cable holder that makes the cutting process easier and precise. It can be easily adjusted to the gauge of the cable. The cutting is made through a blade depth knob that adjusts the blade (which is also replaceable) to fit the size of the cable.

Always calibrate the tool on the wire end to make sure the blade is adjusted properly.

Cable stripper

Lug Crimping Tool

This product is specially intended for installations where battery banks are used. The product can crimp battery cable lugs with standard sizes between #8AWG and 1/0AWG.

The tool is generally built with a high-quality carbon steel material that ensures a long service life, and that is equipped with an ergonomic grip that is wrapped up with an anti-slip rubber material that makes it comfortable to use. The stripping of the cable to introduce the lug must be done with another tool.

Lug crimping tool

Hammer Lug Crimper

Another option for the same purpose is a hammer lug, which is a manual and more economical solution to crimp the cable lugs for your battery bank. The tool is capable of crimping cable lugs for gauges between #8AWG and 4/0AWG (which covers all possible cable gauges for battery applications).

The crimping process with a tool like this is done very simply by adjusting the ram head according to the wire and the terminal sizes. Then, the lug is placed in the jaw of the crimper while it is struck with a hammer (1-2 times is enough) to press the lug against the copper or aluminum.

Hammer lug crimping tool

Crimping Tool

This tool is suitable for crimping individual wires. It integrates a ratcheting mechanism that has an adjustable clamping force useful for precise and repeatable crimps that also adds more crimping power into each squeeze.

Its ratcheting mechanism allows you to secure a wire connector even before inserting the stripped wire into the small barrel.
You will be able to crimp wire terminals for gauge sizes between 22 and 10AWG split into three cramping options marked by the colors red, blue, and yellow that will indicate the gauges ranges for each purpose. It has also been designed with an ergonomic material that offers a comfortable and secure grip.

Crimping tool

Conduit Cutter

The next tool in our list is the conduit cutter. Conduit is generally used in electrical installations to protect cables or wires from water and/or physical damage.

However, for the conduit to fit your wiring installation, you must be able to cut it to adjust the length properly. For this purpose, a conduit cutter tool is needed.

The conduit cutter can be used for multiple applications that go from cutting PVC pipe to cutting PEX pipe. It is also suitable for cutting CPVC, PP, and PE-XB pipes that will allow you to cut the pipes within a few seconds.

PVC conduit cutter

Metal Conduit Cutter

The metal conduit cutter is an excellent choice for electrical installations where metal conduit is used.

This tool has been designed to make clean cuts on multiple metal materials such as aluminum, brass, copper, and even thin-wall steel. The steel tube cutter also features a large and ergonomic knob which provides a firm grip to cut tubing faster and easily. It is important to know that a metal tubing and conduit cutter can perform neat cuts for tubes that can go between 3/16 inches to 1-1/8 inches.

Metal conduit cutter

Screwdrivers

Screwdrivers are needed in almost any installation. However, for electrical installations and specifically for photovoltaic installations, using an insulated screwdriver is essential.

For this purpose, purchasing a screwdriver set with 6 pieces that have been tested to be able to resist up to 1,000 Volts AC or 1,500 Volts DC is the best choice. Each tool will be covered with a non-conductive material that can reach such a rating, and that makes it safe for electrical installations where high voltages are used.

Besides, a soft handle with an outer cushion grip allows you to add 40% more torque than traditional plastic handles.

Electrical screwdrivers

Needle Nose Pliers

The needle nose pliers are the perfect tool to bend wires and other metal structures. Their half-round tapered jaws are longer and narrower, quite useful in occasions where other pliers cannot reach.

This tool also features a serrated gripping surface that provides a secure grip with less slipping while featuring an integrated side cutter for cutting soft, medium, and hard wires. These pliers come with a cutting tool but are generally not used for that purpose.

The needle plier can generally be found in three handle styles: plastic coated handles, comfort grip handles, and the 1000V insulated handle that meets IEC standards, which is the model for electrical installations.

Needle nose pliers

Wire Cutters

The wire cutter is another valuable tool that you must consider in any electrical or plumbing installation where you will need to cut wires.

The tool is also integrated with machined jaws to provide the maximum gripping strength and has been designed with an induction hardened cutting edge that stays sharper for longer.

Normal wire cutter

Another valuable option is the flush-cut micro soft-wire cutter with a long jaw and an angled head for flush-cutting applications on wires and soft wire. This kind of tool will have a 21-degree angle for flush-cutting and its heat-treated carbon steel construction can provide durability and long-life performance.

Small wire cutter or flush cutter

Cable Cutter

There may be occasions where the wire cutter alone might not be enough to perform all the required work for heavy-duty applications with thicker cables. The cable cutter is the perfect choice for this purpose since it is capable of cutting up to 0AWG gauge cables, and cutting both copper and aluminum.

Cable cutter

Hex Nut Ratchet Set

The hex nut ratchet set is something that you need in order to perform electrical installations of any kind, including photovoltaic installations. They can be used to tighten the battery terminals. The bits can be used to drive screws to mount to components.

Ratchet set

Torpedo Level

Whenever you are performing measurements to install devices, or for any structure equipment that needs to be installed on a wall or simply recessed, you need to keep the equipment balanced and straight, that´s when a level will come in handy.

Torpedo level

Hole Saw

The sharp teeth of each saw are perfect for making holes in wood, PVC boards, plastic, drywall, and even metal as well.

They are suitable to provide a clean and smooth cut with high precision. The cutting depth can vary from 43-mm to 50-mm according to different sizes. Two mandrels are used for hole saws (large and small with a medium adapter).

Hole saw set

Hacksaw

A hacksaw is another tool that is very useful to cut and fit the installation frame of your solar panels. This item should feature 45° or 90° blade angles that are used for standard and flush cuts. Moreover, the design of the hacksaw can withstand heavy-duty use thanks to the high tension that holds the blade.

Hacksaw with a metal cutting blade

Cordless Drill

A cordless drill is suitable for drilling pilot holes and mounting screws or bolts on any wall-surface. It is just another essential piece of your toolkit.

The cordless drill generally features two-speed transmission sets at low speed (about 500RPM) and high speed (about 1,900RPM), suitable for a wide range of drilling and fastening applications.

The most useful feature is that this kind of drill does not need an AC plug connection.

Cordless drill

Drill Bits

As a valuable complement of the previous tool, the drill bits are also needed for making pilot holes to mount appliances or devices on a wall-surface such as an inverter, or a charge controller.

Drill bit set

Safety Goggles

Last but not least, to protect your eyes during the installation of solar equipment, you will need to use safety goggles.

You can generally find them in different sizes to fit the shape of your head, and they can also integrate bi-focal shatterproof polycarbonate lenses. The lenses can be found in different colors that vary from copper to yellow, gray, smoke, and transparent. These lenses could provide sun protection as well.

Safety goggles

Basic Circuitry

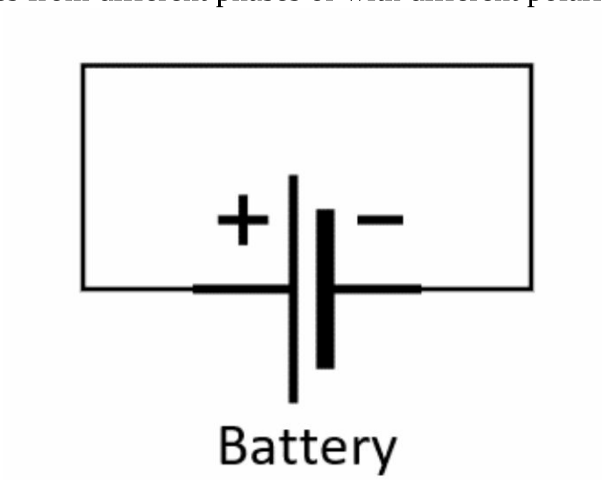
What is a Short-circuit?

A short-circuit can be described as a non-normal operational behavior of an electrical circuit where a large amount of current flows through an unintended path that has a very low resistance.

Short-circuits are generally associated with two scenarios:

- Short-circuits between phases.
- Short-circuits to ground.

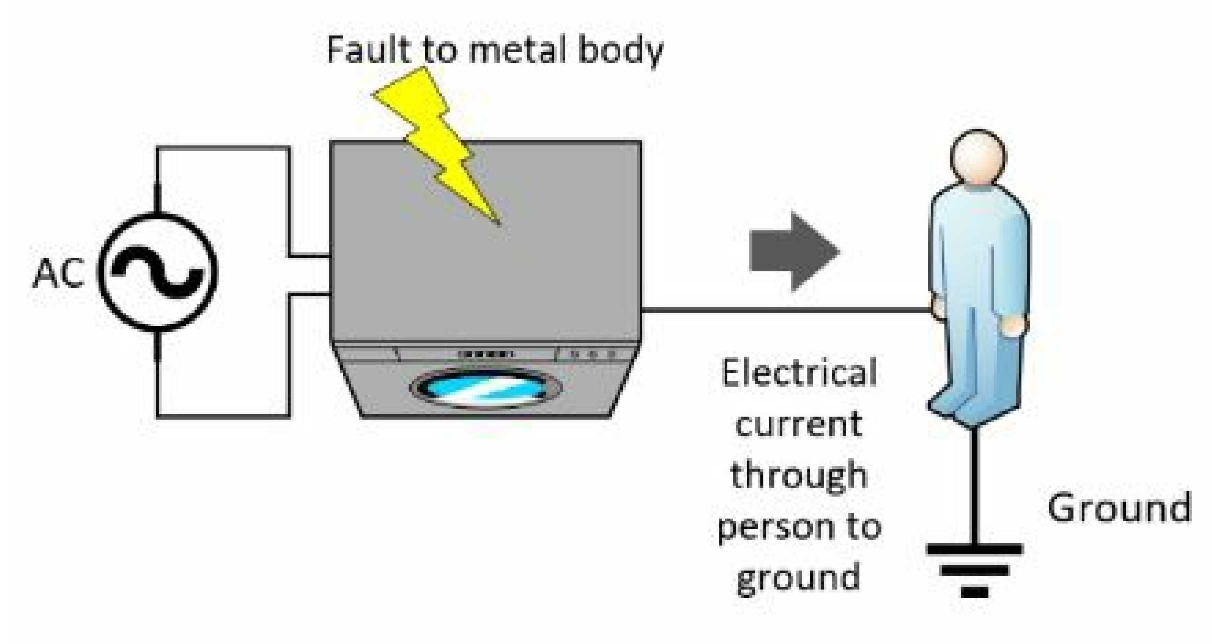
Short-circuit between phases occur when there is a direct contact (metal with metal) between battery terminals or cables from different phases or with different polarities.



Short circuit between terminals on a battery

This is unlikely to happen unless you connect the positive and negative of a battery together with a single wire (do not try!).

The short-circuit to ground occurs when a metallic part from a single wire in an electrical circuit, enters in contact with another metallic component that is not part of the circuit. This creates a large electrical current that flows to the ground and is the most common type of short-circuit.



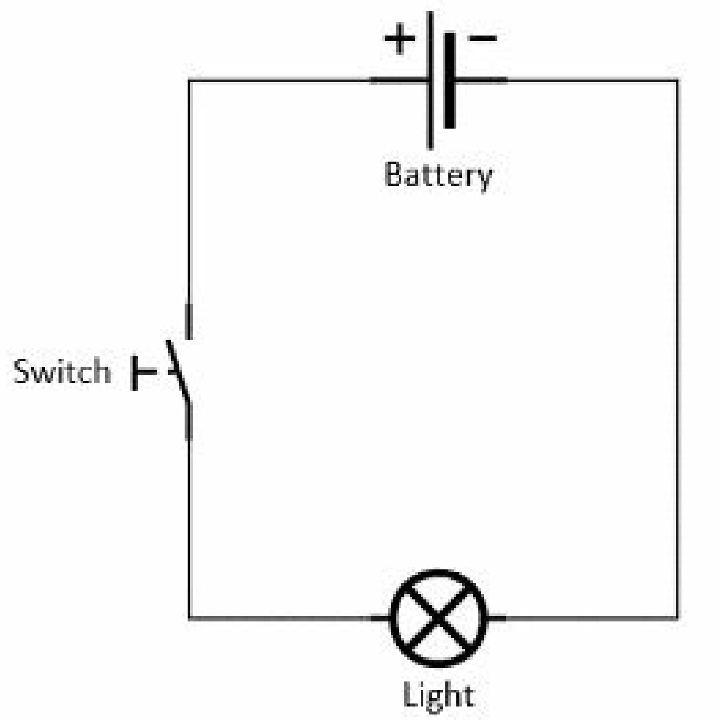
Electrical current flowing through a person to the ground

A way to prevent this short circuit from happening and to protect a person from getting an electrical shock is to ground the metal body of the appliance. In an RV, ground is the chassis of the vehicle. In a cabin or tiny house, you need to use copper rods in the ground.

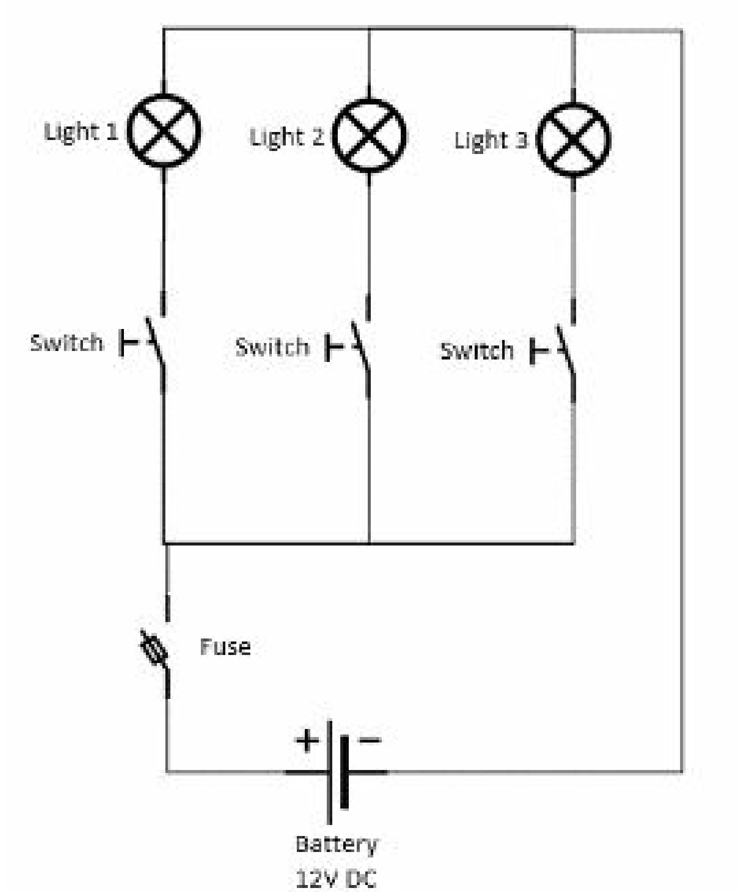
Basic Light Circuit

A light circuit is one of the most basic electrical circuits that you can have. You will need a battery (power source), a switch (control device), and a lightbulb (load).

Placing the battery with the positive terminal toward the switch and then connecting the bulb between the switch and the battery will allow you to activate or deactivate the light manually.



Basic light circuit



Multiple lights with fuse

It is always a good practice to draw out your system before purchasing components for it. It doesn't need to be a fancy computer drawing; you can do it with a simple pen and paper.

Load Types

One of the most important steps that you need to do when sizing your PV system is to estimate the load that you will have.

This topic covers mainly two aspects: power and energy.

An off-grid PV system works as a variable and a limited source of energy.

Therefore, you must determine the electrical loads that will be consuming power in the PV system and also specify how much time you are estimating they will be used.

In this matter, it is extremely important to know the type of loads you will be connecting to the PV system and understand how they work to size it properly. Let’s see some of the typical loads that you will be using for off-grid purposes.

Resistive Loads

There are mainly two types of resistive loads:

- Linear loads
- Non-linear loads

Linear type loads consume an average amount of power that is constant over time. There are no big fluctuations while running or starting them. These are generally associated with the behavior of electrical resistance; therefore, they are called resistive loads. This can be a lightbulb or water heater.

Non-linear loads have a behavior similar to inductors or capacitors, which have a consumption over time that is not constant. The resistive loads have a specific power consumption in their datasheets. This power consumption can be expressed in watts or amps.

You will typically find the nominal voltage of the load in the datasheet as well. Using the power formula:

$\text{Watts} = \text{Voltage} \times \text{Amps}$, you will be able to find the equivalent power that the load consumes.

In the following table, we can take a look at some resistive loads that are used for residential purposes.

Appliance	Running Watts
CD/DVD Player	35-100
Clock Radio	50
Desktop Computer	60-200
Laptop	20-50
Printer	30-50
Coffee Maker	650-1,200
Hair Dryer	1,000
Blender	1,200
Electric Water Heater	1,500
Fan	30-100
Iron	1,000-1,500
Microwave	1200
24” TVs LED	40-50
Air conditioner 5000 BTU	500
Electric Stove	2,000

Electric Fry Pan	1,200
Electric Blanket	200
LED lights	6-20

Typical resistive load consumptions for an RV

As you can see, the loads that consume more power are the ones that:

- Heat the space.
- Cool the space.
- Generate heat for cooking.

These loads must be selected very carefully as they will draw a lot of power and energy from the PV system. Elements such as an electric stove, an electric frypan, or a waffle iron should be avoided and replaced by alternative energy sources like a natural gas stove. Replacing these energy-demanding appliances will reduce the cost of your setup.

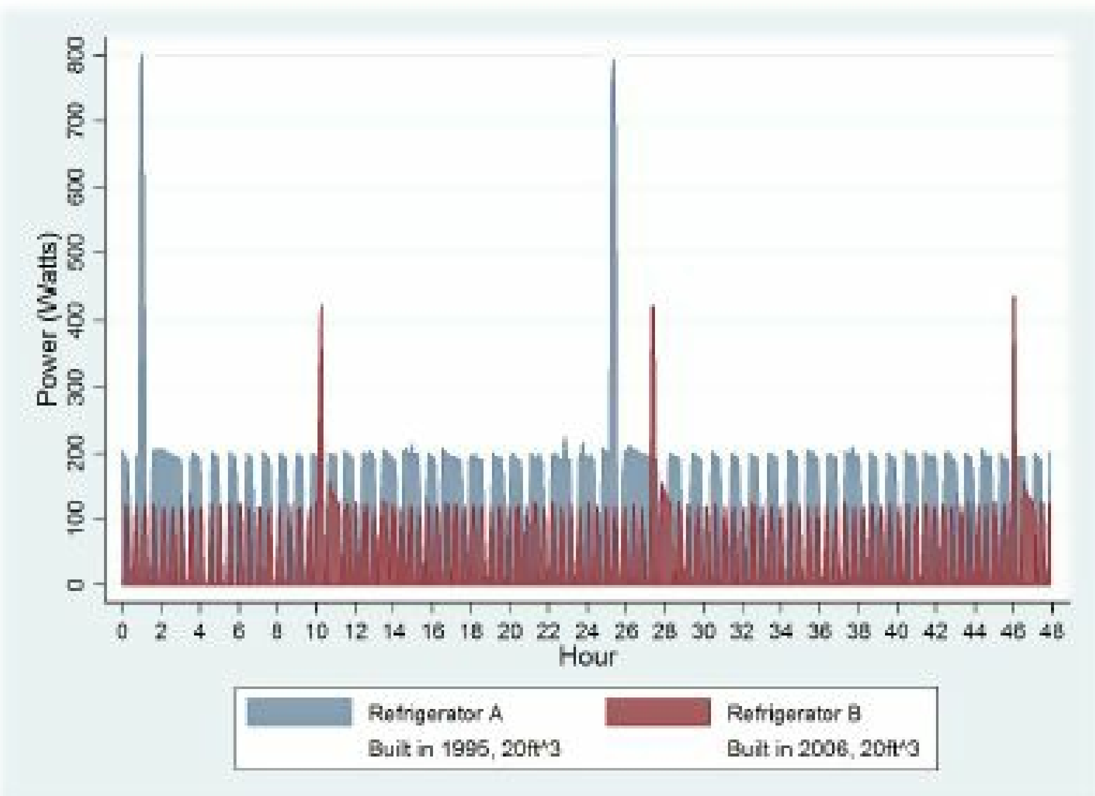
Inductive Type Loads

Inductive type loads draw more amps during their start cycle. If you are using inductive loads, you need to consider the surge current when starting these devices.

Refrigerator

Maybe the most important one of the inductive loads is the refrigerator. This load has multiple components, but the two most important for us are the electric motor and the compressor. The compressor takes a cool refrigerant liquid and transforms it into a hot refrigerant liquid with a higher pressure that is needed to complete the refrigeration cycle. To perform this task, the compressor needs an electric motor that generates movement inside the compressor. This means we will have a power surge while starting.

In the following image, you can look at the curve pattern of two refrigerators of 20 cubic feet.



Refrigerator starting pattern old vs. new
Source: Is your refrigerator running?

- Refrigerator A has a nominal power consumption of 200W and a starting wattage of 800W.
- Refrigerator B has a nominal power consumption of 100W and a starting wattage of

400W.

As we can see, in both cases, the starting wattage is **four times** the nominal power required for operation. Therefore, the off-grid PV system must always be able to provide this surge power.

Another factor that you must consider with refrigerators when sizing the PV system is that you cannot take the nominal power consumption and multiply it by 24 hours, which is the time that the refrigerator generally operates per day. This will lead to oversizing and is a common mistake.

Refrigerator datasheets often include a yellow label where you will find the energy consumption of the product per year or day. This is the reference that you must use in your calculations for energy yields. Power consumptions must be considered for the inverter's power rating.

Energy consumption of a fridge depends on many factors:

- **Type of fridge**: A top loader will consume less power than a display fridge.
- **Size**: The volume of the fridge will play a role in energy consumption.
- **Location**: If the fridge is well ventilated at the condenser, it will require less energy.
- **Season**: During the summer, the fridge needs to work harder because the temperature difference is bigger.
- **Usage frequency**: Opening the doors frequently will lead to more energy usage.
- **Temperature set point**: Check to make sure the temperature setpoint is not too cold.
- **Age**: The age of the refrigerator also decides the energy usage. The newer, the less energy it will use (if it is the same type).
- **Quality of the seals**: If the seals do not properly close the door, cold air will leak out.

Depending on all these factors, refrigerators will generally consume 50% of their rated power in one day. For example, a fridge that is rated at 100 Watts and runs for 24 hours a day will consume:

$$100 \text{ Watts} \times 24 \text{ hours} = 2{,}400 \text{ Watt hours per day}$$

$$2{,}400 \text{ Wh} \times 50\% = 1{,}200\text{Wh per day}$$

Washer/Dryer

Washers and dryers are also important pieces of equipment that require special attention.

There are two types of dryers: gas- and electric-based dryers. Electric dryers, similar to other heat applications, circulate an electric current through an electrical resistance to generate heat. Electric dryers consume a huge amount of electricity that can reach up to 725kWh per year and also consume a lot of power, reaching over 5,500W.

The amount of energy and power required to supply a dryer is simply too much for an RV or simple off-grid application where there is a very small space available for solar panels. If you live in an RV and have an electric dryer included, solar power might not be the best option to supply it.

For these purposes, the best choice might be to go for a gas-based dryer. Using a dryer that works on natural gas comes with other important safety regulations like placing it in a well-ventilated place and allowing fresh air to enter the intake of the dryer. This can be accomplished by installing an external intake and exhaust pipes. Installing a propane detector is a good safety precaution.

RV Water Pump

An RV water pump is another type of load that you can add to your list. RV water pumps generally work at 12 VDC. They can draw between 2.5 Amps and 3 Amps under regular operation.

3 gallons per minute RV pump from SeaFlo

However, as they also include a DC motor, they could draw between 7.5 and 10 Amps, depending on the model during the starting process.

Keep in mind that these 12V water pumps are only designed for intermittent use. In other words, they are designed to be used during the time that you take a shower, wash your hands, or the time it takes you to flush a toilet. Therefore, energy consumption would be low. They work on DC, so they do not add to the peak power of an inverter.

Air Conditioner

The air conditioner is a very practical and very demanding type of load.

If you are thinking about powering an A/C unit with solar panels, you must accurately estimate the energy consumption that this load will have. Otherwise, the consumption will be just too big to handle.

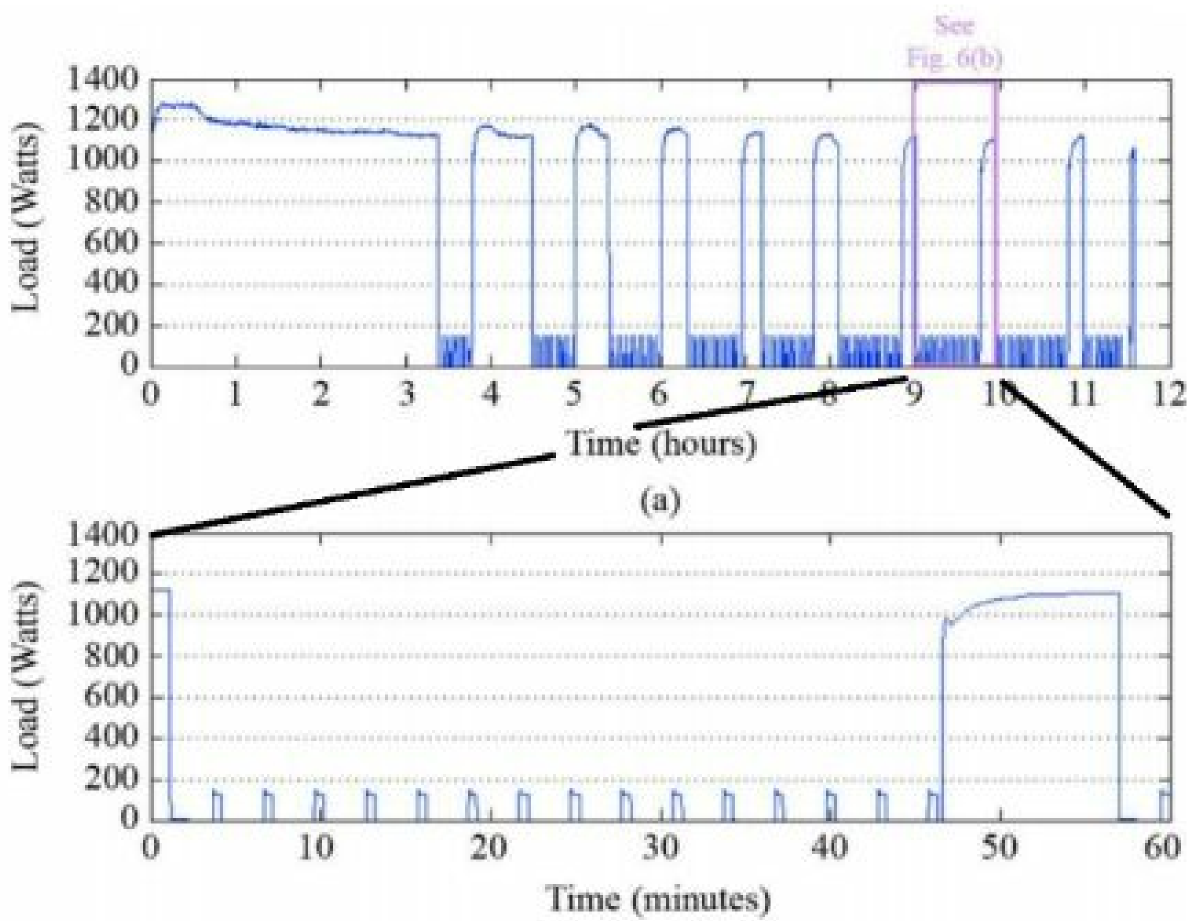
An A/C unit consumption cannot simply be calculated based on the nominal power by the number of hours of use. Doing this will represent a tremendous increase in energy demand, and your solar panel system will be oversized.

Commonly, you will find in datasheets or in A/C models that the air conditioner is expressed in kW. Despite that this is the same electrical power unit, kW is a thermal power unit, so make sure you do not use this unit for your electrical calculations.

This device also has a motor that runs the compressor. Therefore, it also requires a surge current. For A/C units, a good assumption is that the surge power will be equal to **three times** the electrical power that is on the technical datasheet.

A common mistake generally made is to assume the energy consumption of the air conditioner will be related to the number of hours of use.

You will notice that energy consumption will be much lower. The following image shows the pattern of consumption of an A/C wall unit to give you a reference of performance behavior.



Load curve of an A/C unit

Source: Load profiles of selected major household appliances and their demand response opportunities

As you can see in the beginning, the A/C unit will consume its rated power of 1,200 Watts to cool down the room. After that, the compressor (outside unit) will stop while only the fan inside will work. The compressor and the fan will, therefore, have the highest energy consumption.

The energy consumption will greatly depend on the difference in temperature between the inside and outside and time of day, how many times you open the doors, the insulation, just to name a few.

Sizing your Solar System

Now that you know the different types of loads, and what it takes to run them, we go to work estimating how big your system needs to be to run all your devices.

I’m going to explain the process using an example.

Let’s say you are converting a van to an off-grid mobile home. And you would like to use the following devices:

- Phone charger
- Laptop charger
- Water pump
- 5 DC led lights
- Speaker system
- 12V top-loading fridge/freezer combo
- 12V ceiling fan
- Blender
- Egg cooker

Next, you need to separate the AC devices from the DC devices. Try to do this in a spreadsheet.

Everything with a normal household plug will be an AC device. Anything that works on 12 or 24 Volts DC goes into the list of DC devices.

Try to use DC devices instead of AC because it will limit the load on the inverter so you can choose one with a lower power rating.

Let’s continue with the example:

DC appliances			
Item			
5 Led lights			
Phone charger			
Water pump			
Speaker system			
Fridge			
Ceiling fan			

AC appliances			
Item			
Laptop charger			
Blender			
Egg cooker			

Categorizing devices into DC and AC

Next, you are going to determine the wattage for each device. There are several options to find the wattage:

1. By looking at the sticker.

Start by searching for the sticker on the appliance you want to use. If you are lucky, you might find the power (wattage) that the device consumes. If you are not so lucky or there is no visible sticker on the device, move on to option two.

Sticker on the device

2. By searching online.

If you have not bought the device yet, or can't seem to find the sticker, search online. This can be done by searching for the item name in Google. You will find some websites that list the power rating there.

Another method is to try amazon.com and search in the product details for the power rating.

3. By using the 'kill a watt meter.'

If you cannot find the power rating for the device, you can use a 'kill a watt' meter to read the power consumption of the appliance. This is especially useful for devices that are not constantly in use, like a fridge or air conditioning unit.

The ‘kill a watt’ meter

4. By applying the power formula.

The last method and the most complicated one is to search for the current of the device. Try to locate the current of the device by using method one or two.

$$\text{Power} = \text{Voltage} \times \text{current}$$

Now, we know the voltage of the device ether 12 Volts DC or 120 Volts AC, and we know the current through the device, we can determine the power rating of the device.

Let's take this example and calculate the power it consumes.

$$\text{Power} = 120\ \text{Volts} \times 11.5\ \text{Amps} = 1{,}380\ \text{Watts}$$

This would be different if we were using a DC device. Let's take a phone charger that is charging at one amp.

$$\text{Power} = 12\ \text{Volts} \times 1\ \text{Amp} = 12\ \text{Watts}$$

Now we fill in the power of each device in the spreadsheet.

DC appliances			
Item	Watts		
5 Led lights	25		
Phone charger	24		
Water pump	40		
Speaker system	25		
Fridge	45		
Ceiling fan	25		
AC appliances			
Item	Watts		
Laptop charger	50		
Blender	1000		
Egg cooker	500		

Filling in the power rating in the spreadsheet

Now you can decide the wattage of your inverter. If you do not use your blender and egg cooker together, you can use a 1,500 Watt inverter.

The next step is to determine how long you are going to use these devices each day in hours.

Use the following formula to convert minutes to hours:

$$\text{number of minutes} \times \left(\frac{1}{60}\right)$$

Example:

I’m using a blender for two minutes each day.

$$2 \text{ minutes} \times \left(\frac{1}{60}\right) = 0.033 \text{ hours}$$

Put these values in the spreadsheet.

DC appliances			
Item	Watts	Hours per day	
5 Led lights	25	4	
Phone charger	24	1.5	
Water pump	40	0.5	
Speaker system	25	4	
Fridge	45	4	
Ceiling fan	25	1	
AC appliances			
Item	Watts	Hours per day	
Laptop charger	50	4	
Blender	1000	0.03	
Egg cooker	500	0.16	

Inputting hours per day

The following step is a bit more complicated. In this part, we are going to calculate the number of watt-hours the devices consume in one day. We do this by using the following formula:

$$\text{Watt hours} = \text{Watts} \times \text{hours}$$

DC appliances			
Item	**Watts**	**Hours per day**	**Watt hours**
5 Led lights	25	4	100
Phone charger	24	1.5	36
Water pump	40	0.5	20
Speaker system	25	4	100
Fridge	45	4	180
Ceiling fan	25	1	25
		Total Watt hours DC	461
AC appliances			
Item	**Watts**	**Hours per day**	**Watt hours**
Laptop charger	50	4	200
Blender	1000	0.03	30
Egg cooker	500	0.16	80
		Total Watt hours AC	310
Total Watt hours per day:			771

Calculating the total watt-hours for our system

The next step is to calculate the battery we are going to need. Battery capacity is expressed in amp-hours or simply Ah.

You need to decide which battery voltage you are going to use. Let’s say for this example we are going to use 12 Volts.

$$\text{Amp hours} = \frac{\text{Watt hours}}{\text{Voltage}}$$

$$\frac{771 \text{ Watt hours}}{12 \text{ Volts}} = 65\text{Ah}$$

If you are using a lead-acid battery, you need to double the capacity because the lead-acid battery can only be discharged to 50%. A 100Ah lead-acid battery only has 50Ah of usable energy. You can get 50% of usable energy out of the lead-acid battery.

Lithium batteries can be discharged to 20%. A 100Ah lithium battery has 80Ah usable energy. You can get 80% of usable energy out of the lithium battery.

A requirement of 65Ah per day will need a battery with the capacity of:

For lead-acid:

$$65\text{Ah} \times \frac{100\%}{50\%} = 130\text{Ah}$$

For lithium:

$$65\text{Ah} \times \frac{100\%}{80\%} = 81.25\text{Ah}$$

Unfortunately, there are going to be some days of shade where your batteries are not going to be fully charged. This will depend on:

- The place you have your setup (latitude).
- Time of year (summer or winter).
- Weather (cloudy or sunny).

I recommend having at least 2 days of autonomy, but 3 days is better. This means that you need a battery bank that is:

For lead-acid:

$$130\text{Ah} \times 3 \text{ days} = 390\text{Ah}$$

For lithium:

$$81.25\text{Ah} \times 3 \text{ days} = 243.75\text{Ah}$$

Next, you need to consider the efficiency of the type of battery you are going to use. Here are the efficiencies of various batteries:

- Lead-acid: 80%
- AGM: 90%
- Lithium: 99%

For lead-acid:

$$390\text{Ah} \times \frac{100\%}{80\%} = 487.5\text{Ah}$$

For Lithium:

$$243.75\text{Ah} \times \frac{100\%}{99\%} = 246.2\text{Ah}$$

If you were using a lead-acid battery, you would need a battery pack of 487.5Ah at 12 Volts.

If you are using a lithium battery, you would need a battery pack of 246.2Ah at 12 Volts.

The next step is to determine the recommended wattage of the solar panels we need.

To do this, we need to convert our battery bank size from amp-hours to watt-hours. We have chosen for a 12 Volt battery system, so we are going to multiply the amp-hours by 12 Volts.

$$\text{Watt hours} = \text{Voltage} \times \text{Amp hours}$$

For lead-acid:

$$12 \text{ Volts} \times 487.5\text{Ah} = 5{,}850 \text{ Watt hours}$$

For lithium:

$$12 \text{ Volts} \times 246.2\text{Ah} = 2{,}954 \text{ Watt hours}$$

Remember that in a lead-acid battery, you can use 50% of the energy and a lithium battery 80%? Let’s calculate the usable watt-hours that can be stored in these batteries.

For lead-acid:

$$5{,}850 \text{ Wh} \times 50\% = 2{,}925 \text{ Wh}$$

For lithium:

$$2{,}954 \text{ Wh} \times 80\% = 2{,}363 \text{ Wh}$$

Now, you would think: ‘Why is the stored energy not the same, I’m running the same appliances?’

That is because lithium batteries are more efficient than lead-acid batteries. Which we accounted for with the efficiency factor a few calculations before.

The amount of watt-hours we have calculated is what we need to supply the system within one day to fully recharge the batteries.

In the U.S., the amount of sun hours that hits the surface is ranging from 5 hours to 10 hours of sunlight per day in New York.

We need to use the worst-case scenario, and we will use 5 hours of available sunlight in a day. Then we divide our required watt-hours by the hours of sunlight per day.

For lead-acid:

$$\frac{2{,}925 \text{ Watt hours}}{5 \text{ hours}} = 585 \text{ Watts} \rightarrow 600 \text{ Watts}$$

For lithium:

$$\frac{2{,}363 \text{ Watt hours}}{5 \text{ hours}} = 472 \text{ Watts} \rightarrow 500 \text{ Watts}$$

Choose which solar panel you are going to use. In this example, I will be using 100 Watt panels.

For lead-acid:

$$\frac{600 \text{ Watts}}{100 \text{ Watt panel}} = 6 \text{ Panels}$$

You would need 6 panels of 100 Watts each to charge your 12V lead-acid battery bank.

For lithium:

$$\frac{500 \text{ Watts}}{100 \text{ Watt panel}} = 5 \text{ Panels}$$

You would need 5 panels of 100 Watts each to charge your 12V lithium battery bank.

We can see that lithium batteries require less solar input because the battery bank is more efficient. Lithium batteries will pay themselves off in the long run.

Wiring

Wiring is an essential part of any electrical installation. Solar PV installations also need special considerations in this matter.

In this chapter, we are going to look at the different types of wires, factors that contribute to wire sizing and how to calculate the diameter of the wire.

Wire Types

We can divide the type of wire that you need to use by sections of the PV system:

- Solar panels - Combiner box
- Combiner box - Charge controller - Loads
- Battery cables

Solar Panels – Combiner box

According to the UL-4703 standard, there are mainly two types of wires for PV applications that must be considered for the connection of PV modules.

The best type of wire that should be selected for common RV, boat, or roof applications is called the PV wire.
The PV wire is a single-conductor wire that can be used to connect the solar panels in series or parallel to the combiner box or directly to the charge controller.

These wires meet UL-4703 requirements, and they are made of either copper, aluminum, or copper-clad aluminum.

UL-4703 PV wire with MC4 connectors

Their insulation cover is based on cross-linked polyethylene (XLPE), or ethylene-propylene rubber (EPR), and they are rated to work at 600V, 1kV, or even 2kV.

The most important factor and what makes these wires different from others is that they are specially designed to endure strong ultraviolet (UV) radiation at which the wires of the solar panels will be exposed to.

Other wires would deteriorate over time and get their insulation damaged, which could cause exposure of the copper or aluminum material and lead to short-circuit failures. The temperature rating of these wires is close to 195°F (90°C) under wet conditions and between 220-300°F (105°C-150°C) under dry conditions. Also, a PV wire is designed to be flame-retardant, which is a very important feature for the safety of your system.

These wires must be used for the connections between the solar panels up to the combiner box. They can also be used for connections directly to the charge controller if you do not have a combiner box.

The second type of wire that can be used is the USE-2, which stands for underground service entrance wire.

The USE-2 wire is also used in solar PV applications, especially in ground-mounted applications where the wires can go underground and are considered as the alternative option when the PV wire (UL-4703) cannot be purchased. This type of wire is rated at 600V (suitable for our purposes). They are cheaper than PV wires. However, they do not have UV protection. They are not flame-retardant, and their maximum operating temperature under dry conditions is 195°F (90°C). USE-2 is also less flexible than PV wire.

It is recommended to use PV wire (UL-4703) because it's more temperature resistant, flexible, and has thicker insulation. It is not forbidden to use the regular USE-2 wire.

Combiner box – Charge Controller – Loads

In this section, there will be no exposure to sunlight conditions. Therefore, wire insulation can be simpler.
For the output between the combiner box and the charge controller, it is suitable to use THW wire insulations. THW stands for Thermoplastic Heat and Water-Resistant cable and is one of the simplest wires that you can select.

Stranded THW wire

These wires are generally used for machine tools and internal wiring of multiple appliances. They are rated to work at 600V, up to 195°F (90°C) in dry conditions, and 140°F (60°C) under wet conditions.

You can use these wires between the combiner box and the charge controller, as well as between the charge controller and the DC loads. It is also suitable for internal wiring loads of the house or the RV. Therefore, you can also use it between the inverter and the main breaker panel. As already mentioned, make sure you order stranded wire. This makes them more flexible than single-core wire.

Battery Cables

The batteries will generally be located in a compartment of the RV or a separate compartment, depending on your off-grid application. During summer conditions, these spaces could be exposed to high-temperature values as well as an increase in moisture and humidity values.

Moreover, they could also be exposed to wet conditions during the rainy season, especially if you are in an RV.
Besides, deep cycle batteries that are used for off-grid purposes would occasionally expel internal gases to the environment, and in case of damage or leakage, they would expose chemicals to the wires.

Therefore, a THW will not be suitable for this section. In this case, you must use a THWN-2 cable.

THWN-2 stands for Thermoplastic Heat and Water-Resistant Nylon Coated. This cable is suitable for temperature ratings up to 195°F (90°C), in both dry and wet locations. They also have a flame retardant feature, and they have a high resistance to abrasion from oil and chemical agents thanks to the nylon coating.

These features make it ideal for applications where you need to connect 12V batteries. Alternative options that can be considered are:

- THHN (Thermoplastic High-Heat Resistant Nylon Coated)
- XHHW-2 (Cross-Linked Polyethylene High-Heat and Water Resistance)

These wire types must be used in the battery compartment between the charge controller and the battery system, as well as for interconnections between batteries if you are doing series or parallel connections between them.

This means that the wire from the charge controller should be of this type. The wire that goes to the busbar, inverter, and DC fuse box should also be this type of wire because they all start in the battery compartment.

Sizing Factors

Wires are rated according to the wire diameter. The one we will use throughout this book is the American Wire Gauge (AWG). Each wire type will offer a different amperage capacity (ampacity) rating depending on the wire size that is selected.

These are classified in pair numbers that go from #18AWG up to MCM scale cable sizes (which will not be used here). For our solar PV off-grid applications, we will generally only use cables between #12AWG and up to 2/0AWG wire sizes.

To size the wire that you need for your PV system, you must consider these factors:

- Current Capacity or Amperage.
- Ambient temperature.
- DC voltage drop.

Current Capacity

The current or amperage capacity is provided by the wire manufacturer in their spreadsheet. When taking a look at the wire, you should be able to see all the electrical current ratings for every size of the wire.

The following table offers a reference from the National Electric Code 2017, but the most accurate value that you can get is from the manufacturer.

Table 310.15(B)(16) (formerly Table 310.16) Allowable Ampacities of Insulated Conductors Rated Up to and Inc 60°C Through 90°C (140°F Through 194°F), Not More Than Three Current-Carrying Conductors in Raceway, Ca (Directly Buried), Based on Ambient Temperature of 30°C (86°F)*

Size AWG or kcmil	Temperature Rating of Conductor [See Table 310.104(A).]					
	60°C (140°F)	75°C (167°F)	90°C (194°F)	60°C (140°F)	75°C (167°F)	90°C (194°F)
	Types TW, UF	Types RHW, THHW, THW, THWN, XHHW, USE, ZW	Types TBS, SA, SIS, FEP, FEPB, MI, RHH, RHW-2, THHN, THHW, THW-2, THWN-2, USE-2, XHH, XHHW, XHHW-2, ZW-2	Types TW, UF	Types RHW, THHW, THW, THWN, XHHW, USE	Types TBS, SA, SIS, THHN, THHW, THW-2, THWN-2, RHH, RHW-2, USE-2, XHH, XHHW, XHHW-2, ZW-2
	COPPER			ALUMINUM OR COPPER-CLAD ALUMINUM		
18**	—	—	14	—	—	—
16**	—	—	18	—	—	—
14**	15	20	25	—	—	—
12**	20	25	30	15	20	25
10**	30	35	40	25	30	35
8	40	50	55	35	40	45
6	55	65	75	40	50	55
4	70	85	95	55	65	75
3	85	100	115	65	75	85
2	95	115	130	75	90	100
1	110	130	145	85	100	115
1/0	125	150	170	100	120	135
2/0	145	175	195	115	135	150
3/0	165	200	225	130	155	175
4/0	195	230	260	150	180	205
250	215	255	290	170	205	230
300	240	285	320	195	230	260
350	260	310	350	210	250	280
400	280	335	380	225	270	305
500	320	380	430	260	310	350
600	350	420	475	285	340	385
700	385	460	520	315	375	425
750	400	475	535	320	385	435
800	410	490	555	330	395	445
900	435	520	585	355	425	480
1000	455	545	615	375	445	500
1250	495	590	665	405	485	545
1500	525	625	705	435	520	585
1750	545	650	735	455	545	615
2000	555	665	750	470	560	630

*Refer to 310.15(B)(2) for the ampacity correction factors where the ambient temperature is other than 30°C (86°F). Refer to
more than three current-carrying conductors.
**Refer to 240.4(D) for conductor overcurrent protection limitations.

Ampacity ratings for multiple insulated conductors.
Source: National Electric Code 2017

To view a PDF of this chart, go to:
https://cleversolarpower.com/ampacity-ratings
(direct download)

To select the right wire size, you must estimate the maximum electrical current that will flow through that section and then select the wire gauge that withstands that amount of current.

For example, A 1,000 Watt inverter that feeds itself from a 12 Volt battery:

$$\text{Current} = \frac{1000 \text{ Watts}}{12 \text{ Volts}} = 83.3 \text{ Amps}$$

If we use THW copper wire which insulation is rated at 167°F (75°C), at a temperature of 83°F (30°C) and use the previous table, we need a 4AWG wire.

Temperature Correction

There is another factor that must be considered, the ambient temperature. Ambient temperature also influences the resulting temperature of the conductor, and it can increase it (hot climate) or reduce it (cold climate).

The permissible electric current values of the previous table are calculated assuming a 86°F (30°C) ambient temperature.

This may not be the temperature that your location has, or even be the temperature inside the compartment of your batteries. Therefore, a temperature correction factor must be applied. This can be done by two methods:

- Equation
- Predetermined tables

The equation method consists of applying the following equation:

$$I' = I \sqrt{\frac{T_c - T_a'}{T_c - T_a}}$$

Where:

I’= Ampacity corrected for ambient temperature.
I= Ampacity shown in the previous table.
Tc= Temperature rating of the conductor (°C).
Ta’= New ambient temperature (°C).
Ta= Ambient temperature used in the table (°C).

The I’ value will represent the new ampere rating permissible for that conductor in that specific ambient temperature.

Let’s explain this with an example:

Let’s assume that after you did your ampacity sizing, you determined the wire that you needed for your battery interconnection cables was a THWN #2AWG cable, which at 167°F (75°C) has an ampacity of 115A as it can be seen in the table.

Let’s assume that the ambient temperature inside the battery compartment is 104°F (40°C). The expression would be as follows.

$$I' = I\sqrt{\frac{T_c - T_a'}{T_c - T_a}} = 115 \times \sqrt{\frac{75 - 40}{75 - 30}} = 101.42\ A$$

This means that the new capacity rating in amperes for the THWN #2AWG cable under 40°C ambient temperature conditions would be reduced from 115A to 101.42A. As you can see, the ambient temperature can have an important impact.

The second method uses pre-established correction factors by sets of temperature ranges using the values that can be found in the following table.

Table 310.15(B)(2)(a) Ambient Temperature Correction Factors Based on 30°C (86°F)

For ambient temperatures other than 30°C (86°F), multiply the allowable ampacities specified in the ampacity tables by the appropriate correction factor shown below.				
Ambient Temperature (°C)	Temperature Rating of Conductor			Ambient Temperature (°F)
	60°C	75°C	90°C	
10 or less	1.29	1.20	1.15	50 or less
11–15	1.22	1.15	1.12	51–59
16–20	1.15	1.11	1.08	60–68
21–25	1.08	1.05	1.04	69–77
26–30	1.00	1.00	1.00	78–86
31–35	0.91	0.94	0.96	87–95
36–40	0.82	0.88	0.91	96–104
41–45	0.71	0.82	0.87	105–113
46–50	0.58	0.75	0.82	114–122
51–55	0.41	0.67	0.76	123–131
56–60	—	0.58	0.71	132–140
61–65	—	0.47	0.65	141–149
66–70	—	0.33	0.58	150–158
71–75	—	—	0.50	159–167
76–80	—	—	0.41	168–176
81–85	—	—	0.29	177–185

Ambient temperature correction factors for ampacity.
Source: National Electric Code 2017

Visit this link for a better visual of this table:
https://cleversolarpower.com/temperature-correction

In this case, let's assume that the ambient temperature reduces to 59°F (15°C) and that your current demand estimation value is 140A, which makes you select a THWN 1/0AWG cable.

SIZE AWG OR kcmil	Copper Conductors		
	Temperature Rating of Conductor		
	60°C	75°C	90°C
	TYPES TW UF	TYPES RHW THW THWN THHW XHHW USE	TYPES RHH RHW-2 XHHW XHHW-2 XHH THHW THWN-2 THW-2 THHN USE-2
14**	20	20	25
12**	25	25	30
10**	30	35	40
8	40	50	55
6	55	65	75
4	70	85*	95*
3	85	100*	110*
2	95	115*	130*
1	110	130*	150*
1/0	125	150*	170*
2/0	145	175*	195*

Selecting a 1/0AWG cable

Now, since the cable has been rated by the manufacturer at 167°F (75°C) and ambient temperature is 59°F (15°C), then the temperature correction factor would be 1.15.

The next step is to apply the following expression:

$$\text{Current} = \text{Current Load} \times \text{Correction Factor}$$

$$150 \text{ Amps} \times 1.15 = 172.5 \text{ Amps}$$

We can see that this wire will be able to carry more current than it is rated for. This is because the colder it is, the more efficient the wire will work. We could use a 1AWG wire to carry 140 Amps of current in this situation.

$$130 \text{ Amps} \times 1.15 = 149.5 \text{ Amps}$$

However, when calculating this, you should always use the worst-case scenario. This means using the warmest value your wire will be susceptible to. Let’s re-do this calculation with realistic numbers.

Let's say the hottest time of summer is about 105-113°F (41-45°C). From the table, we can see the corresponding temperature correction factor.

Ambient Temperature (°C)	Temperature Rating of Conductor			Ambient Temperature (°F)
	60°C	75°C	90°C	
10 or less	1.29	1.20	1.15	50 or less
11–15	1.22	1.15	1.12	51–59
16–20	1.15	1.11	1.08	60–68
21–25	1.08	1.05	1.04	69–77
26–30	1.00	1.00	1.00	78–86
31–35	0.91	0.94	0.96	87–95
36–40	0.82	0.88	0.91	96–104
41–45	0.71	0.82	0.87	105–113

Correlating temperature factor

$$150 \text{ Amps} \times 0.82 = 123 \text{ Amps}$$

We now see that this wire is only able to carry 123 Amps at the specified temperature safely. We need to increase our wire sizes to account for this.

$$170 \text{ Amps} \times 0.82 = 139.4 \text{ Amps}$$

If we are using a 1/0AWG wire that is rated for 170 Amps, we become the required 140 Amps in the worst-case scenario. This concludes that you must use a 1/0AWG wire.

DC Voltage Drop

The other factor that must be considered when selecting wire gauge sizes is the voltage drop across the wire. The voltage drop is referred to as losses in the cable. If your cable diameter is small and long, the voltage drop will increase.

For example, a single solar panel that has an 18 Volt output, wired to the charge controller with a 5% voltage drop, will lose 0.9 Volts.

$$18 \text{ Volts} \times \frac{5}{100} = 0.9 \text{ Volts}$$

The initial 18 Volts drops to 17.1 Volts, which is not ideal. To remedy this, we need to reduce the resistance in the wire by selecting a wire with a bigger diameter.

Voltage drops are associated with the wire size selected, the length of the cable, and the voltage of the system. Voltage drops are undesirable in a PV system because they lead to power losses. They also influence the minimum voltage input rating for various devices.

Therefore, you must calculate the voltage drop for a specific wire gauge and verify if that voltage drop is permissible or not.

Common standards for this parameter establish that a voltage drop lower than 3% must be ensured between the modules and the charge controller, which is in the DC side of the PV system. A lower voltage drop of 1% is preferred.

To calculate the voltage drop, you must apply the following expression:

$$A = \frac{\rho \times 2 \times l \times I}{v \times Vsys}$$

Where:

A= Transversal section of the cable [mm^2]

ρ= Specific Resistance [Ω $\bullet\ mm^2/m$]

$0.0171\ \Omega \times mm^2/m$ for copper

$0.026\ \Omega \times mm^2/m$ for aluminum

2= Total travel length for both + and - wire
l= Length of the cable [m]
I= Nominal current through the cable [A] (Imp in this case)
v= Permissible voltage drop in the cable [no unit]
Vsys= Open circuit voltage [V] (Vmpp of the string)

As an example, we can consider two solar panels in series that has a range of 82ft (25-meter) from the most distanced connection point to the charge controller, and that the string has a maximum power point current (Impp) of 5.8A and a maximum power point voltage (Vmpp) of 35V ($17.5V \times 2$).

The desired voltage drop in the system will be 1%.

Applying the expression:

$$A = \frac{\rho \times 2 \times l \times I}{v \times Vsys} =$$

$$\frac{0.0171 \left[\Omega \times \frac{mm^2}{m}\right] \times 2 \times 25m \times 5.8A}{0.01 \times 35V} = 14.16mm^2$$

As you can see, the result is established in mm^2. This represents the transversal section that the copper wire must have to ensure a 1% voltage drop. We can transform this mm^2 to AWG by referring to the following table. As listed in the following table, for this application, we would require a #4AWG size cable.

AWG to mm² CONVERSION TABLE	
AWG/kcmil	[mm²]*
20	0.52
18	0.82
16	1.31
14	2.08
12	3.31
10	5.26
8	8.36
6	13.3
4	21.2
2	33.6
1	42.4
1/0	53.5
2/0	67.4
3/0	85.0
4/0	107
250	127
300	152
350	177
400	203
450	228
500	253
600	304
750	380
800	405
1000	507

* Equivalent mm² cross-sectional area

AWG to mm^2 conversion table
Source: GEMSA

Voltage drop is only important when the length of the wire is long. It doesn't need to be calculated for the rest of the system as long as the components are close together.

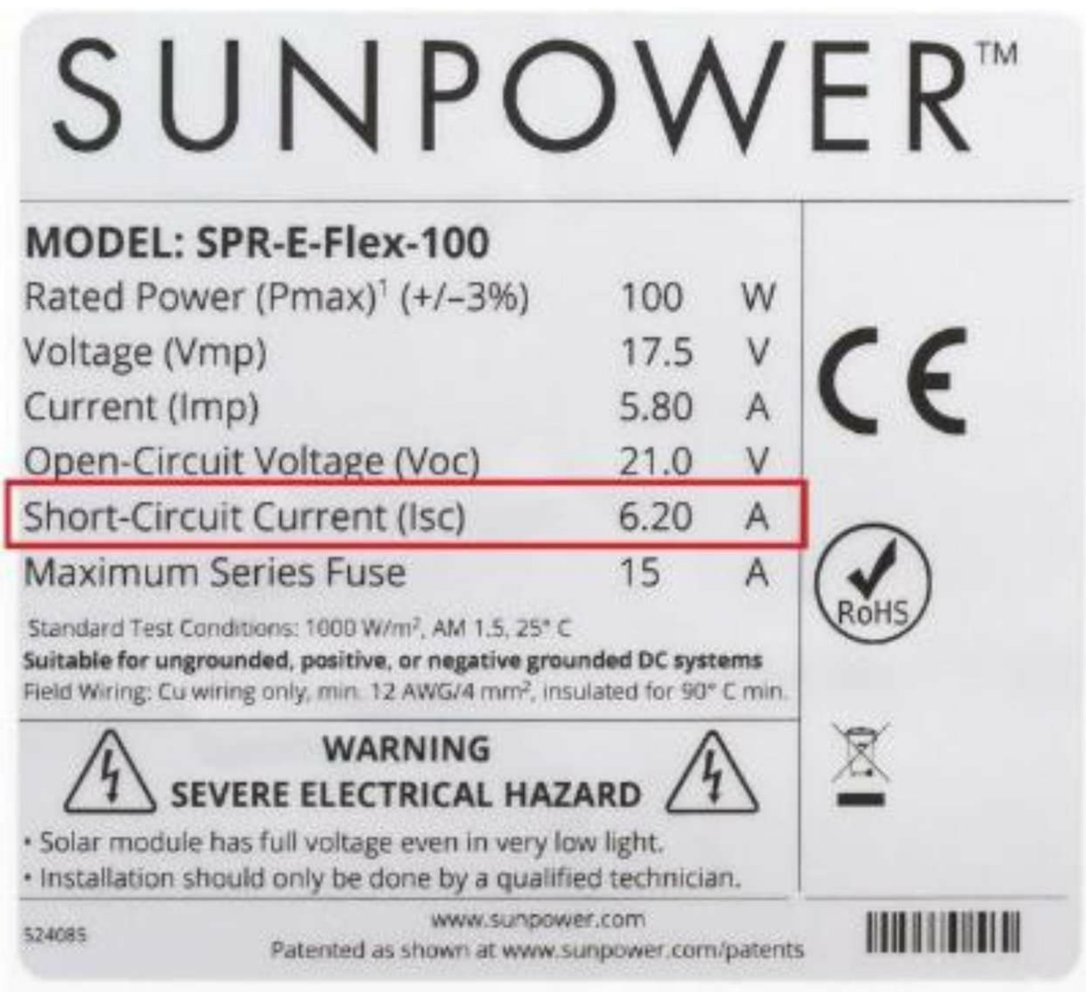
Calculating Wire Sizes

In this chapter, we will calculate the wire size you need for each stage of the solar system. We have to take the sizing factors into consideration.

PV Modules – Combiner box

In this section, your reference must be the short-circuit current that is established in the datasheet of the PV module and then apply a security factor associated with higher irradiance levels, as well as the voltage drop. The maximum current a solar cell can produce is:

$$Imax = Isc \times 1.5623$$



Sunpower 100 Watt PV module specifications

Calculate the maximum current through the wire:

$$Imax = 6.20A \times 1.5623 = 9.7Amps$$

For this section of the PV system, you will note that wire sizes with a manufacturer's temperature rating of 90°C can be as small as #14AWG.

However, this is without taking voltage drop into consideration. We need to calculate the wire size to reduce the voltage drop to an acceptable 1% at 20ft (6 meters).

$$\frac{0.0171\left[\Omega \times \frac{mm^2}{m}\right] \times 2 \times 6m \times 9.7A}{0.01 \times 17.5V} = 11.37mm^2$$

11.37mm² or #6AWG is needed to wire the solar panel to the combiner box. However, if you buy MC-4 connector cables, they will only be available in #10AWG. The reason for this is that they limit the voltage drop to 3% instead of 1%. Let's explain this with an example. These cables are 20ft (6 meters) long.

$$\frac{0.0171\left[\Omega \times \frac{mm^2}{m}\right] \times 2 \times 6m \times 9.7A}{0.03 \times 17.5V} = 3.79mm^2$$

3.79mm² is rounded up to a wire that is #10AWG. This will only be the case if you were to wire the cable for 20ft (6meters) without an extension. Therefore, it is important that you calculate this correctly to avoid unnecessary power loss.

This wire will be used for every connection between modules and to send the electric current up to the fuses in the combiner box.

Combiner box – Charge Controller

The output of the combiner box will go to the charge controller. This section will contain all the electric current that flows from all the strings of solar panels. To estimate the wire size, we must use the following expression:

$$Ibox = Isc \times \text{number of strings} \times 1.5625$$

The number of strings represents the number of parallel connections made in the solar array, and the factor 1.5625 is associated with security factors. For this section, wire sizes between #10AWG and #6AWG should work depending on the type of solar array.

For example, one array of two panels in parallel:

$$\text{Ibox} = 6.2\ \text{Amps}\ \times 2\ \text{strings}\ \times 1.5625 = 19.37\text{Amps}$$

Calculate the voltage drop if the wires travel 16ft (5 meters) to the charge controller:

Using a 1% voltage drop:

$$\frac{0.0171\left[\Omega \times \frac{mm^2}{m}\right] \times 2 \times 5m \times 19.37A}{0.01 \times 17.5V}$$
$$= 18.9mm^2 \text{or } \#4AWG$$

Using a 3% voltage drop:

$$\frac{0.0171\left[\Omega \times \frac{mm^2}{m}\right] \times 2 \times 5m \times 19.37A}{0.03 \times 17.5V}$$
$$= 6.3mm^2 \text{ or } \#8AWG$$

If you have your panels connected in series, the voltage will increase, but the amperage will stay the same.

Example of two panels in series with a 1% voltage drop:

$$\frac{0.0171\left[\Omega \times \frac{mm^2}{m}\right] \times 2 \times 5m \times 6.2A}{0.01 \times 35V}$$
$$= 3.02mm^2 \text{ or } \#12AWG$$

We can see that a series connection requires a wire with a smaller diameter. This is because the wire diameter is decided by the number of amps that run through the wire. In parallel, amps will be added up. In series, the voltage will be added up.

Charge Controller – Battery

The current that flows from your charge controller to the batteries is decided by the charge controller itself. It will have a maximum charging current listed in its datasheet.

It will also recommend the wire size. There is no need to calculate this size as long as the cable is not very long.

Following the manufacturer's recommended guideline is the best advice to follow. If you do calculate this yourself, make sure the terminals of the charge controller are big enough to accept your wire diameter.

Power cable（AWG/mm^2）	PV/BAT:14AWG(2.5mm^2) LOAD:18AWG(1.0mm^2)

Charge controller recommended battery and load cables
Source: Epever

Make sure you use the recommended THWN-2 cable. For more information about why you need to choose this cable, refer to the wire types chapter.

Battery – Inverter

To size the wires that go from your batteries to the inverter, you need to know the power rating of the inverter that you are going to use. If you are using a 1,500 Watt inverter with a 12 Volt battery bank, you apply the following formula:

$$\text{Current} = \frac{\text{Power}}{\text{Voltage}}$$

$$\frac{1{,}500\ \text{Watts}}{12\ \text{Volts}} = 125\ \text{Amps}$$

You need a wire that can supply 125 Amps to your inverter.

Next, you need to use the temperature correction factor. Because we are using a different type of wire (THHN), the temperature rating of the conductor will be higher at 194°F (90°C).

SIZE AWG OR kcmil	Copper Conductors		
	Temperature Rating of Conductor		
	60°C	75°C	90°C
	TYPES TW UF	TYPES RHW THHW THW XHHW THWN USE	TYPES RHH THHW RHW-2 THWN-2 XHHW THW-2 XHHW-2 THHN XHH USE-2
14**	20	20	25
12**	25	25	30
10**	30	35	40
8	40	50	55
6	55	65	75
4	70	85*	95*
3	85	100*	110*
2	95	115*	130*
1	110	130*	150*

Selection of 2AWG wire

Next, decide the maximum ambient temperature in the battery compartment. In this example, the maximum temperature in the battery compartment up to the inverter will be 105-113°F (41-45°C).

Ambient Temperature (°C)	Temperature Rating of Conductor			Ambient Temperature (°F)
	60°C	75°C	90°C	
10 or less	1.29	1.20	1.15	50 or less
11–15	1.22	1.15	1.12	51–59
16–20	1.15	1.11	1.08	60–68
21–25	1.08	1.05	1.04	69–77
26–30	1.00	1.00	1.00	78–86
31–35	0.91	0.94	0.96	87–95
36–40	0.82	0.88	0.91	96–104
41–45	0.71	0.82	0.87	105–113
46–50	0.58	0.75	0.82	114–122

Temperature correction factor

$$130 \text{ Amps} \times 0.87 = 113.1 \text{ Amps}$$

We can see that by using the temperature correction factor, we do not get to the 125 Amps our inverter can draw. Therefore, we need to increase the wire size. Instead of #2, we use #1AWG.

$$150 \text{ Amps} \times 0.87 = 130.5 \text{ Amps}$$

If we select a #1AWG wire, we are able to handle the maximum current the inverter can draw. The voltage drop is not calculated here because the distance between these two will be almost negligible.

One advantage of using a battery with a higher voltage is that you don’t need to use big wires. If you have the same inverter with a battery bank of 24Volts, you only need a wire that is capable of transporting 62.5 Amps, as can be seen in the following calculation:

$$\frac{1{,}500 \text{ Watts}}{24 \text{ Volts}} = 62.5 \text{ Amps}$$

Interconnecting Batteries

In this section, the reference will be the maximum charging or discharging current that will flow through the batteries. The discharging current will most likely be the highest.

If you are interconnecting batteries, they should have the same diameter and the same length. If not, more resistance is created in the wires, and the charge or discharge current won't be the same for individual batteries in the battery pack.

The thickness of the wire depends on the total current draw of the loads in your system. If the total load current in your system is 200 Amps at 12 Volts, then size your cables on that number.

The wiring of the interconnecting wires is the same as the battery to inverter.

Wiring for Electrical Loads

This section applies to DC and AC loads.

Typical DC loads will work with #14AWG or even #16AWG wire sizes.

Typical AC loads such as lighting, TVs, microwaves, fans, small motors, and others will generally use #12AWG or #10AWG wire sizes. These are typically used for outlets.

A/C units, washing machines, and refrigerators may require #8AWG and up to #6AWG, depending on the model.

You can find the electric current demand for your appliance on the product or in the datasheet of the product. If you are only presented with the power rating, use the following formula to figure out current:

$$\text{Current} = \frac{\text{Wattage}}{\text{Volts}}$$

For an AC appliance:

$$\frac{1{,}000 \text{ Watts}}{120 \text{ Volts}} = 8.33 \text{ Amps}$$

For a DC appliance:

$$\frac{1{,}000 \text{ Watts}}{12 \text{ Volts}} = 83.3 \text{ Amps}$$

Batteries

How do Batteries Work?

Batteries work through an electrochemical process that involves a double conversion of energy. The first conversion is done to charge the battery and consists in passing from electrical to chemical energy. The second conversion process is developed by passing from chemical energy to electrical energy. This is done during the discharge process.

All batteries base their functioning on this principle. To make this energy conversion possible, two electrodes from different metal components must be used to act as the positive and negative terminals of a voltage source. Also, there must be an ionic medium that connects both electrodes. This is commonly known as the electrolyte and is a liquid composition that allows the transfer of electrons between electrodes. This whole arrangement receives the name of the *voltaic cell*. The arrangement of several cells makes the battery.

A direct current voltage source must be connected with the right polarity to the terminals (electrodes) of the battery to get it completely charged. To make electric current flow from the source to the battery, the voltage of the DC source must be higher than the battery.

Lead-Acid

As it is stated before, lead-acid batteries have two electrodes. One electrode acts as the positive terminal and is filled with lead oxide (PbO_2), and the other one acts as the negative terminal and is made of pure lead. That's why lead-acid batteries are heavy.

The medium used for lead-acid batteries is sulfuric acid. Lead-acid batteries can be classified into two main groups:

- Flooded
- Sealed

Let's look at them in more detail.

Flooded

The first type of lead-acid batteries is the flooded or ventilated lead-acid batteries (VLA). VLA batteries are identified by having a small ventilated access to their internal structure with removable plugs that allows verifying the specific gravity and the state of charge of the battery (terms that will be discussed later).

The main downside of these batteries is that they emit gases that are generated by the internal electrochemical reactions. Due to this fact, these batteries must be located in an area with vented access where air circulates constantly. The accumulation of these gases within a small closed area can be dangerous.

Flooded deep cycle lead-acid battery

The internal electrochemical reactions and the expulsion of gases also reduce water levels inside the battery. This is why they also require periodic maintenance by adding distilled water to the battery through the ventilated access.

Maintenance also involves cleaning the terminals to remove oxide that can accumulate over time (although this applies to all batteries). You can recognize these batteries if you see removable caps on top. The caps can be removed easily with a twisting mechanism. Do not confuse it with the sealed or vented caps, where the caps are not meant to be removed.

Keep in mind that VLA batteries must always be placed in the right vertical position. Otherwise, the internal fluid will spill out. At the same time, vented batteries can also be classified into three categories.

- **Ignition Batteries**

These batteries are mainly used for automotive purposes. They seem to be economical for solar builds, but they are not suited for solar applications.

Ignition batteries are made to deliver a high amount of current for a short amount of time. This makes the build of the battery different and not suited for long-duration low current applications.

- **Deep Cycle Batteries**

Deep cycle batteries are used for applications where low amounts of current are needed to be supplied, but for longer periods of time. These batteries can endure many deep charge and discharge cycles. Since these are requirements used in photovoltaic applications, this kind of lead-acid battery is the one used for solar power storage.

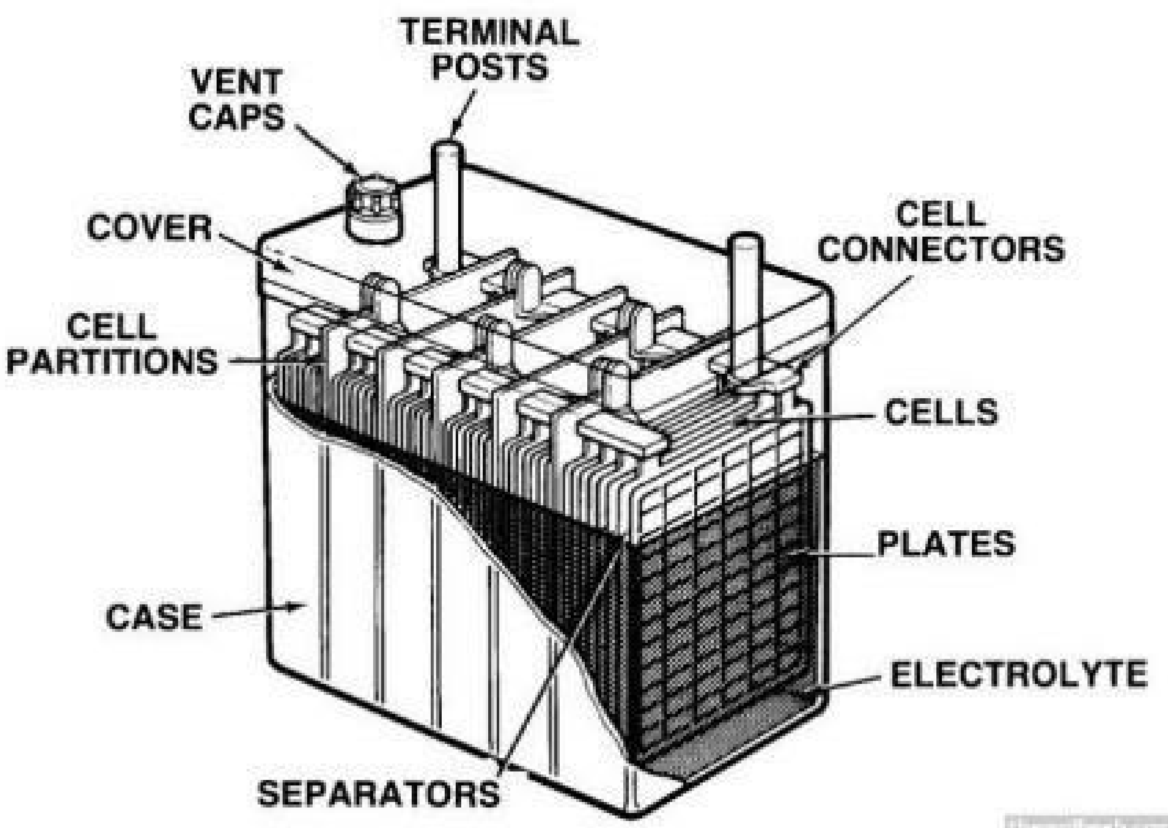
- **Backup Batteries**

These batteries are used to provide energy in control operations and backup in sub-stations. These are not generally used for off-grid solar power applications.

You might be able to pick these up when a factory, hospital, or network company wants to switch their backup battery bank every few years. However, these are not considered as the first choice for lead-acid batteries in solar systems.

Sealed or Vented

There are also batteries which are partially sealed to avoid the evaporation of electrolyte. VRLA batteries have a pressure-sensitive valve that automatically controls the emission of gases that is normally closed. They can be opened to release these gases in case there is high-pressure inside the battery. This will automatically happen if there is something wrong with the battery.



Vented lead-acid battery
Source: thewolfweb.com

These batteries recombine oxygen and hydrogen through an electrochemical process that allows them to reincorporate water back in the cell, instead of evaporating it and constantly releasing it as the VLA batteries do.

Thanks to the pressure valve, gas emissions and contaminations are minimum. The downside of these batteries is that the state of charge cannot be reliably verified, and in some cases, there is a higher sensitivity to the operating temperature when compared to the vented batteries.

There are two other types of VRLA batteries, depending on the electrolyte: Gel and AGM.

- **Gel Cell**

These batteries have a silicon compound. When added to the liquid electrolyte, the substance acquires a gel-type consistency.

Gel cell batteries have a longer lifespan when compared to flooded-type batteries and guarantee more charging and discharging cycles. This gel consistency is also an important advantage. Even when the battery is not placed in the upright position, or in case the battery case breaks or deteriorates, the sulfuric acid will not spill because the gel structure is solid.

Gel-type batteries also withstand deep cycle discharges with high-temperature values and even vibrations. Besides, they have a stable voltage during the discharge and do not require maintenance like vented batteries do.

They are also corrosion-resistant, and they are resistant to lower temperatures. Their main disadvantage is that they have a high internal resistance, which translates into a lower discharge current.

- **Absorbed Glass Mat (AGM)**

In AGM-sealed batteries, the electrolyte is absorbed by a fiberglass that works as a sponge that immobilizes the sulfuric acid. AGM batteries offer the same benefits as gel cell batteries, but the difference lies in that AGM batteries withstand higher charging voltages than gel types.

These batteries have a lower internal resistance due to their structure, which is why AGM batteries can deliver or absorb higher electrical currents during charging and discharging processes when compared to gel-type batteries. A lower internal resistance also increases efficiency and discharge voltages.

Unlike VLA batteries, these models can be placed vertically or horizontally. It is recommended when initiating the charge of AGM batteries. The charging current represents 20% of the battery capacity in Ah. This will be taken care of by your charge controller when you set the correct battery type.

Alkaline Batteries

The alkaline battery is one of the most common battery technologies available in the market. The basic principle still applies for these batteries, but in this case, the reaction occurs between zinc metal (negative electrode) and manganese dioxide (positive electrode).

The electrolyte solution used in these batteries is based on potassium hydroxide. There are mainly two types of alkaline batteries.

- Nickel Cadmium
- Nickel Iron

Nickel Cadmium (NiCd)

Nickel-cadmium batteries have different charging voltage points when compared to lead-acid models, and since they are rarely used in commercial applications, finding charge controllers compatible with Ni-Cd may be hard.

Ni-Cd batteries have a good low and high-temperature performance. They have a high life cycle expectancy, and they can be more deeply discharged than lead-acid batteries without losing capacity. Ni-Cd batteries are mainly used when large capacities and high discharge rates are required.

These batteries require higher charging voltages when compared to lead-acid batteries, which means that the charge controller will probably be more expensive.

The main disadvantage of these batteries is related to their high toxicity, since cadmium is a deeply toxic material. Moreover, another important disadvantage is their efficiency conversion values, which range between 70-75% when compared to lead-acid ones that are usually 80%.

Due to these properties, Ni-Cd batteries are not recommended for solar power applications and even less for portable RV or cabin solar power applications.

Nickel Iron (Ni-Fe)

Ni-Fe models are rechargeable batteries that have a long life expectancy, a high depth of discharge, and a durable performance (estimated at 20 years). These batteries are strong enough to withstand overcharge, over-discharge, and short-circuits.

Their disadvantages outweigh their benefits. In matters related to costs, they represent nearly 30% higher initial costs when compared to lead-acid models. Regarding efficiency, these batteries have lower efficiency in energy conversion (60-65%). They have a high self-discharging rate, and they need good ventilation since they constantly gas out hydrogen gas, which is explosive.

Finally, if finding charge controllers and inverters compatible with Ni-Cd batteries is hard, then Ni-Fe batteries are much harder.

Considering all of these downsides, Alkaline batteries, like Ni-Cd and Ni-Fe, are not recommended for solar power applications.

Lithium Batteries

Lithium batteries are the ultimate technology used in solar power applications. There are many lithium chemistry configurations, but the predominant technology for solar power applications is the Lithium Iron Phosphate (LiFePO4) and Lithium-ion (Li-ion) technologies.

Lithium batteries have the highest depth of discharge (about 80%). They also have low self-discharging rates (able to be stored for 5 to 10 years), and they have a high energy density, which means smaller dimensions.

They have a superior efficiency (95-99% efficiency) and a very low internal resistance, which makes them faster to charge.

Another important advantage of lithium batteries is that they can deliver more charging and discharging cycles than lead-acid batteries would.

LiFePO4 12V battery from Victron Energy

An important fact for RV applications is that lithium batteries can weigh less than half of what an equivalent lead-acid battery would.

The main disadvantage of lithium batteries is related to increased costs when compared to lead-acid.

For solar power applications, lithium batteries are probably the most powerful, efficient, and long-lasting solution, including RV applications. However, a trade-off with costs must be made to see if your budget reaches the initial cost difference.

In any case, lead-acid models have been the most widely used batteries in off-grid and RV applications. Therefore, if you cannot afford a lithium battery, but prefer to go with a deep cycle lead-acid battery, your solar system will still perform within the acceptable parameters.

Make sure that the Lithium battery you get is able to connect in series if you wish to do so. Some batteries cannot be connected in series because of the battery management system. This can be verified in the datasheet of the battery.

Lead-Acid vs. Lithium

Lithium can pay for itself after a certain amount of time. If your application is not permanent or seasonal, it might be a better idea to use lead-acid batteries.

Let's explore this with a comparison:

Lead-acid discharge rate: 50%.
Lithium discharge rate: 80%.

Lead-acid weight: Heavy.
Lithium weight: Half the weight of lead-acid.

Lead-acid cycles: 1,000 if you discharge it to 50% max.
Lithium cycles: 3,000-5,000 if you discharge it to 20% max.

Lead-acid maintenance: Self-discharges over time.
Lithium maintenance: Can be stored longer without charging.

Lead-acid venting: Needs to be able to vent gases, even if sealed.
Lithium venting: doesn't vent gases.

Lead-acid efficiency: 80%
Lithium efficiency: 95 – 99%

The true cost of ownership is higher in lead-acid batteries. If you plan on cycling your lithium battery 4 times more than a lead-acid battery, it is worth it to purchase lithium.
If you would only use your solar setup seasonally, the number of cycles will be reduced, so it makes sense to use lead-acid.

Temperature and Lead-Acid Batteries

Lead-acid batteries are extremely temperature-dependent.
Each lead-acid battery is designed with a specific capacity in ampere-hours (Ah). However, this capacity can be affected by the internal operating temperature drastically.

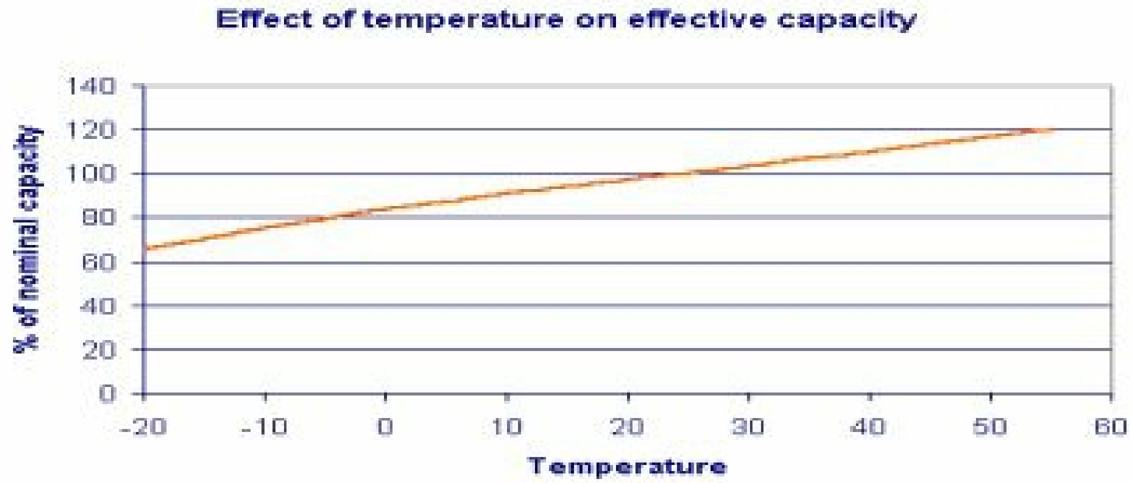
Chemical reactions are deeply influenced by temperature, and since lead-acid batteries charging and discharging is based on a chemical reaction, then temperature plays an important role for lead-acid batteries.

High temperatures result in an enhanced reaction rate, which at the same time increases the instantaneous capacity that the battery can have. Adversely, it can also reduce the life cycle drastically.

Every 10°C increase concerning the optimum operating temperature value 77°F (25°C) reduces the life of a battery to half of its rated lifespan. In other words, if an AGM battery is supposed to last nearly 10 years operating at 77°F (25°C), then increasing the operational temperature value to 95°F (35°C) will reduce its life expectancy to 5 years. As you can see, the effects can be deeply devastating for life expectancy.

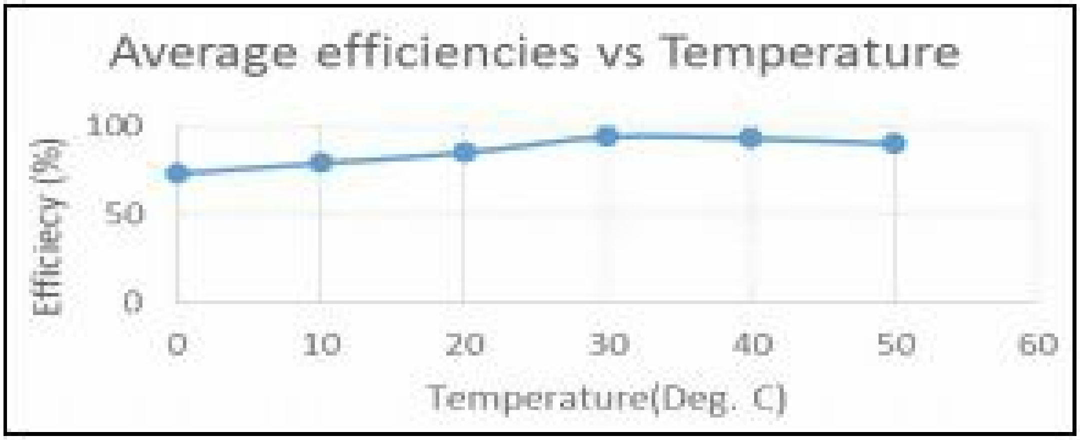
On the other hand, low temperatures have another impact on battery capacity. The nominal reference at 77°F (25°C) equals 100% capacity. As can be seen in the following figure, increasing the temperature also increases the available capacity that the battery can provide (up to 120% at 122°F or 50°C).

However, as temperature reduces, the percentage of nominal capacity that the battery will have available will start reducing as well. Capacity reductions could reach 65% of the nominal capacity at -4°F (-20°C).



Effect of temperature (°C) on effective capacity
Source: Sandia Report

Efficiency values are also affected by temperature drops, as can be seen in this figure.



Average efficiencies vs. temperatures.
Source: allsciencejournal.com

In case ambient temperature values cannot be modified, then the way to compensate internal temperatures is to use lower or higher charging currents.

Under low temperatures, the batteries should be charged at higher voltages and C-10 current values (more on C-rates later). Meanwhile, if high temperatures are present, then the charging current should be reduced to 75% of the rated C-10 current.

This is something that the charge controller performs. The device must have a temperature compensation feature (more on this later).

It is recommended to keep an ambient temperature between 77-86°F (25-30°C) for lead-acid batteries. That's why it's better to keep these batteries at room temperature, instead of a box outside.

When the winter season arrives, you will likely need to store your RV and battery bank as well. When doing this, remember that the battery must get fully charged before storing it.

Later, you will need to keep the battery in a dry and warm indoor location. The stored battery will self-discharge over time. You must use a smart charger that keeps the state of charge value at its fullest during the storage season. A smart charger will periodically charge your battery without leading to overcharging.

Lithium batteries have a higher tolerance for temperatures.

Lithium has the best operating temperature between 59-95°F (15-35°C). It can operate in a wider temperature range of 32-95°F (0-35°C) and can be stored at temperatures between -4 -113°F (-20-45°C). Lithium batteries cannot be charged if they are below freezing, as it will destroy the battery.

Using car Batteries

Some homeowners tend to think that a car battery may be used to power your RV appliances in a small off-grid PV system. However, the truth is that this is a bad technical decision.

Car batteries fall in the category of ignition batteries that were discussed previously in the vented battery type section.

Ignition batteries are characterized by delivering a large amount of current that is needed to start the engine. This is done in an instant. In other words, car batteries are designed to deliver large amounts of current for a very short period of time.

Batteries needed for solar power applications do not work the same way. For these systems, lower amounts of current and longer periods of use are needed to keep the system running. They must also have a deep depth of discharge rating and have higher conversion efficiencies.

Choosing to install car batteries may be more economical, but you are likely to end up in the middle of the road with no continuous power, even after fully charging your batteries.

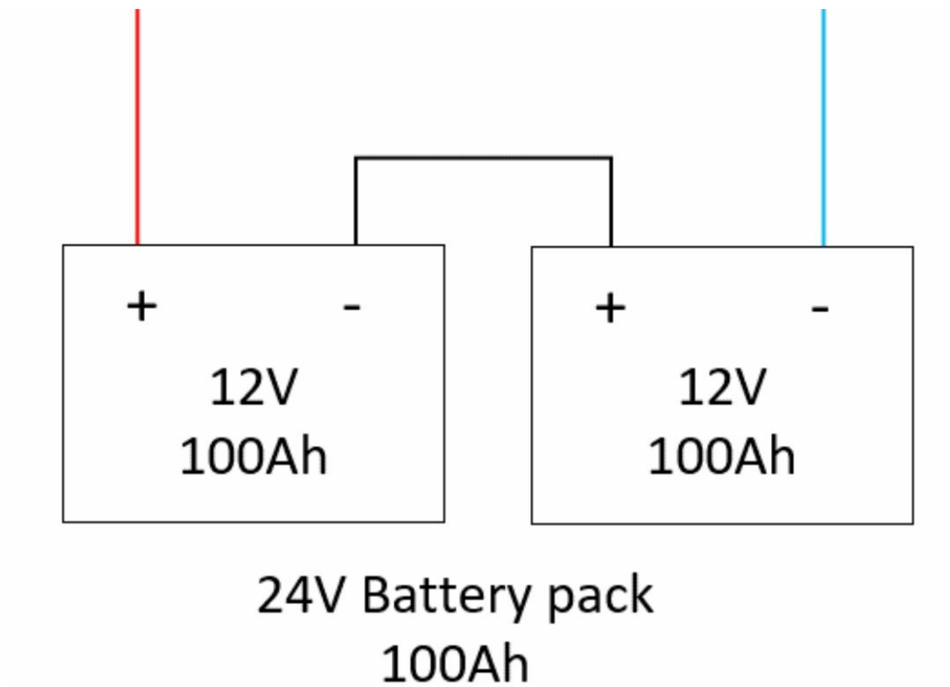
Therefore, choosing a car battery will have low reliability in the long-, medium-, and short-term for solar power applications.

Series and Parallel

Batteries can get connected in three configurations:

- Series
- Parallel
- Combination of series and parallel

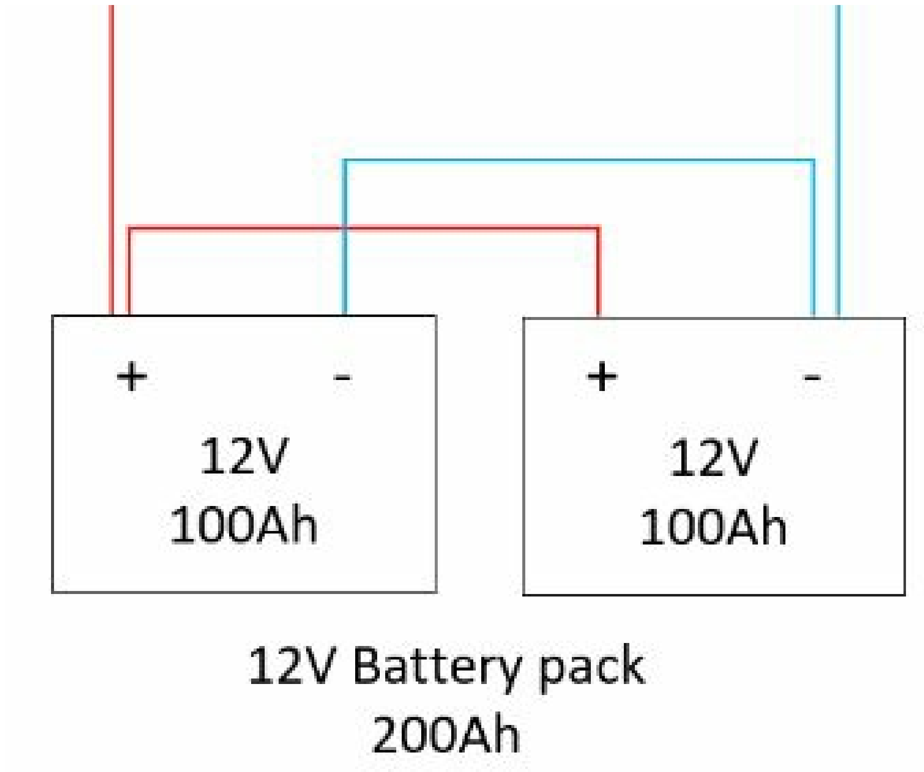
Similar to solar panel connections, wiring your batteries in series will increase the voltage of the battery bank while keeping the same energy capacity (Ah) of the battery. To connect your batteries in series, you must wire the positive terminal with the negative terminal of the other battery. A schematic of the series connection is shown in the following image.



Batteries joined in series

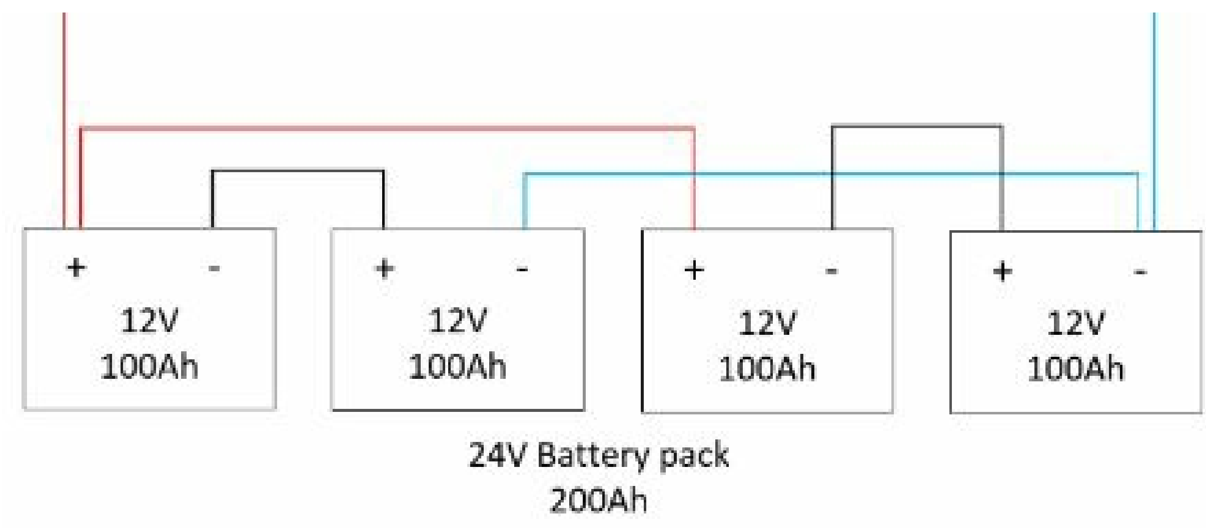
On the other hand, a parallel connection consists of joining the positive terminal of one battery with the positive terminal of the second battery and the negative terminal of the first battery with the equivalent negative terminal of the second one. This connection maintains the voltage of the battery set but increases the energy capacity of the battery bank in Ah.

It is important to use both terminals of the outer batteries as the main terminals instead of the terminals of one battery. If you are using lithium cells, make sure they can be connected in parallel.



Batteries joined in parallel

Finally, the series/parallel connection combines the two approaches explained before when both voltage and energy capacity need to be increased. This consists of making the series connections first and then joining the endpoints of the string of batteries according to their polarity.



Combination of series and parallel

The typical configurations used in off-grid systems are:

- 12V

- 24V
- 48V

It is recommended that you choose one of these voltage options since most charge controllers and inverters are designed to work under these configurations.

You may be wondering, what is the influence of the voltage selection and how can you know which voltage and connection you need for your specific application.

This is entirely linked to the capacity that you need to run your appliances effectively during a period of time. Once you have sized your demand estimation, you will need to estimate the capacity requirement. This can be done by using the following expression.

$$C_{load} = \frac{P_{load} \cdot \text{Hours of consumption} \cdot \text{days of autonomy}}{\text{Eff wiring} \cdot \text{Eff inverter} \cdot \text{Voltage DC} \cdot \text{DOD}}$$

As you can see in the expression, the power and hours of consumption represent the energy demands of your solar system. DOD is referred to as the depth of discharge. The days of autonomy referred to the number of days that the battery bank can provide power to the loads without receiving a charge from solar energy. *Eff wiring* and *Eff inverter* referred to the efficiency levels of cables and inverters, and finally, voltage DC referred to the voltage of the battery bank.

As you can see, since the Voltage DC is placed in the denominator of the expression above, choosing a higher voltage capacity will reduce the amount of energy capacity that will be needed to supply the loads. For small applications below 500W, it may be suitable to use 12V battery configurations.

For other bigger applications from 500W to 2,000W, 24V may be used. And for higher power configurations, the best option is 48V.

Once you have selected your battery voltage, you must do the series or parallel connections to reach both capacity and voltage. Apply series connection to add voltages of batteries until reaching the desired nominal value and apply parallel connections to add capacities of batteries until reaching the required energy demand.

24 Volts systems require cables with a smaller diameter, which will save you a considerable amount of money. See the following example:

$$I = \frac{1{,}000W}{12V} = 83 \text{ Amps}$$

$$I = \frac{1{,}000W}{24V} = 41 \text{ Amps}$$

$$I = \frac{1{,}000W}{48V} = 21 \text{ Amps}$$

If you have a high voltage battery pack, the voltage transformation from the charge controller to the battery will be more efficient. It will reduce the voltage from 54 Volts (open circuit) in a 3 panel (12V) series configuration to 24 Volts instead of 12 Volts.
If you have a 24 Volts system, but you have some 12 Volts DC appliances, you can install a 24V DC to 12V DC transformer. The transformer output power must be rated to the total current of the devices. The wattage of these converters is calculated on the output. For example, a 24 to 12V DC converter with a current rating of 40 Amps has a power rating of 480 Watts.

$$12VDC \times 40 \text{ Amps} = 480 \text{ Watts}$$

They are very cheap to purchase compared to a pure sine wave inverter.

24V to 12V DC 40 Amps step down voltage regulator
Source: Daygreen.com

If you have a lot of 12 Volts devices which require high current, it might be smarter to stick with 12 Volts.

24 Volts systems need more than one solar panel in series if it is rated below at 17.5 Volts. You cannot charge a 24 Volts battery pack efficiently with a 17.5 Volts solar panel.
The stored energy in a series or parallel battery configuration is the same. Two 12 Volt batteries at 100Ah each wired in series and parallel.

Battery pack one in series:

- 24 Volts at 100Ah

$$\text{Power} = 24\text{ Volts} \times 100\text{Ah} = 2{,}400\text{ Watt hours}$$

Battery pack two in parallel:

- 12 Volts at 200Ah

$$\text{Power} = 12\text{ Volts} \times 200\text{Ah} = 2{,}400\text{ Watt hours}$$

We can see that both battery packs have the same amount of stored energy.

C-rate

We have referred to the discharge rate of the battery before, but we haven't described it yet. It is time to do so.

As we have explained before, batteries depend on a chemical reaction to generate electricity. The available capacity of a battery is therefore dependent on how quickly the charging or discharging of the battery is performed, relative to their total nominal capacity.

In other words, the storage or remaining capacity of the battery depends on how quickly the chemical reaction needs to be done. If you discharge a battery very quickly, the capacity will be lower than the indicated capacity on the battery pack. This is because of internal heat inside the battery.
Also, the higher the discharge rate, the lower the voltage of the battery will be (voltage drop).

The total capacity of the battery can be briefly abbreviated as C and represents a measure of how much energy can be stored inside the battery.

The charge and discharge rates of a battery are measured in C-rates. The C-rates are always provided by the manufacturer, and each battery has a nominal current value for each C-rate.

There are different C ratings for batteries. Some say $C_{20,}$ and some say ${}_{10}C$. What is the difference between having the number before or after the letter 'C'?

C_{10}	C/10
C_{20}	C/20
${}_{2}C$	C/0.5
${}_{10}C$	C/0.1

Common C ratings

If the C-rating is in front of the letter C, you multiply it with the battery capacity. If the number is to the right of the letter 'C,' you divide it with the battery capacity.

If the battery has a capacity of ${}_{65}C$, you multiply the capacity with 65. This is only found in small Lipo packs for drones.

65C lipo battery for drones

Let’s calculate the discharge rate for this small battery pack.

$$1.8\text{Ah} \times 65 = 117 \text{ Amps}$$

This battery can provide 117 Amps continuously until it’s empty. However, the battery will get hot, and in practice, the battery capacity will be reduced because of the fast discharging.

One of the most common C rates that manufacturers mention for off-grid applications is the C_{20} rate.

If you have a 100Ah battery with a rating of C_{20}, it can supply 5 Amps for 20 hours (ideal battery with no DOD limit).

$$\frac{100 \text{ Ah}}{20} = 5 \text{ Amps for } 20 \text{ hours}$$

Why is the C rating important?

If you purchase a battery bank, the capacity will most likely be tested with a 20 hour discharge time at a temperature of 68°F (20°C). Discharging a medium-sized battery over a period of 20 hours will not create much heat and will work close to its best efficiency.

If you take that same battery and discharge it over a period of 5 hours instead of 20, the capacity will be reduced. This is because the battery must provide energy quicker, which will increase the amps, the heat, and the internal resistance of the battery.

Capacity ⁸ Amp-Hours (AH)			
5-Hr	10-Hr	20-Hr	100-Hr
344	386	420	467

Battery capacity relating to discharge time 6V 420Ah battery
Source: trojanbattery.com

Let's take the battery from the previous image, and let's see how much energy you can get out of it.

C-rating	Capacity	Current
C_5	344 Ah	68.8 Amps
C_{10}	386 Ah	38.6 Amps
C_{20}	420 Ah	21 Amps
C_{100}	467 Ah	4.67 Amps

$$\text{Energy} = \text{Voltage} \times \text{Current} \times \text{Hours}$$

We can see that the C_{20} rating is used to describe the capacity of the battery, which is 420Ah. Let's see what will happen if we discharge it at a higher C rating.
The 6 Volts battery will drain from 6.36 Volts (100%) to 5.25 Volts (0%) over time. Draining a battery to 0% is not recommended because the battery will get damaged internally. We can use this to calculate the total energy that is stored inside the battery.

$$5.25\text{V} \times 68.8\text{A} \times 5 \text{ hours} = 1{,}806 \text{ Watt hours}$$

$$5.25\text{V} \times 38.6\text{A} \times 10 \text{ hours} = 2{,}026 \text{ Watt hours}$$

$$5.25\text{V} \times 21\text{A} \times 20 \text{ hours} = 2{,}205 \text{ Watt hours}$$

$$5.25\text{V} \times 4.67\text{A} \times 100 \text{ hours} = 2{,}451 \text{ Watt hours}$$

As you can see, longer discharge times are equivalent to higher effective energy capacity storage but imply lower instantaneous electric current demands.

Meanwhile, shorter discharge times allow for a higher instantaneous electric current demand, but they will reduce the effective capacity of the battery. The reduction effect is non-linear.

You will also see mentions of 1C or 0.5C, which is common in lithium batteries. For example, a lithium battery with a capacity of 100Ah, which has a discharge rate of 1C will be able to draw:

$$100\text{Ah} \times 1 = 100 \text{ Amps in one hour}$$

A battery with a discharge rating of 0.5C will be able to draw:

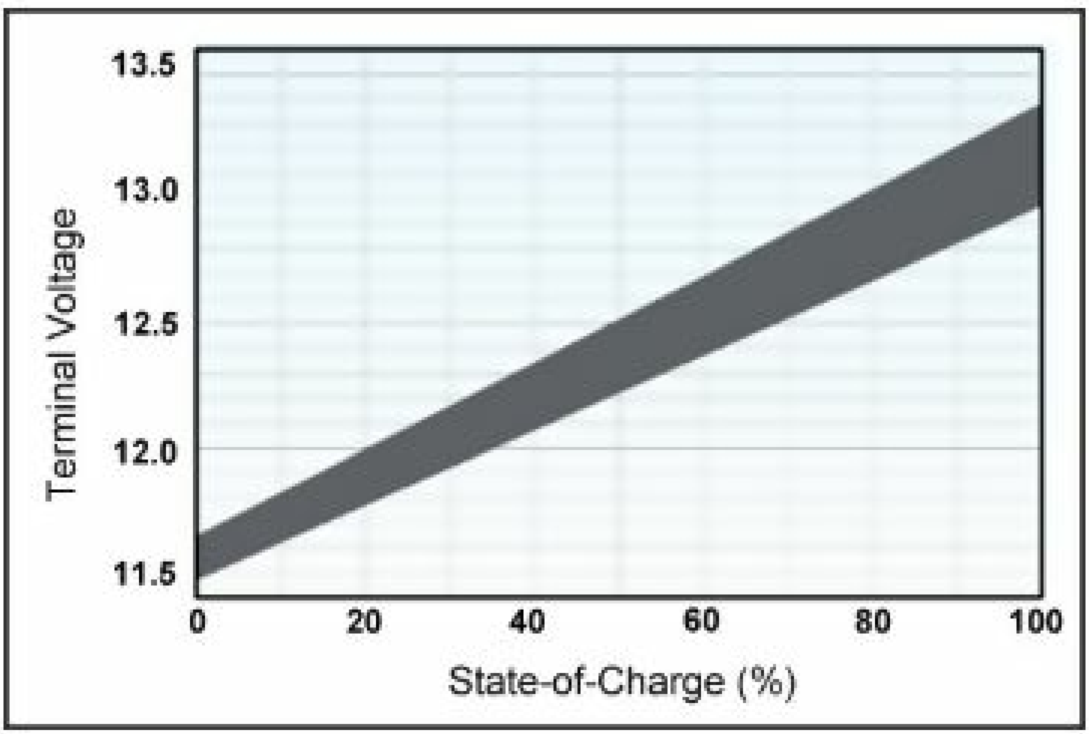
$$100\text{Ah} \times 0.5 = 50 \text{ Amps in one hour}$$

Battery Monitors

One of the most useful gadgets that you can use for solar power is a battery monitor. This is usually an available feature of a charge controller. The charge controller includes a battery voltage that provides a reference to the user related to the state of charge of the battery bank.

Each lead-acid battery is made up of cells. Each cell is approximately 2 Volts. Therefore, a 12 Volt battery has 6 individual cells. A fully charged cell has a voltage close to 2.15 Volts, while a discharged cell is close to 1.9 Volts.

If you choose to size a 12 Volt battery bank, then you may see voltage values ranging from 12.73V to 13.5V (depending on the stage of the charging process). This will give you a reference that the battery bank is fully charged or finishing the process of charging. If you notice voltages below 11.4V, then your battery bank will be discharged entirely.



The state of charge vs. Terminal voltage
Source: Battery University

For 24V systems, fully charged voltages may be located between 25.8V and 28V, while discharged voltage may be located below 23V.

Finally, for the 48V system, a fully charged battery bank will have voltages between 51.6V and 56V while a discharged voltage may be located below 46V.

All of these voltages are temperature-dependent and model/technology-dependent; therefore, they can only provide a general reference.

The best way to check this is by verifying the manufacturer's datasheet where you will likely find a voltage (V) vs. state of charge (%) graph.

Keep in mind that no lead-acid battery should be discharged beyond 2V per cell or 50%. Otherwise, it could cause permanent damage to the battery.

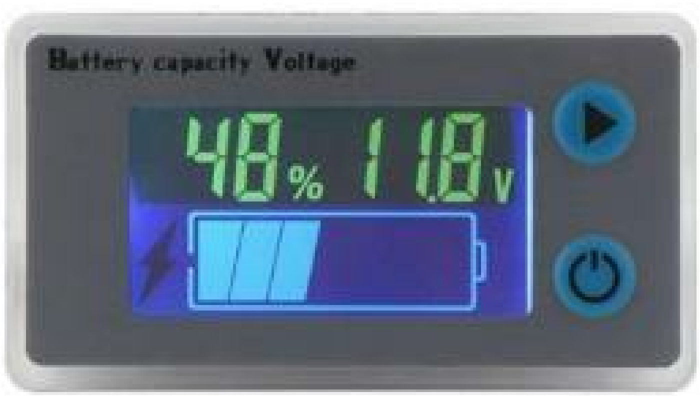
As a reference, the following graph shows the percentage of charge with different lead-acid models.

State of Charge	One cell	6 Volts	12 Volts	24 Volts	48 Volts
100%	2.12	6.36	12.72	25.44	50.88
90%	2.08	6.24	12.48	24.96	49.92
80%	2.07	6.21	12.42	24.84	49.68
70%	2.05	6.15	12.3	24.6	49.2
60%	2.03	6.09	12.18	24.36	48.72
50%	2.01	6.03	12.06	24.12	48.24
40%	1.98	5.94	11.88	23.76	47.52
30%	1.96	5.88	11.76	23.52	47.04
20%	1.93	5.79	11.58	23.16	46.32
10%	1.89	5.67	11.34	22.68	45.36
0%	1.75	5.25	10.5	21	42

State of Charge vs. Open Circuit Voltage

Lithium batteries are different than lead-acid. Each cell has a voltage of 3.2 Volts. Four individual cells make up one 12V battery.

You can purchase battery monitors, which will tell you the current voltage level of the battery. This will only work in an open circuit, which means that no load or power source is attached.



DROK battery monitor

The attached load will decrease the voltage at the terminals of the battery temporarily while the power source (PV panels) will increase the voltage temporarily.

To get an accurate measure of the state of your battery, using voltage alone is not ideal. We are going to use a shunt to measure the capacity of our batteries. More on shunts at the end of this chapter.

Over-Discharging and Sulfation

When you discharge a battery under the recommended depth of discharge (50% for lead-acid), the sulfuric acid and electrolyte of the lead-acid battery can be depleted and become a substance that can be classified as water. This effect creates the formation of large crystals of lead sulfate, which makes the charging and discharging process for the battery much harder, which decreases efficiency.

Sulfation generally occurs after discharge at low currents as a result of acid stratification and crystallization. Sulfation also occurs when a lead-acid battery is stored for a long time under a discharged condition or if it is never fully charged.

Another cause can be related to the electrolyte levels, which are presumed to be unusually low due to excessive water loss from overcharging the battery or evaporation of water inside the batteries.

Sulfation is usually treated by charging the battery at a low current and a higher voltage (higher than nominal), generally in a range between 2.4V-2.5V per cell and 0.5A to 8A (depending on the battery size). In most cases, this will remove the sulfation process gradually.

A sulfated battery can easily be recognized by taking a look at the plates inside the battery. The color of a sulfated plate is lighter, and its surface becomes harsh and gritty. If you have a sealed lead-acid battery, it’s best not to open the caps. Check the datasheet of your battery to know more about maintenance.

Over-discharging will be prevented by your charge controller. If you connect your loads directly to your battery (which I recommend), you need to use another system like a low voltage disconnect. This will disconnect the loads from the battery after a certain voltage is met. Another solution is to use a shunt to monitor the state of charge from the battery. The downside to a shunt is that it does not disconnect your battery automatically.

65 Amp low voltage disconnect from Victron

Overcharging

Overcharging is a process where a high charge voltage is applied to the battery even after the battery achieves 100% capacity.

When this happens, an excessive current flows into the battery after the device has already been charged. This phenomenon causes a decomposition of the water in the electrolyte and causes premature aging as well.

Moreover, it can also degenerate into corrosion of the positive plates and increase water evaporation. A destructive effect of overcharging is related to overheating, which in some cases could lead to another process known as thermal runaway that can destroy the battery in just hours.

You do not have to worry about overcharging your batteries when you have hooked up your charge controller. The charge controller will regulate the flow of current to the batteries and stop it if the battery is fully charged. That’s why a charge controller is an essential part of your solar system.

State of Charge

The state of charge (SOC) represents the available energy inside the battery in a specific moment. It’s expressed in percentage units.

When fully charged, the state of charge is 100%. The SOC is the opposite of the depth of discharge (DOD), where if the SOC is 80%, then the DOD will be 20%.

The SOC depends on the consumption of the load and temperature values. The SOC can be figured out using the following methods:

- The easiest way to find out the SOC is to measure the battery voltage at the terminals. As was already mentioned in the book, it’s best to measure voltage without any wires attached to the battery (no charging and no load).
- You can also check this on the display of your charge controller (if it has a display).
- Use another instrument called a hydrometer. This device measures the specific gravity of the fluid inside a lead-acid battery.
- Read the monitor of the battery capacity shunt.

Depth of Discharge

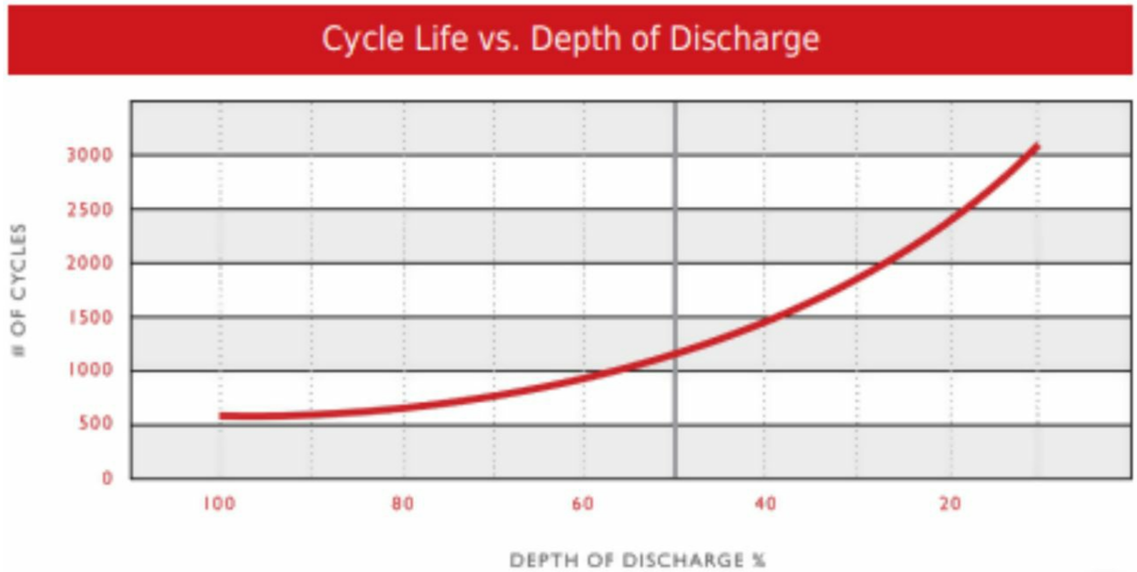
The depth of discharge represents the amount of energy (in percent) of its total capacity that has been extracted from any battery. As mentioned before, the DOD is established as the opposite of SOC, or in other words:

$$DOD = 100 - SOC$$

If your battery has been drained to 80% of its capacity (SOC), the depth of discharge is 20%.

Maximum Cycles

The maximum number of cycles is related to the maximum number of charges and discharges that can be applied to any battery. This value is extremely dependent on the DOD of the battery. For example, an AGM lead-acid model with 290Ah capacity from a manufacturer called Rolls gives a perspective of the variation of this parameter in the function of the DOD, as it can be seen in the following figure:



Cycle life vs. Depth of discharge
Source: Rolls

The nominal reference value in the graph is 50%. This reference value applies to all lead-acid batteries that will be used for solar power applications. In this example, you can get 1,200 cycles at a DOD of 50%.

When sizing your PV system, the basic consideration is to size the battery bank with a 50% DOD (for lead-acid). This means that the loads will be able to draw nearly 50% of the battery bank capacity within the designed autonomy days in the most negative scenario.

In case the system is designed to work daily, then it would mean that the loads may draw a maximum of 50% of battery capacity daily. The solar panels need to recharge 50% of this capacity during the next day to reach 100% SOC.

As can be seen in the graph, by using a 50% DOD, the number of cycles that the battery could have is equivalent to 1,200. That means 1,200 charging and discharging processes that the battery can be subjected to.

The lower the DOD, the higher the cycles.
The higher the SOC, the higher the cycles.

The reason why 50% is generally used as a parameter of design is that it is the best trade-off between the number of cycles and the number of batteries that needs to be used.

Choosing a lower DOD (30%, for instance) will mean that your batteries will last longer. It also means that you will need more batteries to cover the required capacity.

Choosing a higher DOD (80%, for instance) will mean that you will be able to take the best advantage of each battery charging and discharging cycle. It will also mean that the lifetime of each battery will reduce significantly.
Keep in mind that you can never size a 100% DOD since the battery will not be able to recover all its capacity again.

For lithium batteries, the recommended DOD is 80% or a SOC of 20%. This means you can drain a lithium battery to 20% of it’s rated capacity. If you have a 100Ah lithium battery, you can drain it down to a remaining 20Ah. Lithium is also able to have up to four or more times the amount of cycles than lead-acid has.

National Electrical Code

The National Electrical Code (NEC) 2017 (NFPA 70) is the most recent American reference that can be used in any electrical installation, including photovoltaic systems and recreational vehicles.

The NEC 2017 is extensive and covers multiple typologies and electrical systems. For our scope of research, this part will focus only on the most important sections related to battery systems associated with recreational vehicles that you should consider when sizing and performing the installation.

Article 480 Storage Batteries — Section 4 (B)
Intercell and Intertier Conductors and Connections

This section refers to the requirements for series and parallel connections of batteries. As stated in this section*: The ampacity of conductors and connectors must have such cross-sectional area (gauge) that the temperature rise under maximum load conditions and the maximum ambient temperature shall not exceed the safe operating temperature of the conductor insulation or the material of the conductor support.*

There are two ways of covering this requirement:

The first is referring to the thermal equation of a conductor to calculate the temperature of the conductor for a given ampere value. This approach involves a quite extensive and complicated engineering equation as to be explained in this practical handbook.

The second option is to refer to the wiring chapter and look at the maximum amount of amps for each cable diameter.

You must accurately estimate the maximum current load that you will have in your system, and make sure that this value does not exceed the permitted ampere capacity of the selected conductor. This is what was described as ampacity in the wiring section. The conductor heats up as higher electric currents pass through its cross-sectional area. If you size your wire to withstand the ampere load demand of your system, then it will never surpass safe operating temperature values.
Moreover, as stated in section 480.4 (B), you must also consider the maximum ambient temperature of the location. The procedure to calculate the influence of this parameter in cable sizing was explained in the section related to wiring.

Article 480 — Section 4 (C)
Battery Terminals

This section establishes that the connections to the battery terminals using cables cannot put a mechanical strain on them. This can be easily followed by properly sizing the cable and adjusting

the length to give enough flexibility to the wires.
As stated in the section: *Electrical connections to the battery and the cable(s) between cells on separate levels or racks shall not put a mechanical strain on the battery terminals. Terminal plates shall be used where practicable. Informational Note: Conductors are commonly pre-formed to eliminate stress on battery terminations. Fine stranded cables may also eliminate the stress on battery terminations.*

Article 480.10
Battery Locations

This article focuses on establishing that the site for the battery location must have proper ventilation for the sufficient diffusion of gases from the battery to avoid the accumulation of gases that could become an explosive mixture. Checking the Fire Code NFPA 1-2015, chapter 52 will give a further assessment of this aspect.

As stated in section 480.10 (C): *For battery racks, there shall be a minimum clearance of 25-mm (1 in.) between a cell container and any wall or structure on the side not requiring access for maintenance. Battery stands shall be permitted to contact adjacent walls or structures, provided that the battery shelf has a free air space for not less than 90% of its length.*
Another important consideration explained in this section is that the location for the battery bank must have a proper illumination source.

Article 551
Recreational Vehicles and Recreational Vehicle Parks

The National Electrical Code also considers the installation of recreational vehicles and park trailers as a separate electrical installation that has its own standards and requirements.
Article 551 exposes all the general requirements that must be carried out in electrical installations within recreational vehicles. Since there are too many requirements, we can only focus on the most relevant ones for solar power battery applications. However, if you intend to do your RV electrical installation as a DIY project, then you should verify the article 551 of NEC 2017.

From this article, we can extract some relevant sections for this book.

Section *551.30 General Requirements* establishes that storage batteries must be secured in place to avoid any displacement from vibration and road shock.

Section *551.31 Multiple Supply Source* establishes that a multiple supply source (like a battery power station powered by solar energy) must have installed an overcurrent protective device for the feeder of the alternate power source. This section also states that if the alternate power sources exceed 30 amperes at 120V, then it can get wired as a 208Y/120V (three-phase system) or 240/120V (split-phase system) system with the proper overcurrent protection device.

Article 552 Park Trailers

This article focuses on another type of vehicle, but that can also be applied for recreational vehicles, cabins, or boats in solar power installations.

Section 552.10 (C) establishes the minimum separation requirements between the battery and other low-voltage circuits that must be physically separated by at least a 13-mm gap. The best way to ensure such a minimum gap will always be present. The best methods are to use clamping, routing, or any other equivalent means to guarantee a permanent separation.

This section also refers to the ground connections that must be done in an RV:

Ground connections to the chassis must be done in an accessible location and must be mechanically secure. Ground connections shall be using copper conductors and copper or copper-alloy terminals of the solderless type identified for the size of the wire used.

The surface on which ground terminals make contact must be cleaned and free from oxide or paint, and must be electrically connected through the use of cadmium, tin, or zinc-plated internal/external-toothed locking terminals.

Ground terminal attaching screws, rivets or bolts, nuts, and lock washers shall be cadmium, tin, or zinc-plated except rivets shall be permitted to be unanodized aluminum where attaching to aluminum structures. The chassis-grounding terminal of the battery shall be connected to the unit chassis with a minimum 8AWG copper conductor.

Grounding in any PV system is one of the most important elements. Grounding provides a secure path for failure or short-circuit currents to flow securely to the ground to avoid any possible damage to the components of the system. Following these considerations shall guarantee you will have a good grounding system.

In an RV, the ground will be the chassis of your vehicle.
Finally, section 552.10 (D) also refers to the space and ventilation area of the battery bank. As stated in this section, the compartment where the batteries will be installed must be ventilated with a minimum opened area of 1100-mm^2 at both the top and bottom of the compartment. In case the compartment doors are equipped for ventilation, the openings shall be within 50-mm (2 inches) of the top and bottom of the compartment. It is very important to consider that batteries cannot be placed in a compartment that shares space with spark or flame producing equipment.

Maintenance of Batteries

The maintenance schedule depends on the type of battery you have selected for your PV application. As we have discussed earlier, lead-acid VLA batteries need further and more continuous maintenance than VRLA batteries. However, there are many steps in the maintenance procedure that apply for both types.

- Check the battery's state of charge (SOC) as it will give you a reference for the current state of the battery before starting maintenance. This can be done by checking the charge controller LCD screen. Another way is to use a voltmeter to check the voltage on battery terminals and verify the state of charge. Make sure the battery is fully charged before starting the procedure. Voltage has to be measured in an open circuit, which means without loads because it could lower the terminal voltage.
- Wear personal protective equipment such as protective eyewear and gloves when doing maintenance on batteries. It's advisable to wear long sleeves and long pants.
- The next thing to keep in mind while doing maintenance on your system is to first disconnect the PV panels using the solar disconnect switch. Then use the battery bank disconnect switch to disconnect the entire battery bank from the charge controller and loads.
- Inspect the terminals, screws, clamps, and cables of the battery to verify if there is any damage or loose connections. These connections should be clean, tight, and free of any corrosion.
- Remove the battery from the compartment and place it over a non-conductive surface.
- The next step is to proceed to clean the battery. This can be done by using a mixed solution of distilled water and sodium bicarbonate (a proportion of 100 grams per liter). Using this mix, the battery case and terminals must be cleaned using a wet sponge (not dripping).
- Make sure the entire battery is completely cleaned and free of dirt or grime.
- The next step depends on whether or not you have a vented-lead-acid battery (VLA). VLA batteries need to be filled with distilled water periodically to recover their composition. When performing maintenance, open the valve and check for the water level. Water should cover the battery up to the top of the cell. Use distilled water for this purpose. Always use safety glasses when performing this.

  Make sure the battery is charged before starting the procedure. If not charged, then fill the battery with enough water to cover the plates and charge it, then add the remaining water. VRLA batteries do not need this step.
- Put the battery back in place and make sure to adjust the connections properly. Loose connections can cause sparks or partial external discharges in the terminals of the battery that could be dangerous. The recommended torque for threaded battery terminals is 100-120 in-lb or 15 Nm depending on the size of the terminals.

Complete battery maintenance is a procedure that should be performed every 6 months, at least in case of VRLA batteries. While in the case of VLA batteries, maintenance may need to be carried out every month, especially checking the water levels.

For both types of batteries, revision of voltage, the ambient temperature of the compartment, integrity of the battery system, and ventilation check should be performed monthly.

If you have winterized your batteries, keep in mind that even when not using them, you should charge them once every 3-4 weeks to keep self-discharge low.

Buying Used Batteries

Buying used batteries may sound like a good deal, but the truth is that it's generally not. Batteries are very powerful but delicate devices.

Proper handling and maintenance procedures, temperatures, and discharging processes affect the life cycle of the battery dramatically.

Unfortunately, there is no way to test the battery to figure out how many cycles are left.

Purchasing a used battery has a big problem that is related to the remaining lifespan, which is hard to determine. Besides, even when the battery looks good on the outside and can charge and discharge, it cannot be verified with certainty that the battery works properly under a longer term of operation until you buy it.

Even if the seller tells you that these batteries have never been used and they are good as new, then there is also a high probability that the batteries have been exposed to long periods of the discharge as they self-discharge over time. This can damage the battery permanently or reduce its performance drastically.

The bottom line, buying used batteries is never a good idea. If you are low on budget, the best choice available is to select flooded type batteries and install a smaller PV system to cover only basic loads.

You can test the capacity of a battery, but you would need several hours or days to do it. In case you wanted to test your own batteries, you need to do a discharge capacity test. This is how to do it:

1. Charge the battery to full capacity. For a 12 Volt lead-acid battery, this is 12.72 Volts.
2. Get a balance charger (Imax B6), Select the Pb (lead-acid) or LiPo program from the menu.
3. Check that the battery discharge voltage is correct. This should be 12.06 Volts for a 12 Volts lead-acid battery (50%).
4. Select discharge at a rate of 1 Amp.
5. It will take a certain amount of time, depending on your battery bank. If you have a lead-acid battery bank of 100Ah, it will take 50 hours at a one-amp discharge rate to get the battery to 50% state of discharge.
6. The display on the balance charger should read half of the capacity of the battery. If it is less than half, the battery doesn't have its true capacity anymore.

If in doubt, refer to the manual for further instructions.

Imax B6 Balance charger

Weight of Batteries

The weight of batteries is one of the variables that you need to consider when selecting batteries, depending on the placement.

Sometimes space will not be enough to place all the batteries on the floor, but in some cases and maybe more on boats or cabins, it may be needed to install a small shelf to place the batteries. You will need to consider that the support for these batteries will need to resist this weight over a long period of time.

The weight of the battery can be found in the datasheet of the manufacturer. At the time of selection, keep in mind that lead-acid batteries are two or three times heavier than their lithium counterparts.

If you are living in an RV, you want to reduce the amount of weight you are carrying with you. Choosing lithium over lead-acid might be something to consider.

Shunts

The battery indicator is a device that can be used to provide a visual and practical indication of the state of charge of the battery.

Voltage based battery monitors can give you an accurate indication of the battery capacity. However, this is only true if there is no load applied or if the battery is not getting charged.

Unlike battery voltage meters, this counts the number of amp-hours going in or out of the battery. This, combined with the voltage of the battery, gives you Watt-hours. This is more accurate than the voltage meters.
As you already know, the voltage of the battery will drop once you apply a load to it. If you remove the load, the voltage will go back up.

Let’s say the battery is at 80%, which is 12.42 Volts. If you apply a load, the voltage will drop. Because of the drop in voltage, the voltage monitor will say 11.88 Volts which is 40% but in reality, it is at 80% capacity.

This is the same when charging the batteries. The batteries will indicate a higher voltage level when they are in an open circuit. This can be confusing. Therefore there is a need for a real-time battery capacity indicator. This is called a shunt.

There are several types of shunts ranging from very cheap to quite expensive. The first one I’m going to discuss is a type that I do not recommend installing in your solar system.

100A battery shunt

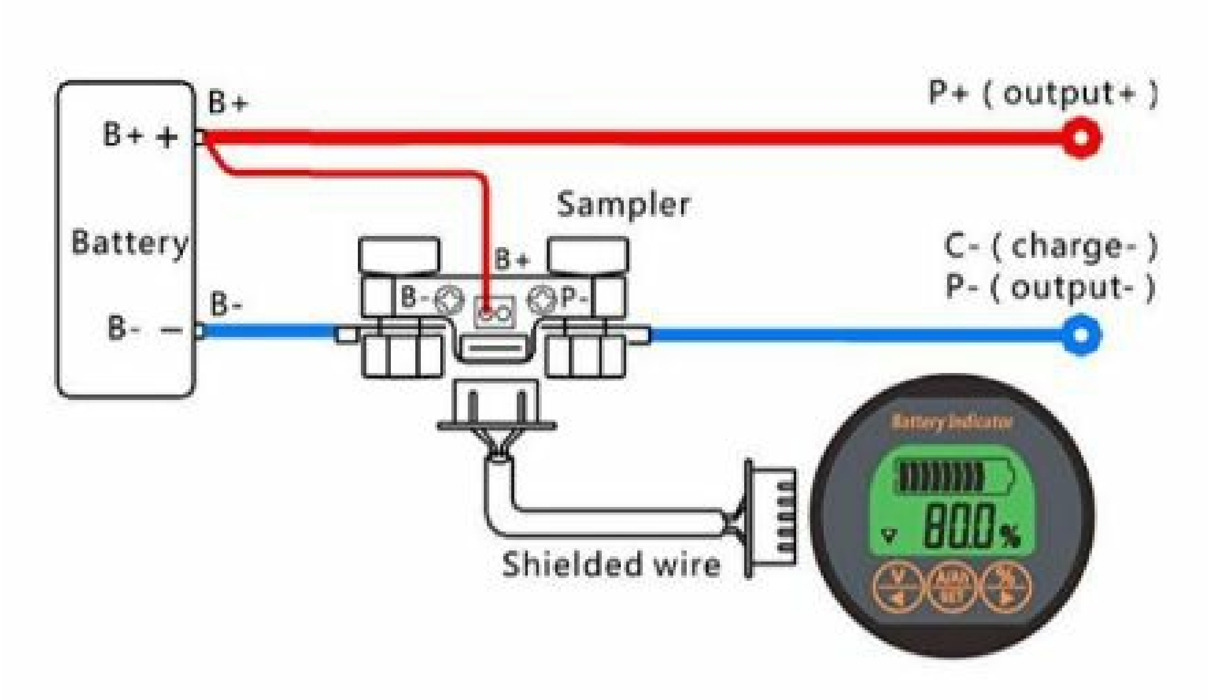
This meter only measures in one direction. This means it only measures the energy going in or out. This is not a good representation of the current state of charge. This can be useful if you do not have solar panels installed. For example, you charge the battery in the RV park and monitor the drawn Watt-hours or Amp-hours over a period of a few days until you reach another RV park. This is not very useful if you are charging the battery bank using solar panels.

The other type of shunt is the one that measures both ways. This is much more interesting for solar applications.

This type measures both the current that flows into your batteries and the current that is being drawn from the batteries. I recommend using this kind of shunt to monitor the true capacity of your battery bank. Victron makes one that has Bluetooth capability so you can monitor the capacity of your battery from your phone.

The one from Victron can be bought for $205 for the 500 Amps shunt. One that is sold by AiLi is rated for 350 Amps and can be bought for $45, but it comes without Bluetooth option.

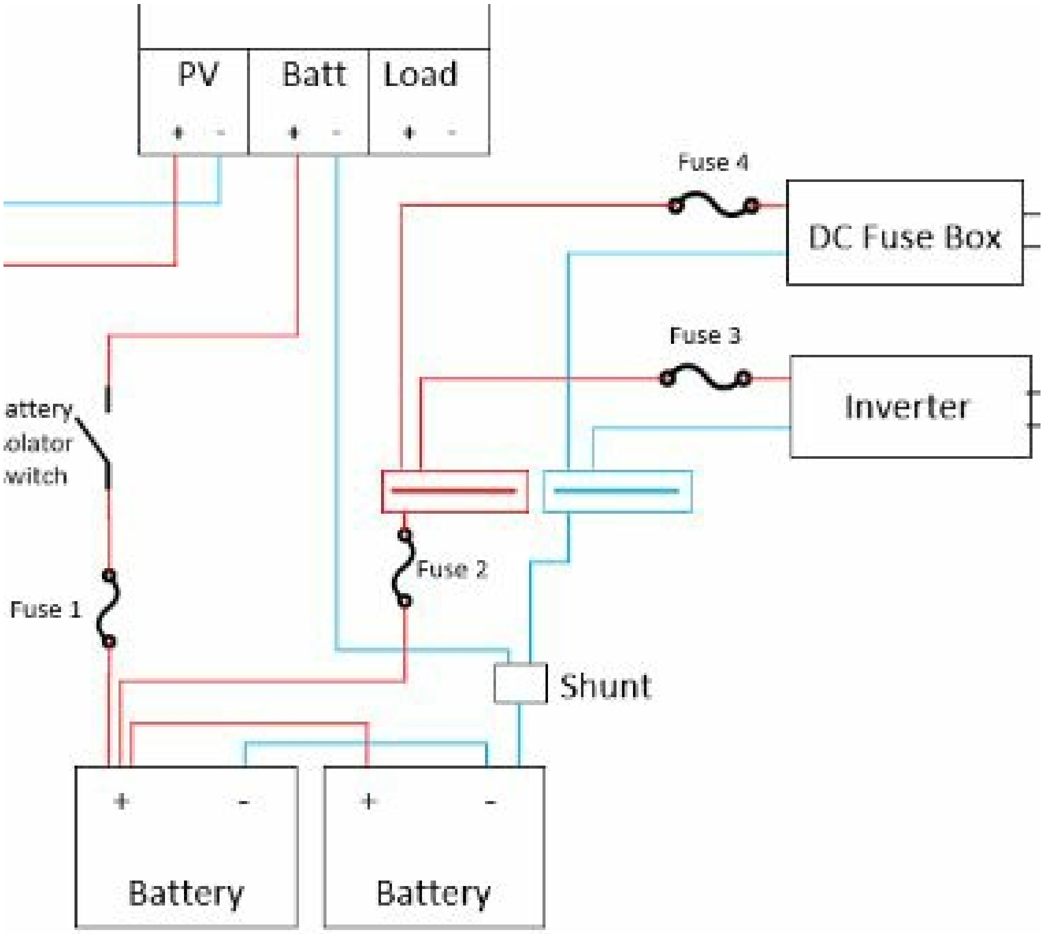
Both meters require that you read the manual to set up the meter according to your battery pack.



Wiring diagram for the Aili 350A shunt

The shunt is placed on the negative terminal of your battery. From here, all the negative leads go to their destination. It's essentially the same as replacing the negative terminal of the battery with the shunt, as can be seen in the following diagram:

It needs a positive voltage which can be taken from the positive terminal of the battery. The shielded wire is going to a display that is easily accessible.



Schematic with integrated shunt

Solar Panels

Solar cells are the source of power in any PV system. These devices are made of silicon, which is the most abundant and economically attractive semi-conductive material (elements that can behave as isolating or conductive materials) for the manufacturing of solar panels. Silicon is composed of electrons, neutrons, and protons as any other element of the periodic table.

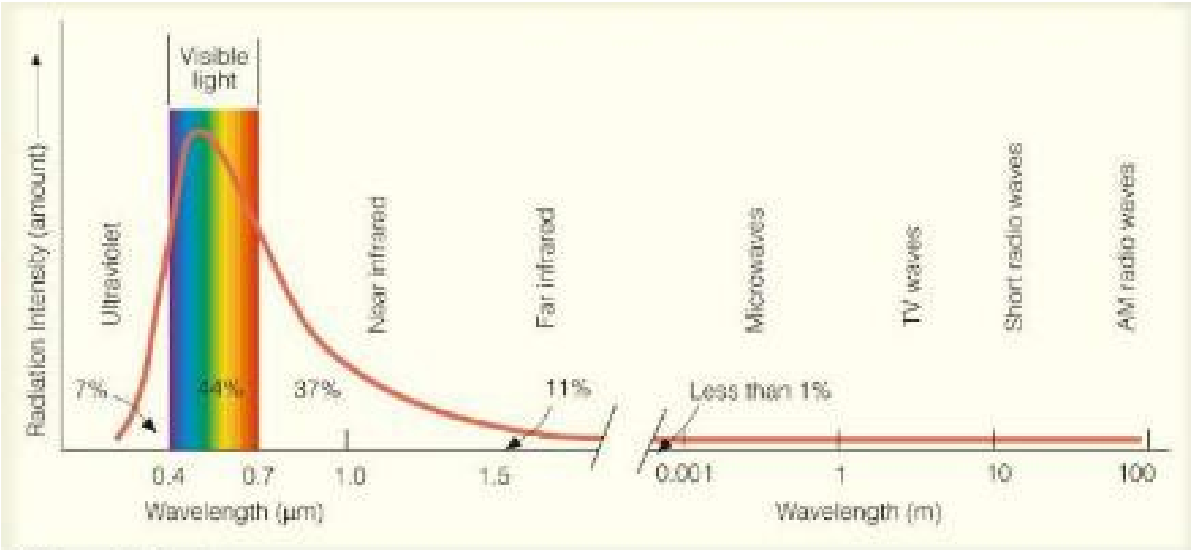
The process carried out to make the solar cells generate electricity is called the photoelectric effect, a physics phenomenon discovered by Albert Einstein. Briefly and easily explained, the science behind it implies energy transformation from light into electricity.

Solar radiation has a wide spectrum. Based on this spectrum, solar radiation can be divided into two major components:

- Heat
- Light

The region of solar radiation wavelength that the solar panels can use for generating electricity is located within the visible light region. Sunlight particles contained within this wavelength range called photons have intrinsic kinetic energy that allows them to travel from the Sun to the Earth.

When these particles reach the surface of a solar cell made of silicon, they transfer this kinetic energy to the electrons of the silicon atom. This energy transfer makes the silicon behave as a conductive material and allows the flow of a small electric current.
Without entering into further physics concepts, the output of the solar cells can be combined through series/parallel connections to create a structure that we commonly call a solar panel or photovoltaic (PV) module. This allows us to increase the electric current and voltage value as well to conceivable power outputs that can be used in common market applications.



Solar radiation spectrum
Source: Atmos Washington

Types of Panels

The theory explained before, applies for all solar panels. Some differences are worth noticing among PV modules. Thus, we can classify solar panels by technology.

Monocrystalline

Monocrystalline solar panels are the top or premium type of PV module available in the market. These modules have the highest light to electrical energy conversion efficiency in the market with values that range between 19-22% (for recent top brands). That is why they are considered in many PV applications, especially those that have little space available for placing solar cells.

Due to this premium performance, they also have a higher cost.

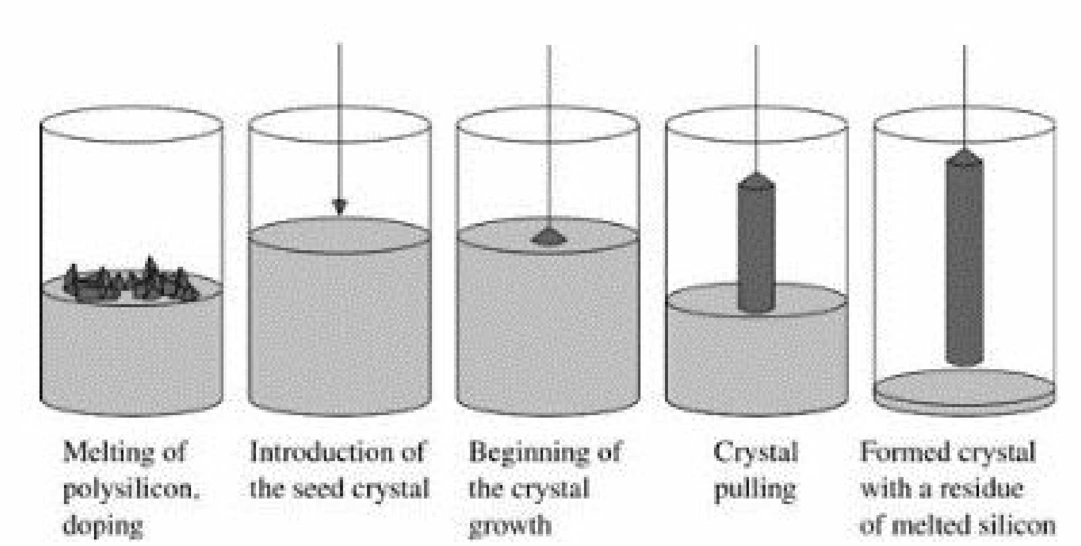
These PV modules are also requested in the market for RVs, cabins, and boats, since they optimize the space available to generate the highest electrical energy output. They are also used in many home type applications because of their elegant black or dark blue color. Monocrystalline solar cells also usually have a rounded shape edge that is created due to the manufacturing process.

Monocrystalline solar panels
Source: Energy Global

The manufacturing of monocrystalline solar panels is done through the Czochralski method. This process consists of melting multiple rocks of silicon at 2,500°F (1,371°C) and dipping a silicon crystal seed into this solution.

As the crystal is slowly pulled upwards, a crystal structure is created around the seed that is commonly called an ingot. The ingot is created with a cylindrical shape (the reason for rounded edges) that is sliced into multiple silicon wafers that are later transformed into cells.

The steps of the process can be seen in the following figure:



Czochralski manufacturing process for monocrystalline
Source: Top-alternative-energy-sources

Polycrystalline

The second option in terms of solar panel technology is the polycrystalline silicon module. These solar panels have lower efficiency values (between 16-19%) than monocrystalline modules, but despite that, their conversion efficiencies are good enough to be considered many times in the same applications as monocrystalline ones. Their greatest advantage when compared to monocrystalline technologies is their price.

The appearance of polycrystalline solar panels has a light blue color, and sometimes granular shapes can be visible on the surface of the module depending on the brand and year of manufacture. These modules look less elegant than monocrystalline technologies, which is why they are less requested when aesthetics is a must. Unlike monocrystalline panels, these modules have a squared shape edge.

Regarding the manufacturing process, these modules follow a similar procedure when compared to the monocrystalline ones.

However, an important difference is that instead of pulling out the silicon crystal from the molted silicon solution, it is cooled down. Then, the structure is sliced down into multiple silicon wafers. The granular shape of some polycrystalline panels is because the ingot is created from multiple silicon rocks.

Polycrystalline solar panels
Source: Solar Advice

Thin-Film Technology

The thin-film solar panel technology is the third and last type of variation in the market. These modules are made of incredibly thin films that are nearly 20 times thinner than the typical silicon-based panel, a property that makes them flexible and lightweight. If encased within plastic materials, the cells are flexible enough to adapt to the roof's shape surface.

Thin-film modules have an important advantage when compared to other silicon-based solar panels, more related to market perspectives than to the technology itself.

In February 2018, President Donald Trump's administration applied Section 201 Trade Remedy tariff of 30% on all silicon-based solar panels that are imported into the U.S. because they were harming local panel manufacturing.

However, these tariffs apply only to monocrystalline- and polycrystalline-type technologies, not to thin-film modules. This adds in favor of the market share that thin-film technologies can have due to lower costs.

Back to technology types, thin-film modules can be divided into four possible types:

- Amorphous-silicon (a-Si)
- Cadmium-Telluride (CdTe)
- Copper Indium Gallium Selenide (CIGS)

- Organic Photovoltaic (OPV)

Amorphous Silicon (a-Si)

The oldest thin-film technology is amorphous silicon. This type of module has a wide range of light spectrum absorption and is manufactured with non-toxic materials. Typically, small gadgets like solar calculators, solar watches, and also solar chargers for outdoors use a-Si cells because these devices need very low amounts of energy to work.

One of the biggest downsides of this technology is related to the efficiency values, which typically range between 10-13%, too low for residential or commercial applications these days. On the other hand, flexibility and cost are their biggest advantages.

The manufacturing process for these modules is different from its predecessors. Unlike polycrystalline or monocrystalline modules, amorphous solar panels are made from a thin plastic roll of 30 micros thick, which passes through a metal deposition machine that places a thin layer of silicon material onto the plastic. Then another machine uses lasers to scribe the material intersections, that define the individual solar cells.

Thin-film roll of solar panels
Source: Clean Energy Authority

Cadmium Telluride (CdTe)

The cadmium telluride is the most common type of thin-film technology that we can see in commercial applications. Here, the leading company is First Solar, which dominates the utility-scale sector. Conversion efficiency values of these modules from First Solar can go from 15% (Series 4) up to 18% (Series 6), good for utility-scale applications.

CdTe modules are made from several thin layers, some for electricity generation and some for conduction and collection of electricity. They are typically applied over fixed supporting materials as monocrystalline modules.

CdTe panels have better efficiency values in terms related to lower light wavelengths and can be manufactured at lower costs since cadmium is abundant as a byproduct of zinc. The main disadvantage of CdTe modules is pollution since cadmium is an extremely toxic material.

Despite that using these modules in residential or commercial applications is not dangerous for human health, the recycling process of these panels is another thing.

First solar PV modules installed in a 40-MW power plant
Source: Renewables Now

Copper Indium Gallium Selenide (CIGS)

CIGS modules are generally produced through co-evaporation or co-deposition techniques. Copper, indium, gallium, and selenide are placed on the substrate (plastic, steel, glass, or aluminum) under different temperature rates and they are sandwiched between conductive layers. When placed on a flexible backing, layers are thin enough as to bend at the will of the user up to a certain point.

CIGS module manufacturers such as Sunflare, MiaSolé, and Solar Frontier typically focus on covering markets that silicon-based technologies cannot cover. For instance, MiaSolé focused on commercial rooftop applications. However, they shifted the market sector to transportation and trucks. The purpose was to provide an environmentally friendly fuel consumption reduction solution.

They also manufacture flexible solar cells placed on a steel substrate with efficiency values that can reach 17%. Their modules can be installed through a peel and stick system that makes them easier and cheaper to install on trucks, carports, or seismic areas. These properties make Sunflare, Solar Frontier, MiaSolé and other CIGS module manufacturers ideal for RVs, vans, and boats where the surface could be curved.

The main disadvantage of CIGS modules, when compared to CdTe panels, is the price.

Sunflare flexible solar panels on a curved trailer
Source: Sunflare

Organic Photovoltaic (OPV)

The organic photovoltaic panel is made from conductive organic polymers that after depositing multiple layers of thin organic vapor between two electrodes, generates an electric current flow.

These solar cells are ideal for new applications such as building-integrated photovoltaics (BIPV). Thanks to the ability of these cells, OPV panels can be colored in several ways or even be made transparent. This is perfect for BIPV applications, where color variation is a good addition to integrating solar panels into windows of buildings. Due to the abundance of organic polymers materials, manufacturing costs are low.

Organic solar cells are thin, flexible, and printable as well.

The main downside of this technology is related to efficiency since organic solar cells generally reach values close to 11%, well under the current standard of the market. Another issue is related to lifespan. Organic degradation does not occur in other technologies and reduces the number of years that the cells can efficiently work.

Unique bus stop using organic solar cells
Source: PVinnovation

Other Cell Types

Gallium Arsenide (GaAs)

The Gallium Arsenide solar cell is another type that can be found in the market. These solar cells are the ones with the highest efficiency values that can be found in the market.

Alta Devices, a GaAs solar cell manufacturer, has been able to bring a 29% efficient cell and promote it at the market level. It is known as the dual-junction cell. GaAs cells have other advantages such as flexibility, lightweight, adjustability to multiple colors, thinner and malleable structure, good temperature resistance, and good performance under low light conditions.

Despite this high-efficiency value, GaAs cells have a very important disadvantage: high costs.

Since gallium is scarce and arsenic is toxic, the raw materials and the manufacturing process costs of these solar cells are much higher than traditional silicon-based technologies. This is the reason why GaAs is mainly used in very small applications where efficiency is crucial (space aircraft applications). You are more likely to find GaAs solar cells than solar panels.

Dye-Sensitized

The dye-sensitized solar cell is based on a semiconductor generated between a photo-sensitized anode and an electrolyte. These cells are easy to manufacture through printing cell techniques. They are semi-transparent. Overall, conversion efficiency rates are close to 11%. These cells also work well under low light conditions.

Their main disadvantage is cost as well, which is why they are not typically used for residential, commercial, or large-scale power plants. This is maybe the most forgotten solar cells in the market.

Perovskite

Finally, the ultimate type of solar cell technology is perovskite. Although not yet manufactured at large-scale, this technology is expected to revolutionize the solar panel manufacturing industry if it is successfully deployed in the next few years.

Efficiency values are expected to be at least 25% and may even reach 30%. Low manufacturing costs, flexible, and printable make it an attractive option for future market development.

Printable perovskite solar cells
Source: Instyle Solar

Conversion Efficiency

The conversion efficiency of a solar panel represents the maximum power output that the module can provide based on a specific module size area. Therefore, a solar panel with higher efficiency needs less area to provide the same power output.

The maximum theoretical value that a silicon solar panel (based on a single-junction structure) can achieve is known as the Shockley-Queisser limit and is 33.7%.

Higher efficiency values are linked to higher costs, but they also imply less solar panels and space to reach the same energy needs.

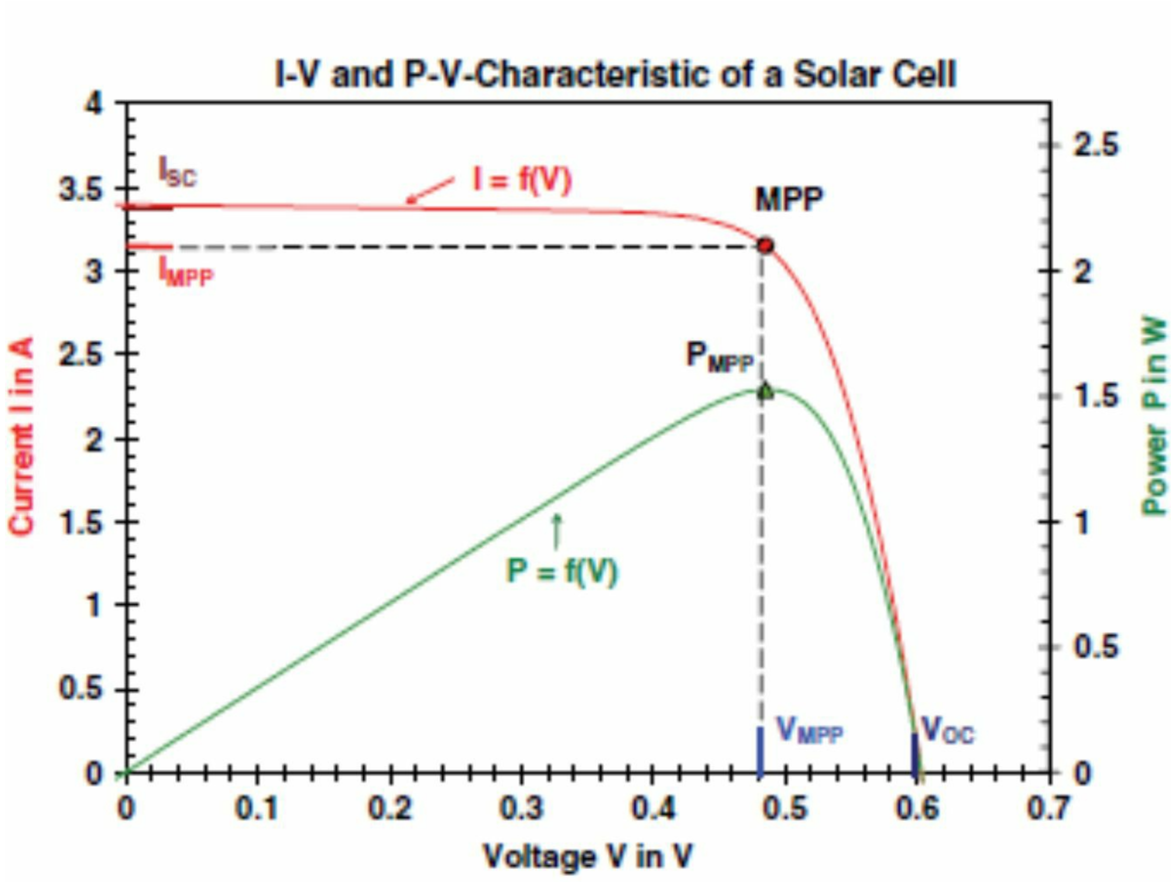
The Voltage-Current Characteristic Curve

Since solar panels generate DC electricity, two parameters determine the power output of the PV module:

- Voltage
- Current

As you already know, voltage (V) multiplied by current (I) makes up the power (Watt) of a device.

As I will explain later, voltage and current parameters are variable according to ambient conditions. The pattern change of these two parameters follows a specific curve. The purpose of this curve is to find out the equivalent power output for two voltage and current values provided.

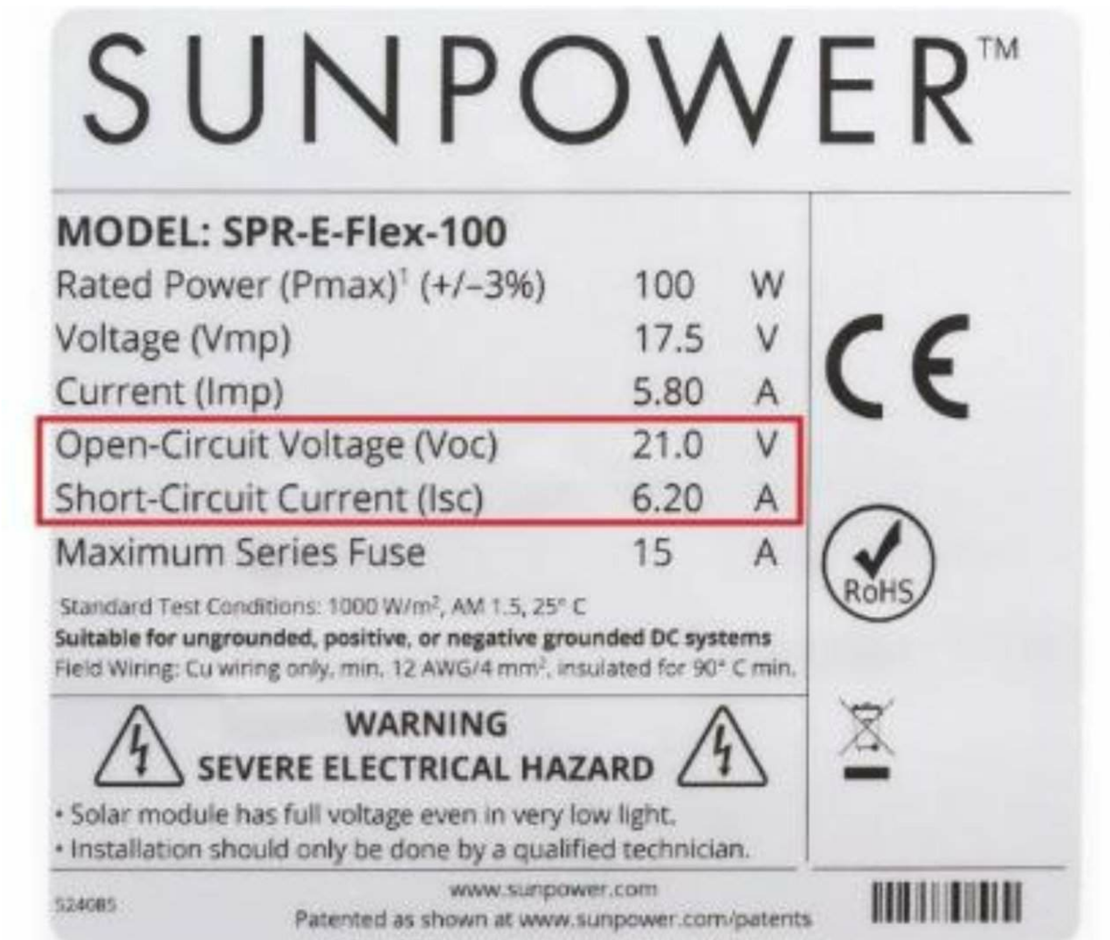


I-V curve of a solar cell
Source: H.Haberlin
"Photovoltaics — System Design and Practice"

If we look closer, there are two curves. The red curve (top) represents the I-V curve that shows variations of current according to voltage values. The I-V curve shows multiple parameters that are worth noticing.

Voc and Isc

The first two that we must notice are the open-circuit voltage (Voc) and the short-circuit current (Isc). These parameters are located on the external points of the curve and they represent the highest values that both voltage and current can have.



Specifications of a solar panel
Source: Sunpower

To understand how this curve works, we can position ourselves in the highest point of the curve, that is Isc. This point represents a short-circuit condition in which the solar panel is connected to a very low resistance (ideally zero) that allows electrical current to flow at maximum value. It would be equivalent to wire the positive and negative terminals of the panel together (do not try!).

Now, as the resistance is increased, the voltage starts rising. The current starts reducing step by step until resistance is too big to allow current to flow, which leads to the open-circuit condition.

Under this condition, voltage is at its highest value (Voc), and the current is zero. This is equivalent to leaving the two terminals of the solar panel without connection to any load (here the maximum resistance is the non-conductive air).

Impp, Vmpp, and Pmpp

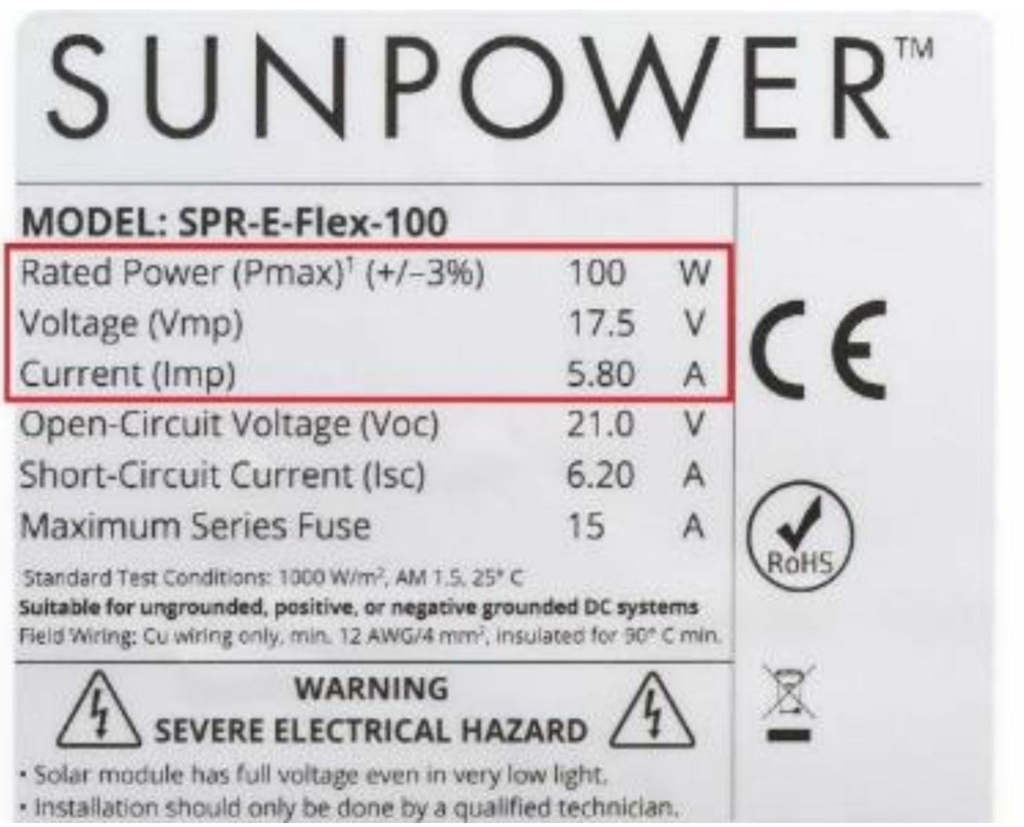
The next two parameters on our list are the maximum power point current (Impp) and the maximum power point voltage (Vmpp). Sometimes Imp and Vmp are used, which are similar to Impp and Vmpp. These two points are linked directly to the fifth point of the curve, the maximum power point (Pmpp or simply MPP).

The MPP represents the maximum power output that the solar panel can provide for specific ambient conditions. Vmpp and Impp represent the corresponding voltage and current values (respectively) associated with the MPP point.

$$\mathrm{Pmpp} = \mathrm{Impp} \times \mathrm{Vmpp}$$

Calculating the Pmpp:

$$5.80\mathrm{A} \times 17.5\ \mathrm{V} = 101.5\mathrm{Watts}$$



Pmpp, Vmpp, and Impp of a solar panel

P-V Curve

The other curve, which is green (bottom), is known as the P-V curve. It represents variations of power output with respect to voltage. Here the Pmpp (MPP) is the only point of interest. The linear relation between current and voltage can be seen until reaching MPP.

STC and NOCT

There are hundreds of solar panel manufacturers available in the market. Therefore, the solar industry needs a way to categorize and compare modules. This is done through a lab test under which all solar panels must be submitted to test their performance under the same conditions. These are known as the Standard Test Conditions (STC).

The STC reference parameters used in lab tests are:

- Irradiance: 1kW/m^2
- Temperature: 25°C (77°F)
- Air Mass: 1.5AM

This temperature is referenced to the operating temperature of the module (not ambient temperature). All parameters explained before in the I-V curve will be referenced to STC in the datasheet of the solar panels.

Another typical reference value is the NOCT, acronym for Nominal Operating Cell Temperature. This standard uses parameters closer to the typical operation of the solar panel since STC conditions are many times, unreal. The temperature value that is stated in NOCT represents the temperature of the cell under the open-circuit condition and under the following circumstances:

- Irradiance: 800W/m^2
- Wind Speed: 1 m/s
- Ambient Temperature: 20°C (68°F)
- The temperature in the surface of the panel: 45°C (113°F)
- Mounting system: Open rack

As we can see, there is a difference between the ambient temperature and the operating temperature of the cell. The NOCT temperature value will generally be located between 45-48°C (113-118°F), depending on the manufacturer.

Effect of Insolation and Temperature

As we mentioned before, the I-V curve depends on ambient conditions, mainly on two of them: irradiance and temperature.

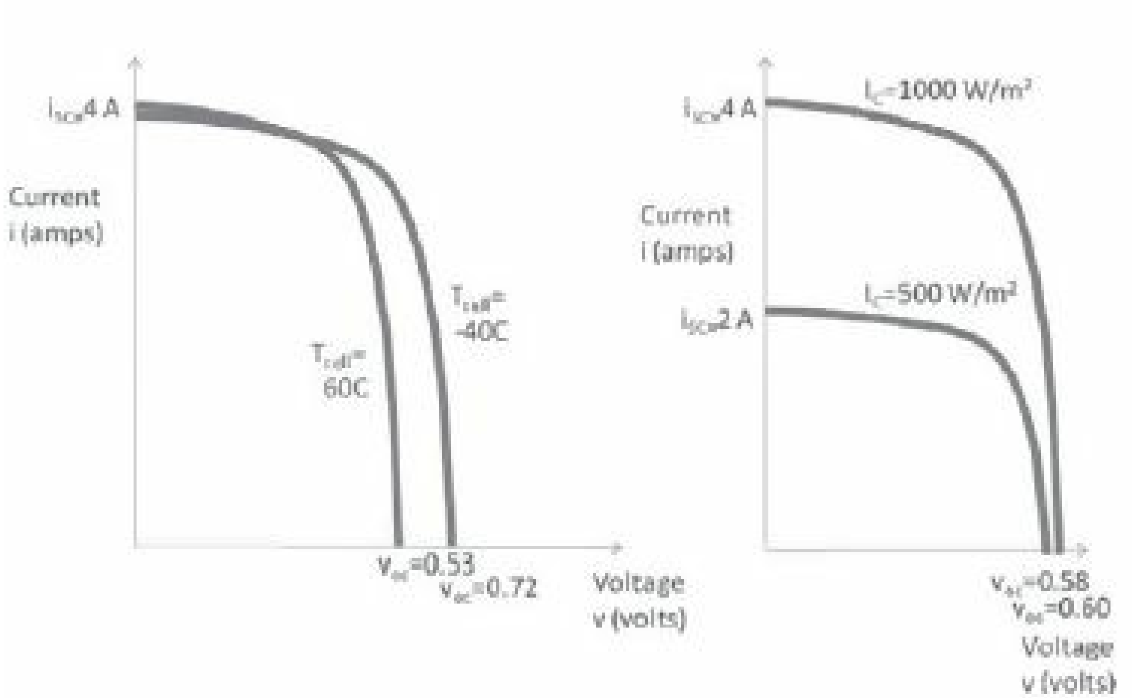
A higher irradiance means more solar radiation. Higher solar radiation also means more photons that reach the surface of the module, and therefore, more moving electrons.

Since the displacement of electrons is linked to the flow of electric current, then more electrons moving means higher current. In other words, more solar irradiance means more current, and less irradiance means less current. The relationship between these two variables is proportional and linear.

Irradiance does not affect voltage.

On the other hand, the temperature is different. The effect of temperature affects all variables. However, the most important effect is on voltage. Unlike irradiance, the relationship between temperature and voltage is inversely proportional and logarithmical.

This means that when the temperature of the cell increases, the voltage reduces, while if temperature decreases, the voltage rises. The following figure shows a graph illustrating the effects of irradiance and temperature on current and voltage respectively.



Effect of temperature on voltage (left)
Irradiance on current (right)
Source: A. Walker.
"Technologies and Project Delivery for Buildings"

On the left, we see that the voltage of the solar cell decreases with increasing temperatures while the current stays the same.

On the right, we see that the current decreases once less irradiance (sunshine) reaches the panel while the voltage stays the same.

Ambient Temperature and Cell Temperature

The cell temperature increases according to two factors:

- The amount of current flowing through the cell.
- The ambient temperature.

The first one depends on the load that the solar panel is connected to and the irradiance levels as well. When current flows through any conductor, an ohmic loss effect is created, which translates into heat. The same happens inside the solar cell. The second factor is entirely dependent on the location where the panel will be installed.

As you can imagine, hot ambient temperatures will add a thermal effect to the module. Therefore, increasing the temperature of the cell. This is an undesirable condition as excessive temperatures decrease voltage, and therefore, reduce the power output of the modules.

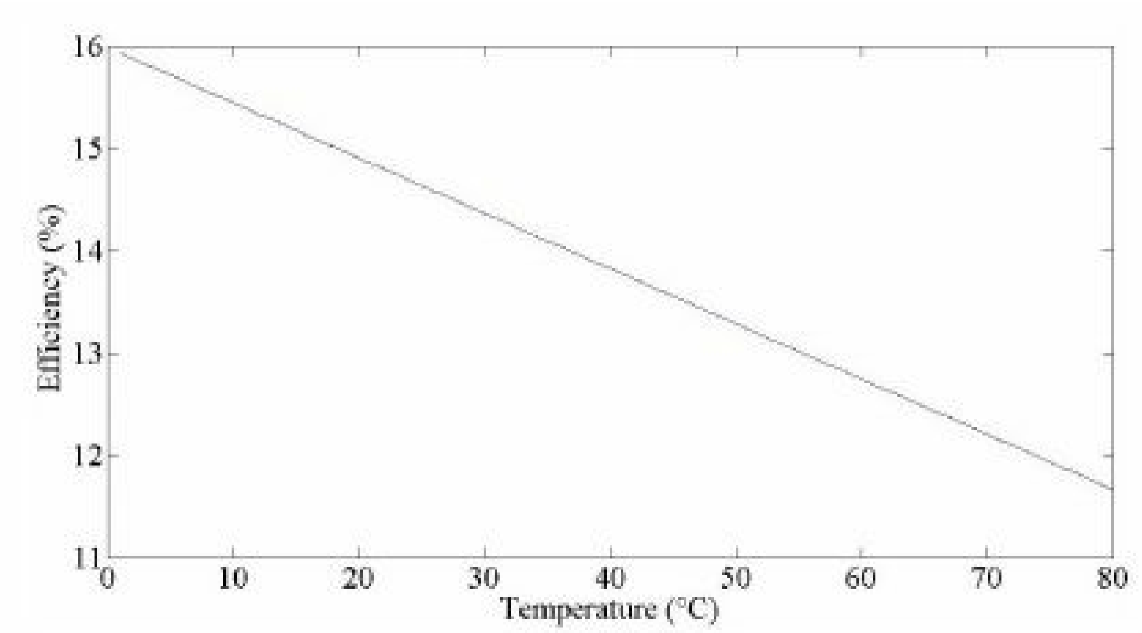
On the contrary, low ambient temperatures favor the thermal cooling of the cell due to ohmic effects. Therefore, cool temperature locations are always desirable for solar panels.

Ironically, many locations with excellent solar resources also have high temperatures that translate into thermal losses (one of the most important photovoltaic losses). Therefore, there are some cases in which a location with cooler ambient temperature and lower solar irradiance could be better for solar since thermal losses will be lower.

You can increase the cooling effect by mounting your solar panels on a stand where circulating air can cool the panels.

Temperature Effects on Efficiency

As stated before, temperature affects the solar panel power output. As we mentioned in the conversion efficiency section, the efficiency of the solar panel is dependent on the Pmpp. Therefore, temperature intrinsically affects the efficiency of the solar panel as well. The relationship of this effect is linear as can be seen in the following figure with an example of a solar panel with an efficiency of 14.8% under STC 25°C (77°F).



Efficiency variations according to temperature changes.
Source: "The Effect of Temperature on Cell Efficiency"

We can see that the efficiency drastically decreases if the temperature increases. Therefore, it is important that your solar panels get as much ventilation as possible.

Series and Parallel Connections

Solar panels have specific power outputs in their datasheets. Despite new models that can reach values close to 400Wp, this power output is not enough to cover the energy needs of household appliances or bigger systems. Therefore, solar panels need to be combined to increase power outputs and the size of a PV system.

Series connections are the same as batteries and consist of connecting the negative terminals with the positive terminals of the solar panels.

Meanwhile, solar panels connected in parallel consist of combining the positive terminals and the negative terminals together in the combiner box.

A set of solar panels connected in series is known as a string. A mix between solar panels in series and parallel connections is known as an array.

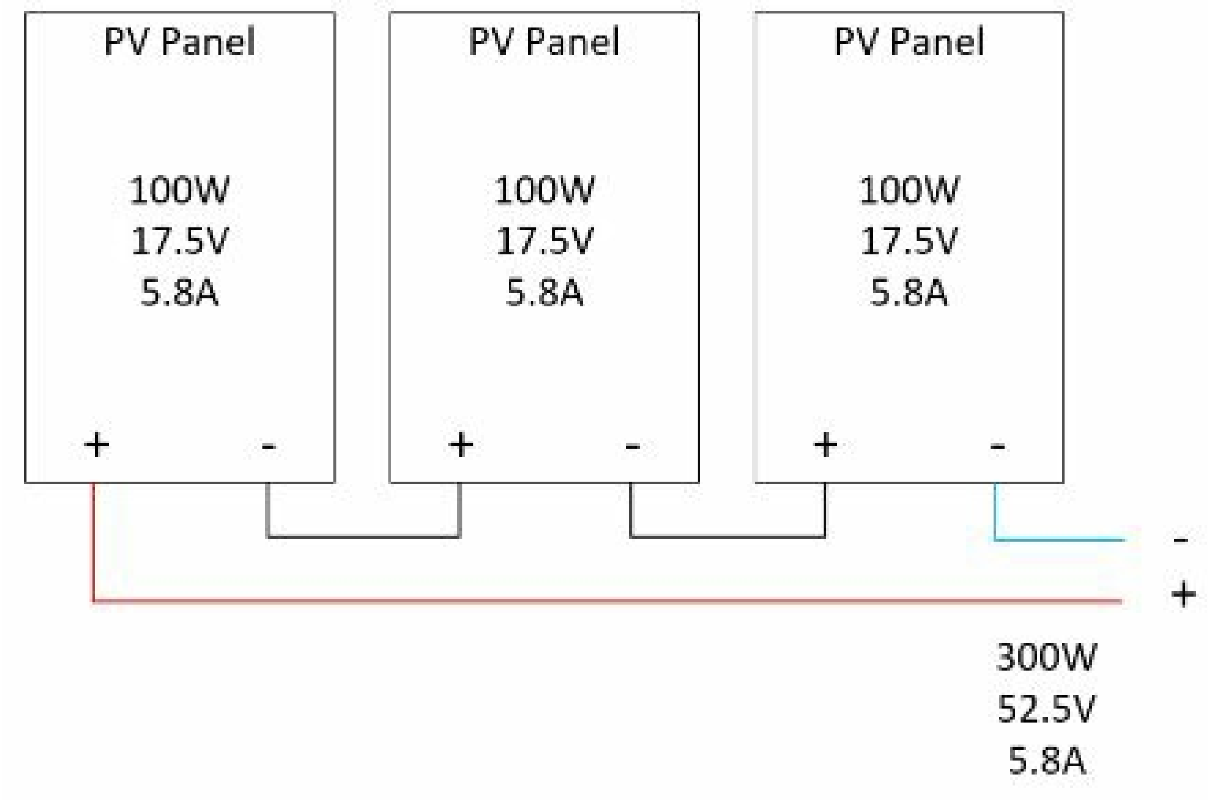
When solar panels are wired in series, the voltage of each module is added while current stays the same. For instance, if the solar panel’s output is 10V and 1A, and you connect 3 modules in series, then the output of the system will be 30V and 1A.

On the other hand, when solar panels are wired in parallel, current increases while voltage stays the same. Based on the same example, if you connect three solar panels in parallel, then the output of the system would be 10V and 3A.

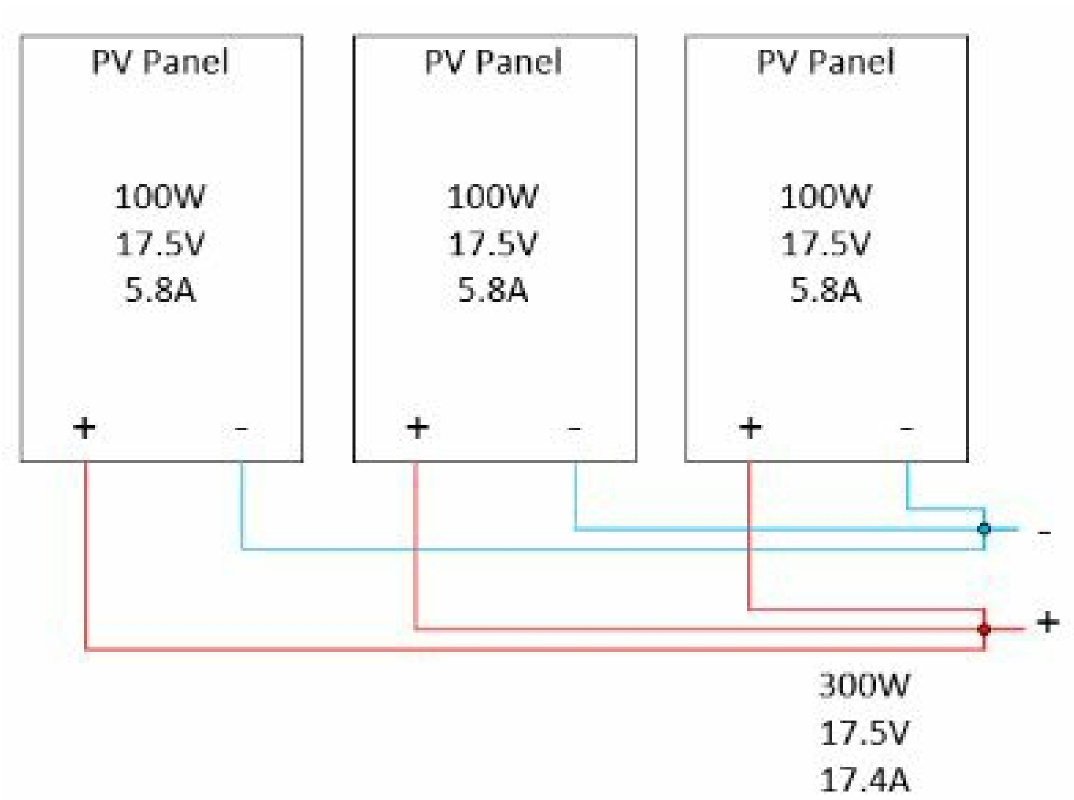
When multiplying the voltage by current, both systems will provide 30W.

Higher current values translate into higher gauges for PV wires. Therefore, series connections are preferred when connecting solar panels.

As a general rule of thumb, solar panels must be wired in series until the accumulated voltage is right under the permissible input voltage of your charge controller.



Series wiring of solar panels



Parallel wiring of solar panels

Placing your panels in series or parallel will depend on the kind of charge controller that you will use. A PWM charge controller will only take 12 or 24 Volts while an MPPT can take voltages up to 100 Volts or more.

As you will learn later in the book, PWM charge controllers are cheaper than MPPT. If you wire your panels in series, the voltage will increase while the current stays the same. This will influence the diameter of your wire. The money you save on wiring in series instead of parallel can be spent on a more efficient MPPT inverter.

Another point to take into consideration is the angle of the sun in the morning and the evening. Because of the low angle, your panels won't generate as much voltage (low irradiance). If you wire three panels in parallel and each one of them generates 5 Volts, you will send 5 Volts to your charge controller, which won't be enough to charge batteries (under the minimum required input voltage).
If you wire the panels in series, you have 15 Volts (5V+5V+5V=15Volts), which can start to charge the batteries early in the morning or late in the evening.

Wiring Different Solar Panels

Another important rule that must be considered is that solar panels with different specs must never be wired together. Once you have selected a solar panel, you must purchase all the required modules for the PV system with that specific model.

The reason why you cannot wire solar panels with different specs is that the PV system will not work optimally. In the series connection, the current output must be the same through the entire system. If four solar panels are wired in series and one solar panel's output is 2A while the others are 3A, then the whole connection will only provide 2A.

The solar panel with lower output would not be capable of providing 3A. Therefore, the system must adjust and provide 2A. This translates into underusing the capacity of the other solar panel(s). A similar problem occurs with parallel connections, but with voltage.

Solar Panel Array

When making series and parallel connections, there is another factor that must be considered.

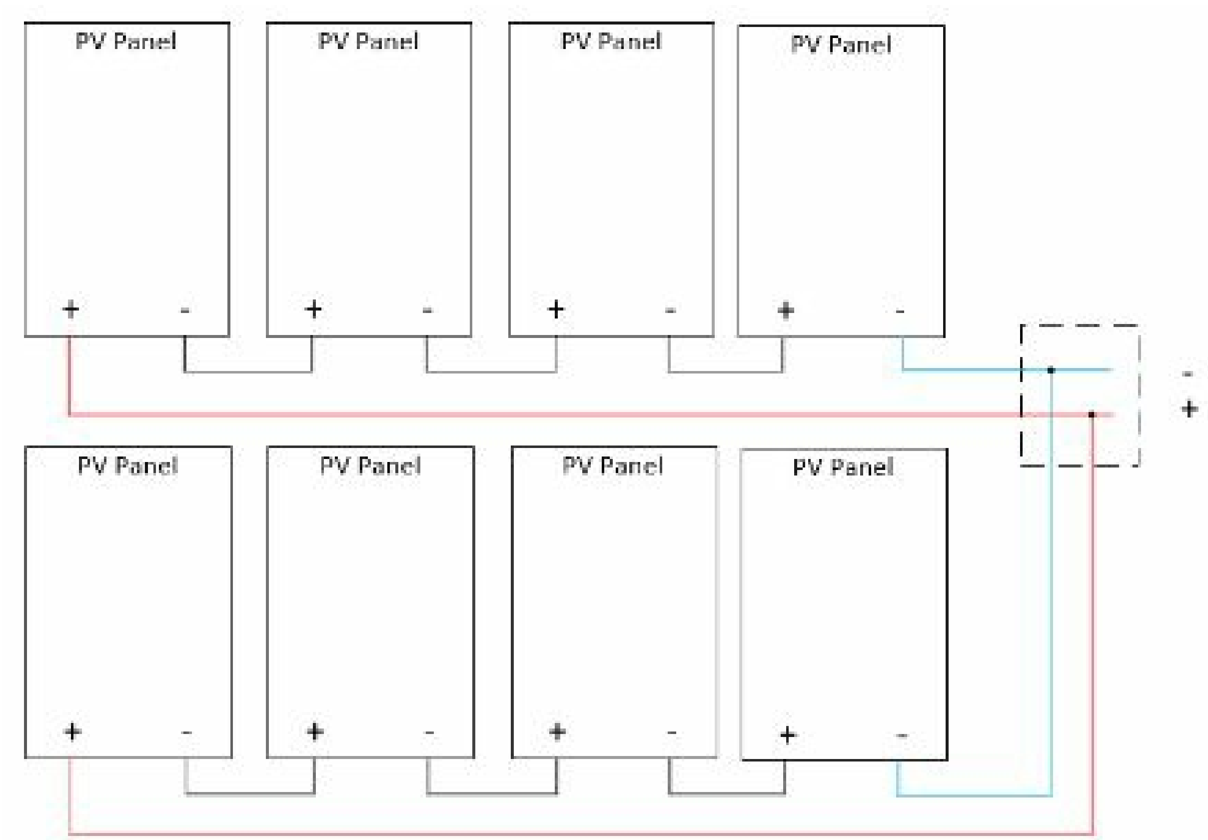
Let's say you have 8 solar panels, and the maximum number of modules that can be connected in series is 5 due to charge controller input restrictions.

Now, you may think that you could make a string of 5 solar panels and another string of 3 modules, then connecting the outputs in parallel and wire it to the inverter. However, this would be incorrect for two reasons.

The first reason is that the weaker string will have a lower voltage. Current always flows from the highest voltage point to the lowest voltage point. This principle will generate an effect in which the other strings will try to make current flow toward the weaker string. This is extremely undesirable since it can lead to malfunctioning and be devastating under short-circuit conditions.

The second reason is more related to energy losses. As it will be explained later, the charge controller must accurately find the MPP of the solar panels every time to operate optimally. If strings of different voltages are connected in parallel, then the I-V curve would lose its regular shape, and it would make tracking of the MPP very hard for the charge controller. This would end up in tremendous mismatch losses due to voltage differences. This will be explained with further details in the charge controller chapter.

Therefore, going back to our example, if you have 8 solar panels, then you would have to size 4 modules in series (string) and put them in parallel to become an array. If the charge controller only allowed for 3 modules, then you would have to either work with 6 panels (which could go below your required power capacity to cover energy demands) or add an extra solar panel to have 9 modules in total, of which 3 are in series.



2 series strings connected in parallel to the combiner box

Azimuth

The azimuth angle is referred to as the direction of solar panels regarding the sun’s orientation. For locations in the northern hemisphere of the Earth, solar panels must face south to harness the maximum power output. Locations in the southern hemisphere, solar panels should face North.

For U.S. cases, a solar panel should take south as reference 0°. If you install your solar panels on RVs or boats, it makes little sense to determine the azimuth angle since the solar panels will vary their azimuth as they go on the road or sea. Also, if solar panels are stuck to the roof of the RV in a flat position, it makes no sense to worry about that either.

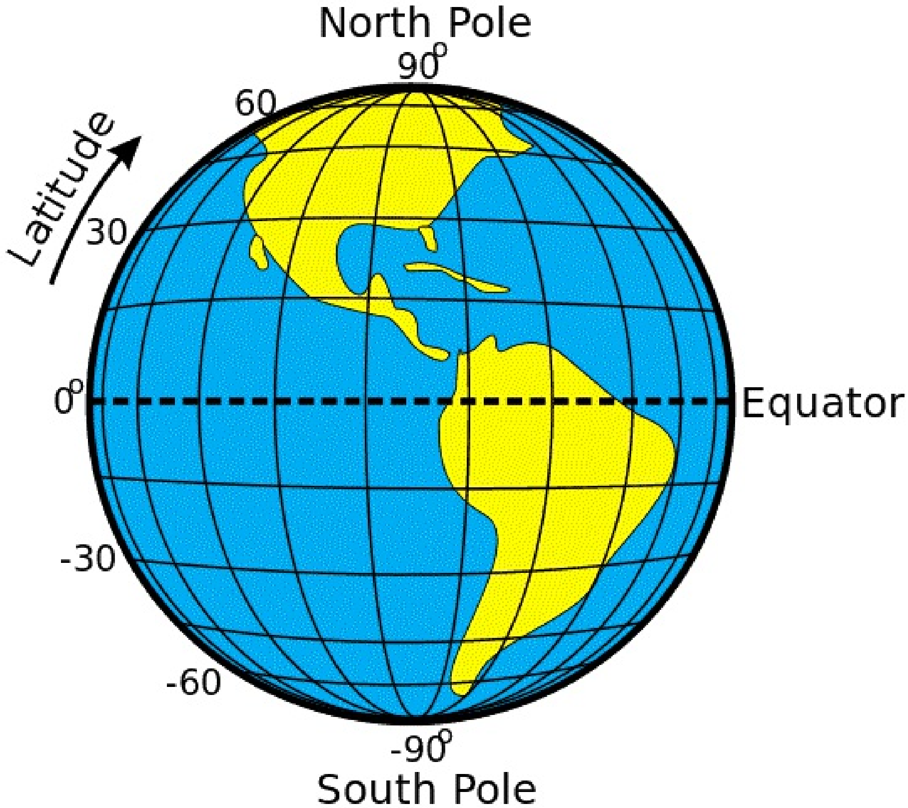
If the solar panels that you have installed can be lifted with a certain tilt for maximum solar power harnessing once you park the RV, then parking the RV in such a way that the solar panels would face 0° south (or as close as possible) would be beneficial.

If you have a portable solar panel, finding the optimum azimuth angle will be beneficial. For this, you must simply use a compass and place the panels facing the south directly if you are not planning on moving the panels throughout the day.

Alternative azimuth directions are east or west, either one of them. Panels should never point north if you are in the northern hemisphere.

Tilt Angle

The tilt angle is another important factor in solar power harnessing. Finding the optimal tilt angle is always related to the latitude of the location.



Displaying latitude
Source: Geography Realm

Most of the time, for locations near the Equator, choosing the latitude directly as the reference is usually the best approach.

Besides the location, another important factor that must be considered before setting the optimum tilt angle is related to the type of system that will be implemented. Also, since the altitude and direction of the sun vary according to the season, it is important to know when the system will be used mostly.

In grid-tied PV systems, the idea is to optimize solar power harnessing to generate as much energy as possible. Therefore, since solar power is generally higher during summer months, then the PV system angle is optimized to harness as much energy as possible during summer. To calculate the optimum tilt angle under these conditions, you must apply the following simple expression.

$$\beta opt = 3.7 + 0.69 \times \varphi$$

Where βopt will be the optimum tilt angle and φ will be the latitude of the location.

Example for New York in summer:

$$\beta opt = 3.7 + 0.69 \times 40.7° = 31.7°$$

For stand-alone PV systems, the priority is not harnessing as much energy as possible but to always be able to cover the energy needs of the system to provide stability. Therefore, the critical season under which the PV system must be optimized is no longer summer, but winter. For these cases, it is advisable to use the simple expression below.

$$\beta opt = \varphi + 10$$

Example for New York in winter:

$$\beta opt = 40.7° + 10 = 50.7°$$

Figuring out the best tilt during the whole year:

$$\frac{31.7° + 50.7°}{2} = 41.2°$$

How to find out the latitude of your location:

Go to google maps and click on the location you would like to know the latitude from. The first numbers are the latitude. The one after is the longitude. In this example, the latitude is 32°.

Figuring out the latitude of your location

Nevertheless, in RV and cabin applications, there is a particular consideration. Despite the fact that RV solar power systems are stand-alone based, RVs are not generally used for traveling during the winter season.

In other words, here you must evaluate if you are using your RV only for recreational purposes during some period of time in the year (mostly summer for vacations) or if you are actually living in an RV throughout the year. If your case is the first option, then you must use the expression to optimize summer tilt angle, while if your case is the second option, then you must use the second expression.

Shading

Shading losses are one of the most underestimated factors in terms of power loss for any PV system, and must always be considered. There are mainly two types of shadings: near-shading and far-shading.

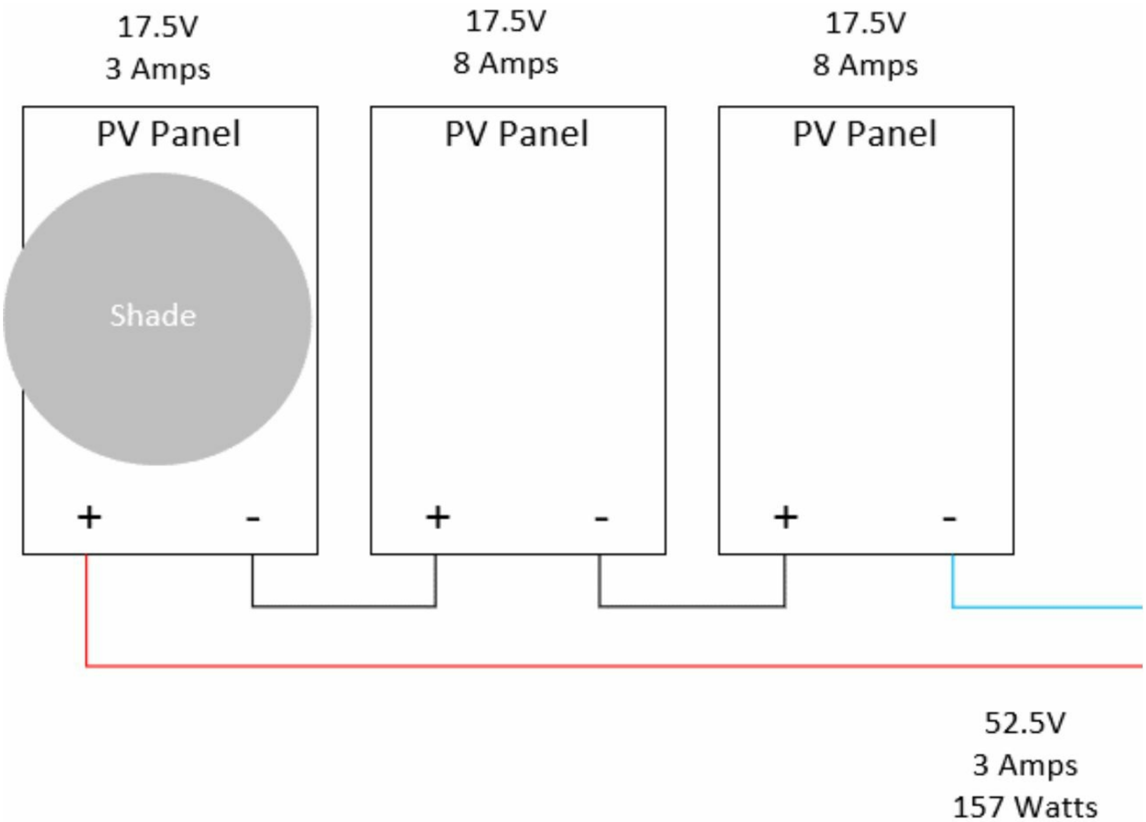
Far-shading is associated with losses in diffused irradiance caused by mountains or high buildings. There is not much that can be done about them.

On the other hand, near-shadings are associated with nearby objects that can project shades over the solar panels. Things such as trees, walls, antennas, or the RV can create shade on the solar panel.

When a solar panel is shaded, the current output of the module is affected since the obstruction represents a reduction in the number of photons that can be absorbed by the module. The power output of the entire string of the shaded solar panel is affected as well because the electrical current that flows through a string must be the same in every module.

If you remember the effects of solar irradiance (Watts/m^2), you will know that it has an effect on the current, not the voltage. So, if you were to shade one panel in a string (series connection), only the panel with the lowest current would decide the power output.

This can be seen in the following image:



Effect of shading on series connections

The electrical current can only be as high as the current generated by the weakest module (shaded module in this case).

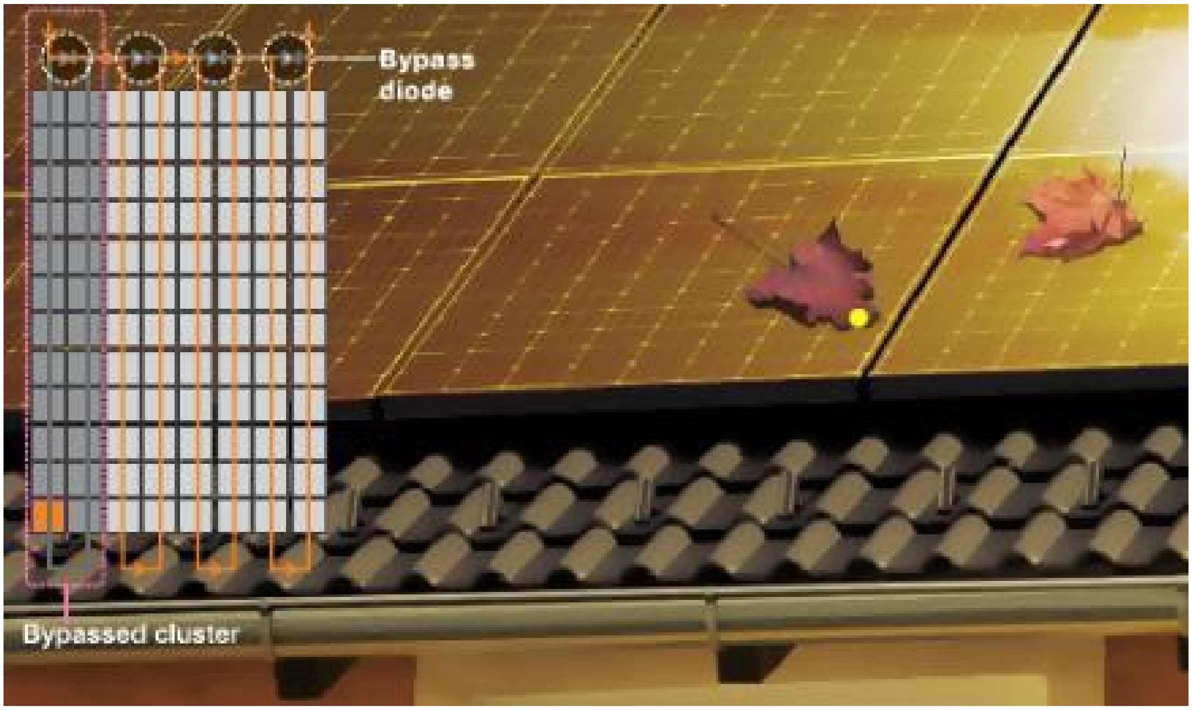
To account for solar power losses due to shadings, solar designers use simulation software that calculates the projection of the shade across the day and its impact on the PV system.

You should try to avoid any near-shading that could cause important power losses to your PV system.

Another useful technique that is used to deal with shading conditions is the position of the module. If the production of the solar panels were to be completely reduced by a small partial shading in the corner of the module, then it would be a very inefficient generation source.

So, solar panel manufacturers install *bypass diodes* in a box located in the backside of the module, known as the *junction box*. In case the solar panel is partially shaded, these bypass diodes allow electric current circulation from the other sides of the module.

This means the reduction in power output due to shading will not be total, but partial. The following figure shows the structure division of a Panasonic solar panel with 4 bypass diodes. When one section is partially shaded by a leaf, the bypass diode of that section activates to allow current circulation from the remaining solar cells. Most solar panels generally have 3 bypass diodes in residential and commercial applications.



Bypass diodes in solar panels
Source: Panasonic HIT module brochure

The trick lies in using this property of solar panels in favor of shading. By placing the module vertically or horizontally, the effect of shading can be very different.

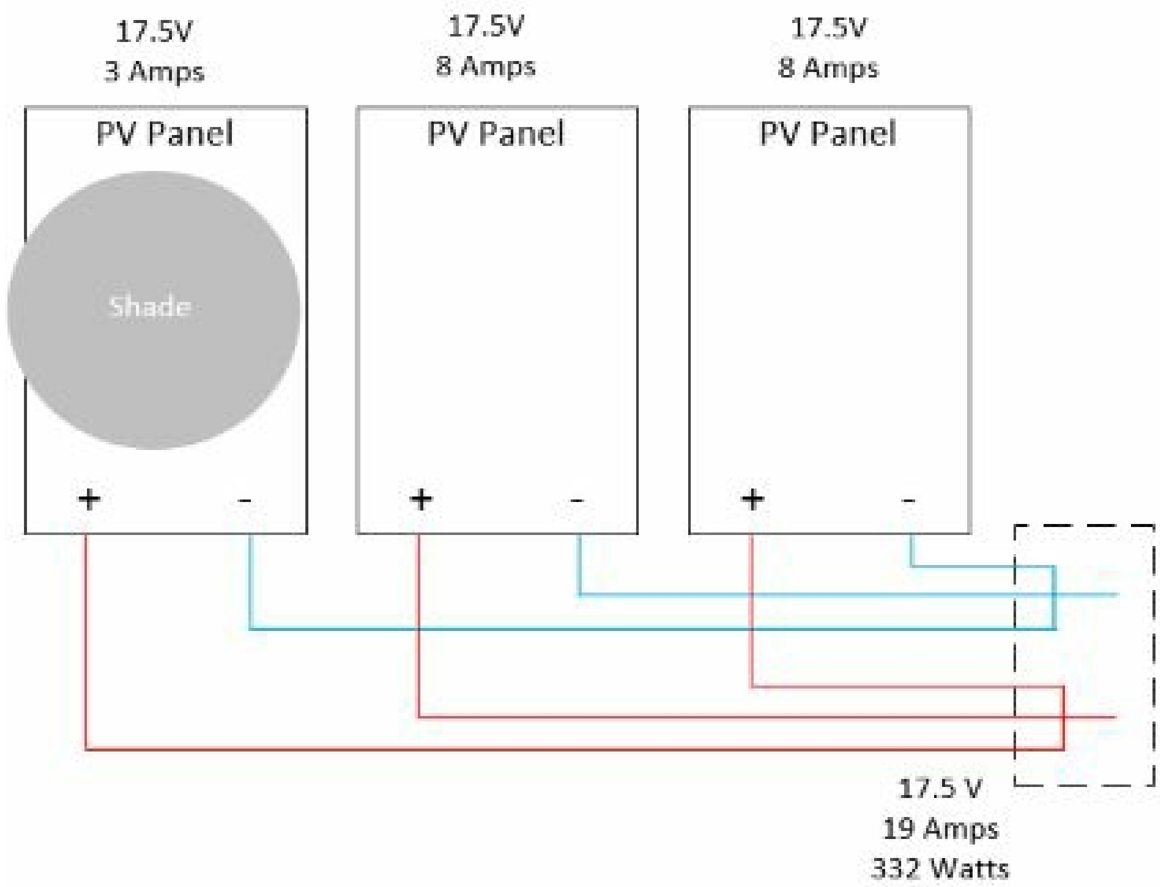
Most modern panels have these bypass diodes. Check the datasheet of the panel to make sure they have bypass diodes before buying the modules.

If your solar panels are in parallel and one of them is shaded, the rest will feed back into the shaded panel. The shaded panel will consume a small current, which is called back-feeding. To remedy this, you could use a blocking diode. A normal diode, or a Schottky diode, will have a voltage drop which is not desirable. Instead, use an ‘ideal diode.’ These diodes have a very low voltage drop.

Ideal diode

If you are on a sailboat and you are sure to expect shade from the sails or boom, I recommend using parallel connections with an ideal diode to prevent back-feeding into other panels. Some solar panels already have a back-feeding diode installed. Make sure you check the datasheet of the panel.

In the following diagram, you can see the effect of shading on parallel connections. If you compare this to the series connection, you can see that we have a higher wattage output. This is because, in parallel, the amps are added together while the voltage stays the same.



Effect of shading on parallel connections

The downside with parallel connections is that you need to have a bigger wire diameter to handle the increased current.

Blocking Diodes

Blocking diodes are also sometimes used in battery-based applications that involve solar panels.

The current flow in any electrical system always goes from the highest to the lowest voltage point. Keeping that statement in mind, during the day, solar panels have higher voltages than the deep cycle batteries. Therefore, voltage naturally flows toward to battery to charge it.

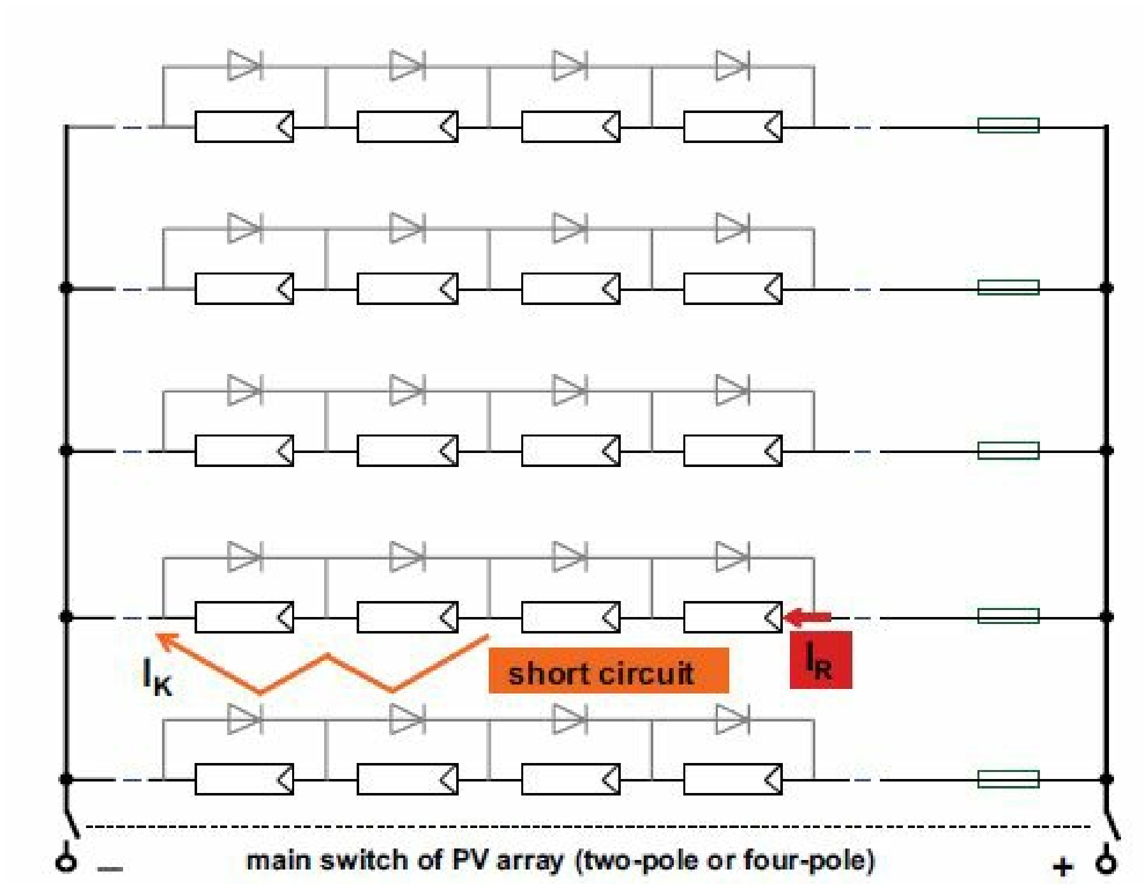
During the night, there is no sunlight, and solar panels generate no power at all.
In a stand-alone PV system, the battery will never be completely discharged (or at least it shouldn't). As the only source of power in the PV system, the battery will try to provide electrical current to any other device. During this time, the electrical current could be flowing back to the solar panels, making you lose power and energy unnecessarily.

Back when charge controllers did not exist, installers needed to add a blocking diode between the module and battery to avoid this reverse current effect.

Nowadays, solar panel manufacturers already take care of this element by adding what is known as a Schottky barrier diode, which combines the functions of both blocking and bypass diodes. Therefore, you do not need to worry about that.

String Fuses

A short-circuit condition in solar panels can occur due to metal to metal contact of the PV wires in one of the strings, due to a mechanical accident or even due to lightning. Under this condition, the faulted string would receive the full contribution of the short-circuit current from every string of solar panels, which is known as the reverse current.



Short-circuit condition for a 5 strings PV system
Source: H.Haberlin
"Photovoltaics - System Design and Practice"

As shown in this image, in a small PV system with 5 strings of modules, the total short-circuit reverse current the faulted string could receive could be 4 times the short-circuit current of the module (close to 9A). In this case, the faulted string would receive a 36A short-circuit current. This would be destructive for both the modules, and possibly the wires, and could even induce fire.

Solar panel strings should be covered or protected against high reverse currents that can damage the modules and the PV wires under a short-circuit condition. To protect PV modules, DC compatible fuses are installed on the positive side terminal of each panel. DC fuses act as overcurrent protection devices that will isolate the faulted circuit from the rest by melting down a conductive material inside the fuse when a specific current passes through the fuse.

These fuses are generally installed inline or in a DC combiner box. However, in RV applications, they can be installed separately without the need for a DC combiner box.

To select the string fuse, two main factors must be considered:

- The open-circuit voltage of the module.
- The short-circuit current of the module.

It is very important to size the string fuse for both factors since only sizing the fuse as short-circuit protection would be unsuitable and could even cause malfunction and fire.

Since the DC signal never crosses through zero volts, safely isolating the circuit from the rest is much harder than with AC power. Therefore, you must make sure that the fuse you selected has been designed for DC connections to interrupt the flow of current safely.

Under specific weather conditions, solar irradiance values could be close to 1,000W/m^2, which will cause additional stress to the fuses due to increased heat. Moreover, the fuse could be submitted to this stress with an additional rated maximum current flow through it, which will increase the heat inside the fuse.

Assuming these conditions, it is recommended to apply security factors to size the fuse. A 25% security factor should be applied due to excess of irradiance, and another 25% due to 3 continuous hours of operation under these conditions. Based on these considerations, rated current for the DC fuse should be calculated as demonstrated in the following expression.

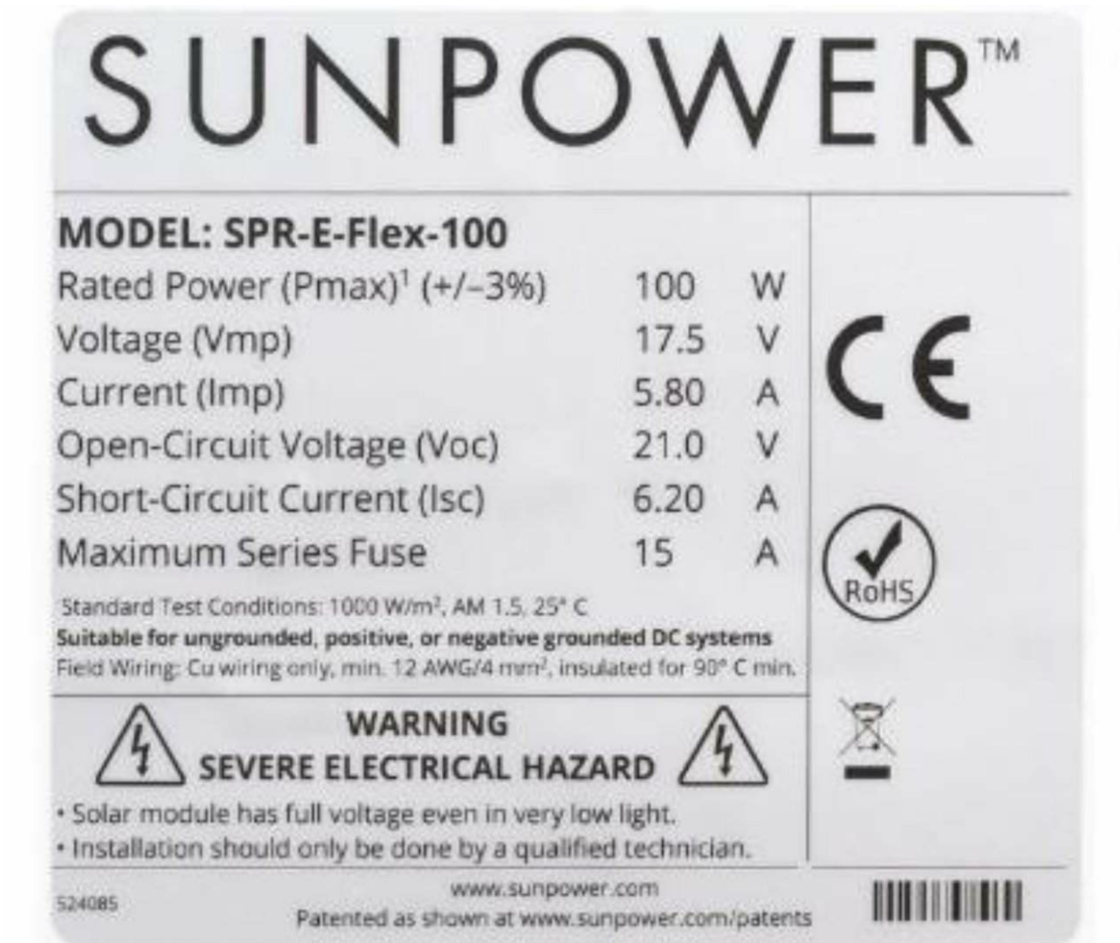
$$\mathrm{Ifuse} = \mathrm{Isc} \bullet 1.25 \bullet 1.25 = \mathrm{Isc} \bullet 1.56$$

On the other hand, considering the open-voltage of the modules, string fuses should be rated for 1.2 times the STC open-circuit voltage of the entire string. This voltage can be simply calculated by verifying the open-circuit voltage of the module model and multiply it by the number of solar panels (n_{sp}) in every string. The result should be your minimum voltage to the DC fuse or breaker.

$$\mathrm{Voc}_{\mathrm{stc\ -\ string}} = \mathrm{Voc}_{\mathrm{stc\ -\ modules}} \bullet n_{sp}$$

$$\mathrm{Vfuse} = 1.2 \times \mathrm{Voc}_{\mathrm{stc\ -\ string}}$$

Example:
Three panels in series with the following specifications:



Minimum current for the fuse:

$$\text{Ifuse} = 6.2\text{A} \times 1.25 \times 1.25 = 6.2\text{A} \times 1.56 = 9.67\text{Amps}$$

You can see on the specifications of the solar panel that the maximum fuse in series is 15A. Do not go higher than the recommended fuse by the manufacturer. You can either use a 10 Amp fuse of a 15 Amp fuse.

Minimum voltage for the fuse:

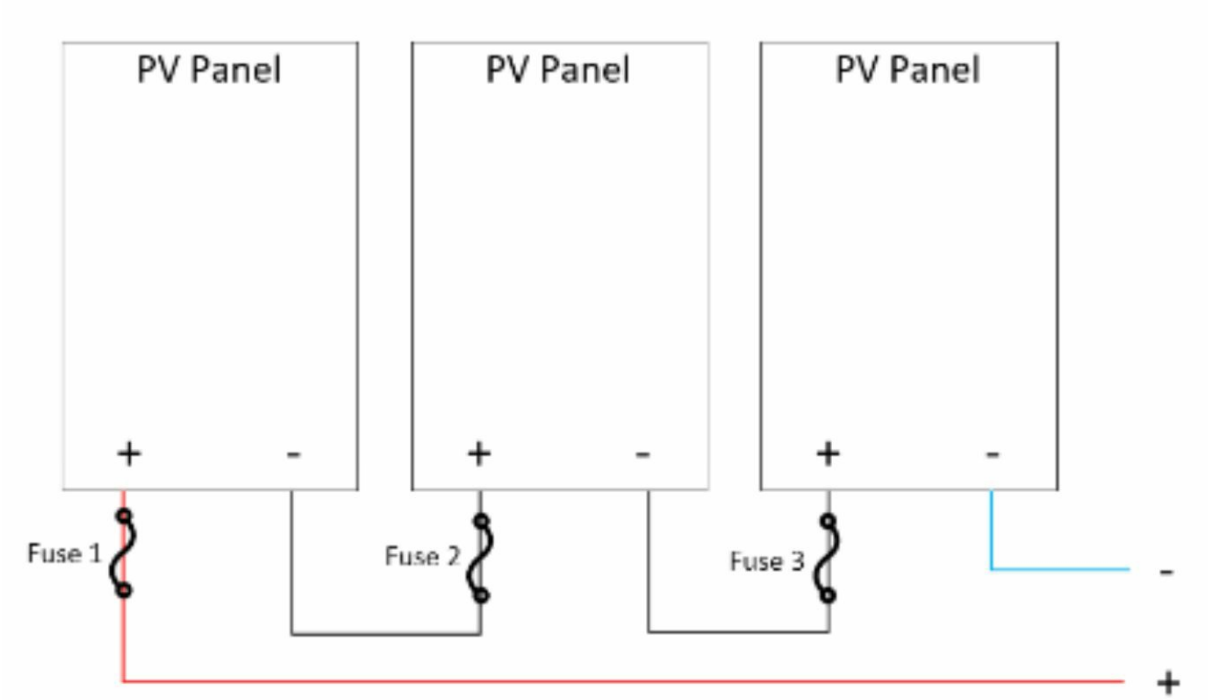
$$\text{Voc}_{\text{stc - string}} = 21.0\text{V}_{\text{stc - modules}} \times 3_{\text{sp}} = 63\ \text{Volts}$$

$$\text{Vfuse} = 1.2 \times 63_{\text{stc - string}} = 75.6\ \text{Volts}$$

DC fuses are also rated for a specific number of volts. Choose a DC fuse that can handle at least 75.6 Volts.

Series Connection

For series connections, inline MC-4 connector fuses are used. You simply use these fuses on the positive lead of every panel.



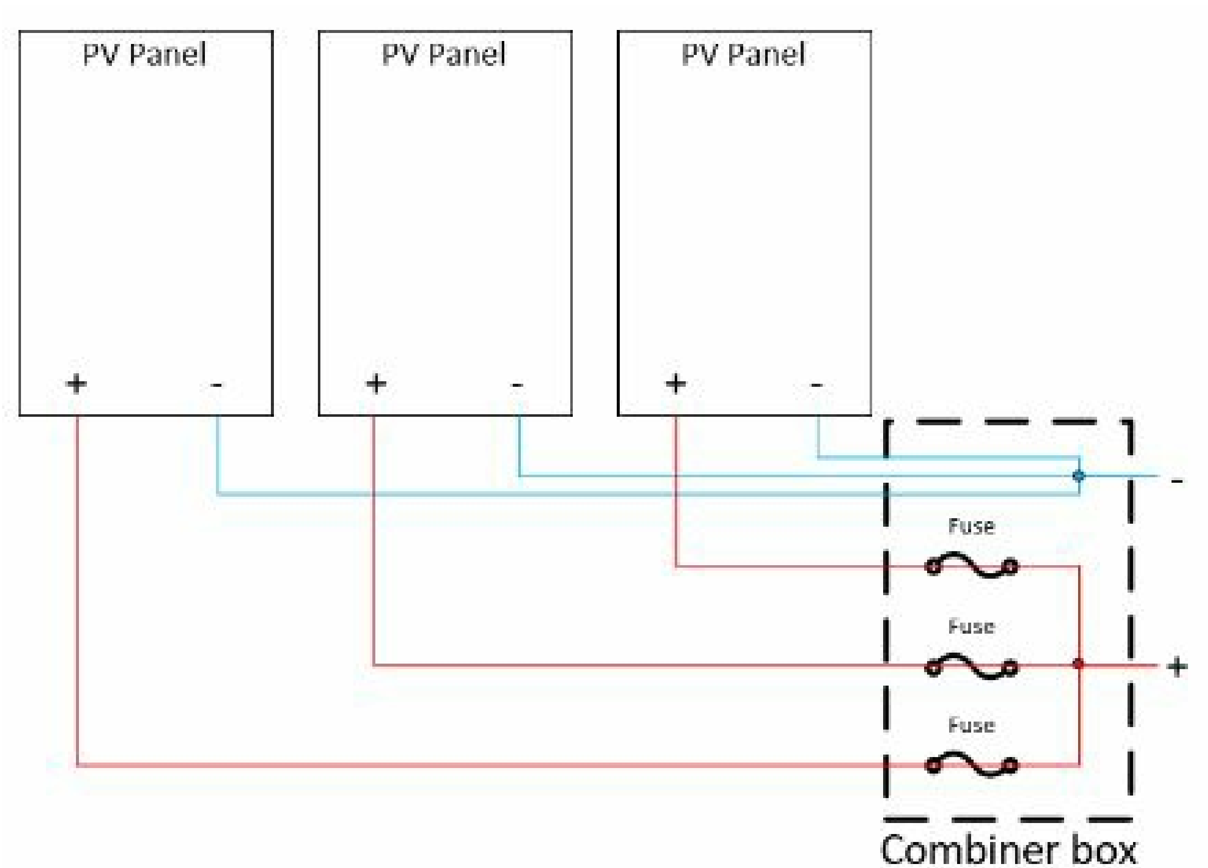
Using fuses in series connections


Example of an inline MC-4 connector fuse

Parallel Connection

You can use inline fuses for parallel connections too. However, most parallel systems use a combiner box because this is also the place where wires are being combined into one wire to the charge controller.

Wiring fuses this way will be cheaper than buying inline MC-4 fuses because you will need the combiner box anyway.



Wiring fuses in parallel connection

Seasons and Solar Map

The solar radiation in the U.S. varies according to the seasons of the year.

Spring and summer are especially good seasons for solar.

Solar radiation also changes according to the location. Before entering into further details, there are three terms that you should be familiar with:

- DNI
- DHI
- GHI

DNI stands for direct normal irradiance, referred to the irradiance [W/m^2] that touches the surface of the modules at a perpendicular angle.

Diffused horizontal irradiance (DHI) is another term used to refer to the radiation reflected or absorbed by the clouds and any other surface.

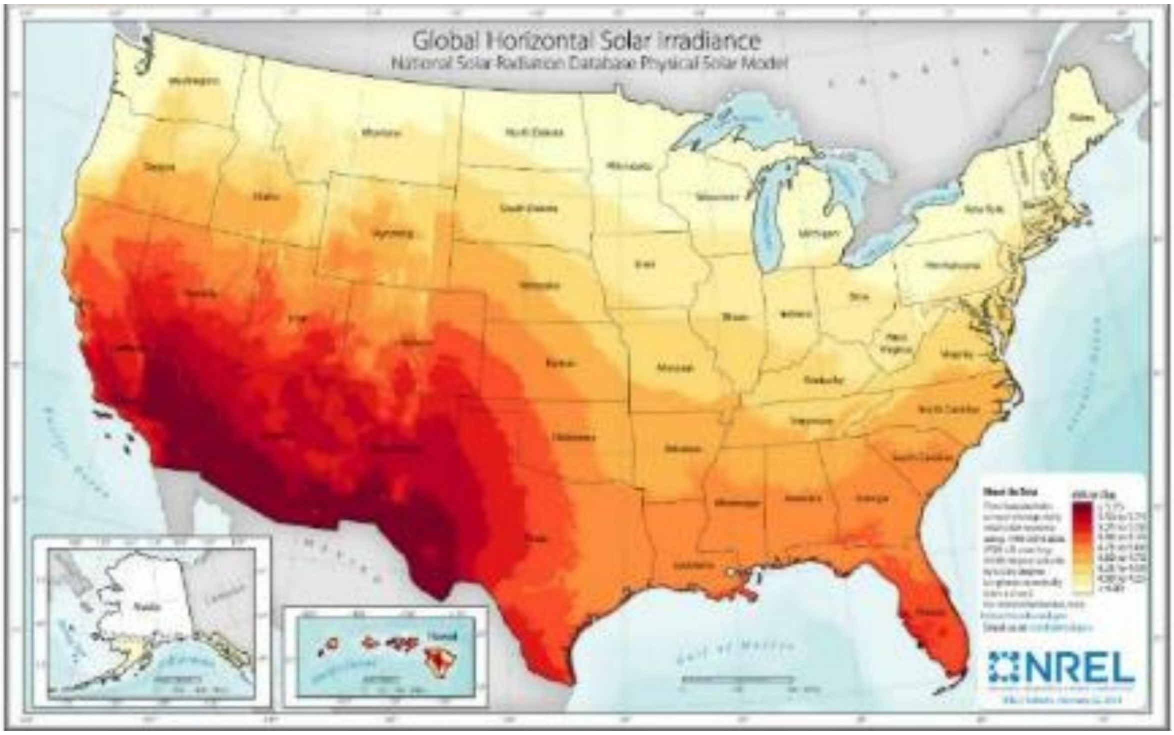
The global horizontal irradiance (GHI) represents the combination of these two components and is the effective irradiance that will be used for solar energy yields.

As can be seen in the following image, the (GHI) across the U.S. changes between 4-6 kWh/m^2/day, where the northern states such as New York, Michigan, and Pennsylvania generally have less irradiation available.

Variations in solar radiation according to the seasons, can be visualized with the U.S. Solar Radiation Resource Maps.

Keep in mind that from a grid-tied or backup perspective, going solar does not only depend on the solar radiation that is available in the location.
More than that, it is also dependent on the electricity rate that is associated with your energy bill. From an RV perspective, the solar radiation of your location is even more relevant since the PV system needs to work on its own every day under off-grid mode. When you are sizing your system, you must also consider the locations through which you are moving.

Looking at a U.S. Solar Radiation Resource Map will give you a good idea of the estimated irradiance value in your location. Keep in mind that this is related to GHI, not to direct normal irradiance (DNI).



Solar Irradiance Map of the U.S.
Source: NREL

To see an interactive map go to:
https://cleversolarpower.com/solar-irradiance

Placement of panels

At the time of installing solar panels, you will always have two options if the system is intended for residential applications.

The first option will be to install the solar panels on your roof. The second option is to use ground-mounting.

There is a set of advantages that you will have by choosing a ground-mounting installation. Orientation and tilt angle variability is much wider with ground-mounting than with roof-type. Also, maintenance procedures are easier since the modules are placed on an accessible location for the homeowner. It is very important at the time to clean the modules of any dirt or removing snow.

These systems usually have a better electrical grounding system since there is a less resistive path. They also have a better cooling system since air circulation on the backside is more than roof types as well. You won't need to make any modifications to your house to install the modules and from an expansion perspective, ground-mounts are much easier to expand.

On the negative side, ground-mounts are generally more affected by shade than roof-mount types since more objects can project shade over the modules. Besides, the installation procedure is oftentimes more complicated than the roof-mount and probably more expensive. Finally, another important point is that you will reduce space in your backyard that could be used for recreational purposes.

If you choose to go with roof-mount to your house property, then you will have many benefits as well. Among them, installation costs will be lower (unless your roof requires important updates). The solar panels can also protect your roof surface from hailstorms and any falling object since they are made to resist impacts (to a degree). The low accessibility to your solar panels may be bad on one side from a maintenance perspective. However, from a security perspective, it is very rare that your solar panels could be damaged, stolen, or even vandalized since they are located on the roof.

Meanwhile, by installing a roof-type solar system, you will need to take care of several details. Things such as roof penetration during the installation, difficult maintenance, limitations on system size due to availability of space, and roof structure upgrades if needed to hold the weight of the modules.

Based on these pros and cons, you will need to make a balance and decide on where it is better to place your solar panels, either on the roof or on the ground.

Mounting Panels

The procedure for mounting the modules depends on the type of mounting system that you would like to use.

Roof-Mount

For roof-mounting systems, the following procedure must be followed:

1. You need to have your equipment and materials — drilling, pencils, chalk blocks, rails, clamps, bolts, and screws.
2. Calculate the distance between rails on the roof based on the pre-drilled holes of the solar panels.
3. Check the required setbacks for rooftops. Generally, 3 feet is an acceptable setback.
4. Locate the rafters of the roof to center the truss that will be the supporting spot for the rails.
5. Install flashings (supporting structures that tight the modules to the roof).
6. Place the rails.
7. Add grounding bolts and wire management clips.
8. Secure the modules to the mounting system by using clamps and T-bolts.

Solar panels mounted on rails
Source: FOEN solar bracket

Ground-Mount

For ground-mounting systems, the steps for the installation are as follows:

1. Excavating the ground to provide enough space for foundations. The type of foundation depends on the soil type in your area.
2. The concrete foundation or helical piles are installed.
3. The base of the mounting system is fixed to the foundations by using bolts.
4. Vertical pipes are installed and fixed to the base of the mounting system.
5. Rails are installed and attached to the structure. Unistrut is a good material to work with.
6. Cross rails are installed if needed to provide additional support for the structure.
7. Middle and end clamps are used to adjust the solar panels to the rails.

Ground-mounted solar panels
Source: Wikimedia.org

RV's

RV solar panel systems have another particular installation process, similar to roof mount, but not equal. The process is briefly explained as follows:

1. Organize the available space on the roof and make a short schematic of the distribution of panels on the surface.
2. While still having the solar panels on the ground, install the mounting brackets. This will save you additional work on the roof.
3. Make the setup process for the charge controller and batteries. From a roof perspective, figure the shortest path to take the wires from the roof to the charge controller's location.
4. Drill a hole through your roof to pass the AWG wires.
5. Install a waterproof cable entry plate in the position of the hole to pass the wire output of the solar panels.
6. Drill the corresponding four holes to secure every module according to the pre-drilled hole positions located in the mounting frame of every module.
7. Secure them to the roof by using bolts and screws.

Mounting solar panels on RV roof with brackets
Source: JdFinley.com

Items used for mounting:

- Brackets from your hardware store.
- 3M 5200 adhesive (no sealant).

If you have selected flexible, thin, solar panels, the installation is far simpler since you can use strong double-sided tape to adhere the panels to the roof.

All vehicles are designed to be aerodynamic. This means reducing air friction during traveling. If the vehicle is not streamlined, noise will be created which you will hear when you are driving the vehicle at high speeds. Try to reduce air friction as much as possible.

Sailboats

In the case of sailboats, the procedure is similar to RVs. Most of the time, you will need to use a boat Bimini cover to place the modules. The flexible solar panels are used much more for boat applications, since drilling holes in the bow or the stern of your boat is something that you are probably not going to like. When you have sized your Bimini cover, you will need to find similar suction cups or plastic attachments that can go through the holes of the panels and lock them in place.

Stitching the solar panel to the Bimini cover is also a popular method. Instead of using the suction cups at the corners, you install a special cloth that you can stitch to the bimini.

Installing solar panels on a Bimini
Source: www.sailrite.com

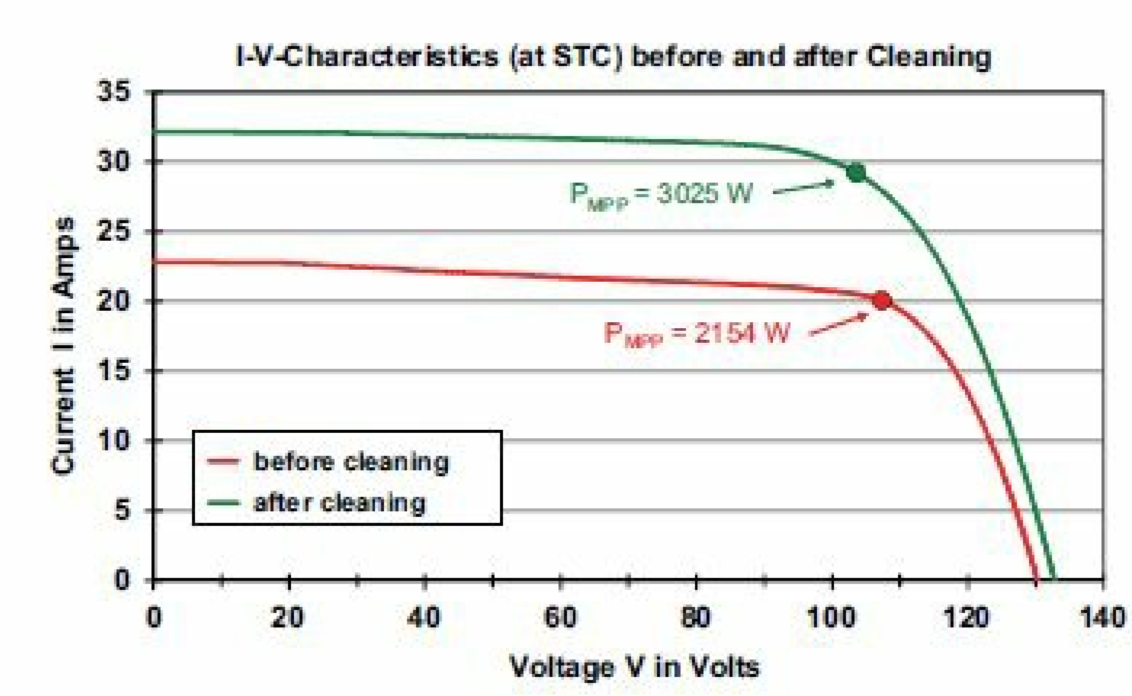
Cleaning Panels

The Effect of Soiling

Maintenance is a very important factor that must be considered when installing solar panels. The performance of PV modules can be severely affected by dirt or dust on the surface of the panels. In most cases, with regular maintenance procedures, this PV energy loss (commonly called soiling) would not be bigger than 2% of the annual energy yields.

Extreme cases with a huge presence of dust and no cleaning can reduce the performance of the modules up to 30%.

The following image shows a graph with the differences in the I-V curve and the MPP before and after performing the cleaning procedure for a small PV system. As you can see, the power output reduces from 3kW to 2.15kW, which is a very significant power output reduction and is the reason why it is so important to clean your solar panels regularly.



I-V curve after and before cleaning
Source: Haberlin Heinrich.
“Photovoltaics System Design and Practice”

How to Clean Your Solar Panels?

The cleaning procedure for solar panels is very simple. The first thing that must be done is disconnecting the PV system by turning off the solar disconnect switch. This is for safety concerns.

Then, you need to get a sponge and submerge it in preferably de-ionized water. Do not use regular water for cleaning, since the minerals contained inside will adhere to the glass of the module. Try to avoid using cold water or hot water to do the cleaning. High-temperature differences are not good for the modules. Using the sponge, start cleaning each module's glass until any noticeable dirt is cleaned up.

Soft brushes can also be used. Telescopic cleaning poles will make it easier for you to clean your modules in case they are located in inaccessible spots. Another option is to use a low-pressure hose to clean the modules easily. Pressure should always be under 580psi (40bar). The hose valve should be able to indicate and adjust the pressure.

Never use laundry detergents, bleach, or any other product. All that needs to be used is distilled water, and if desired, a little bit of dishwashing soap. You can also use specially-designed solar cleaning equipment to make the task easier.

When to Clean Your Solar Panels?

The time to clean solar panels is also important to consider. During noon, solar panels are producing electricity at peak performance. Choosing to do maintenance during this period is not good for two reasons. First, if you do cleaning at this time, you will lose the most important energy yields of the day, and second, at noon, solar panels are also hotter. This makes them harder to handle, and temperature differences can also be wider.

Solar panels can reach temperatures of over 158°F (70ºC), so they can get quite hot. The ideal times for the maintenance procedure are during the early morning (6:00 am) or late afternoon (5:00 pm). At these times, solar panels' performance is lower, and they are much cooler.

Lifespan of a Typical Solar Panel

The lifespan of a solar panel is widely dependent on the brand and model type. However, currently in the industry, all solar panels feature a 25-year life warranty performance.

It is important to notice that this is not the same as the product warranty (which is generally close to 10 years), but it is an estimated life expectancy of the solar panel production. The warranty performance states how many years the solar panels are expected to be working and producing with at least 80% of their power output in the initial year.

The best solar panels available can reach almost 30 years of performance and have a 15-year product warranty. You can find the life warranty performance in the datasheet of the module.

Panel Voltage

As we have discussed in previous sections, the current flow goes from high to low voltage. Solar panels are designed to be a generation source. Therefore, they must have a higher voltage than the load itself.

In battery-based applications, the solar panels must be able to charge a battery bank. For instance, in case of a 6V battery, you would need a solar panel with a voltage output of at least 6.75V. Moreover, assuming that the battery has a 12V nominal voltage, then the modules need to charge that battery with a higher voltage (at least 13.6V).

If the battery bank voltage was 24V, then you would need to wire solar panels in series to achieve a higher voltage (at least 27V). However, some bigger solar panels are already able to reach 30-40V.

Keep in mind that the key factor in reaching the required voltage levels lies in adding as many solar panels in series as possible.

Buying Used Solar Panels

Solar panel installers will always provide you with new PV modules. However, on some occasions, you will find available modules on the web that are set for sale at lower prices, but they are used.

Purchasing used solar panels for residential or commercial installations presents multiple problems that far outweigh the possible economic benefits.

Used solar panels can be on sale for different purposes, but mainly there are two reasons:

- First, the homeowner no longer wants to use all the panels for his/her PV system and wants to get some money back.
- Second, the solar panels suffered some sort of damage, or their performance is not what was expected from them.

This can be a serious problem if you choose to purchase multiple used solar panels since you can end up investing a substantial amount of money and not receiving the expected performance. Solar panels also degrade over time, and it is hard to specifically estimate the number of years that the solar panel has been working. Reduction in performance would be hard to determine if it's related to aging, damage, or manufacturing failures.

Used solar panels have another problem that is related to technology. The solar panel industry has quickly evolved in the last decade. Solar panels from 5 years ago are nowhere close in terms of power output, technology, and efficiency as solar panels today.

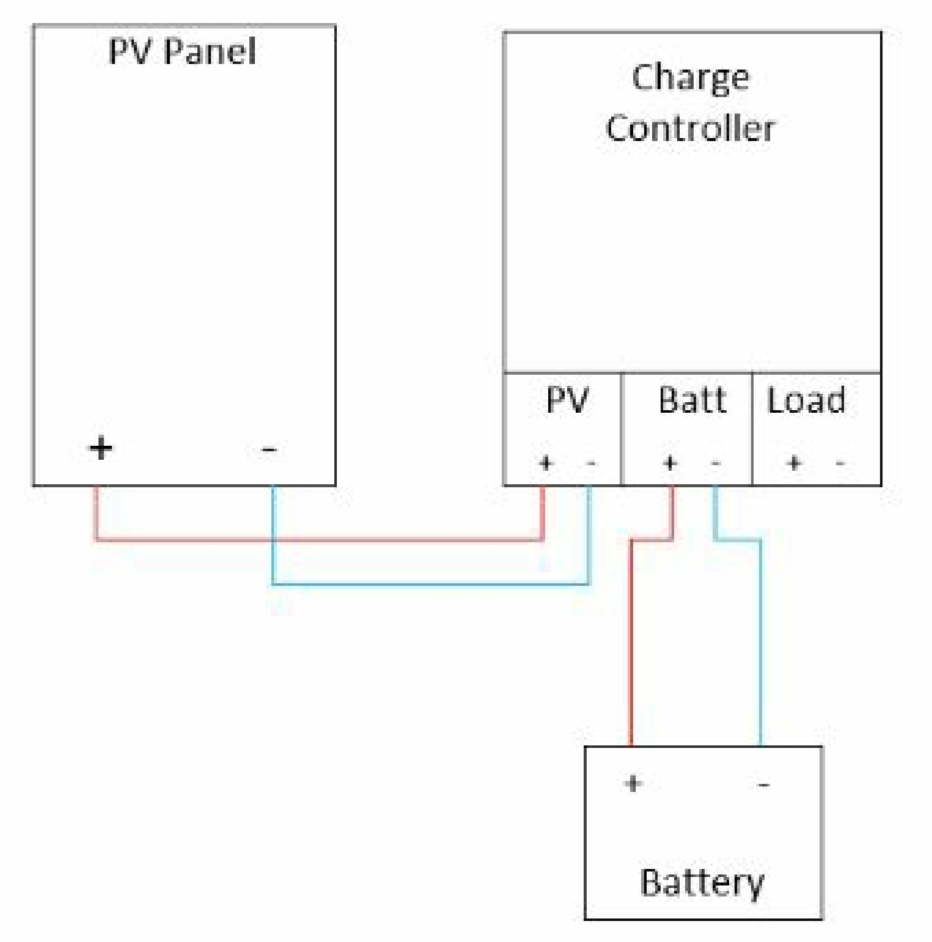
Therefore, by the price at which you are purchasing old technology that was expensive at the time, you could obtain similarly good performance at a lower price nowadays. A used solar panel will probably not have the product warranty available.

The only case where purchasing a used solar panel might be a good fit would be for very small applications. Things like charging small gadgets, phones, and iPads in which case you will not need much power output, and the investment required will not be substantial.

Charge Controller

What is the Task of a Charge Controller?

A charge controller is an electronic device designed to regulate the rate at which the electric current is added or drawn from a battery. Basically, it has three functions. The first one is to safely operate the charging process of the battery to ensure that the storage device will have a long lifespan.



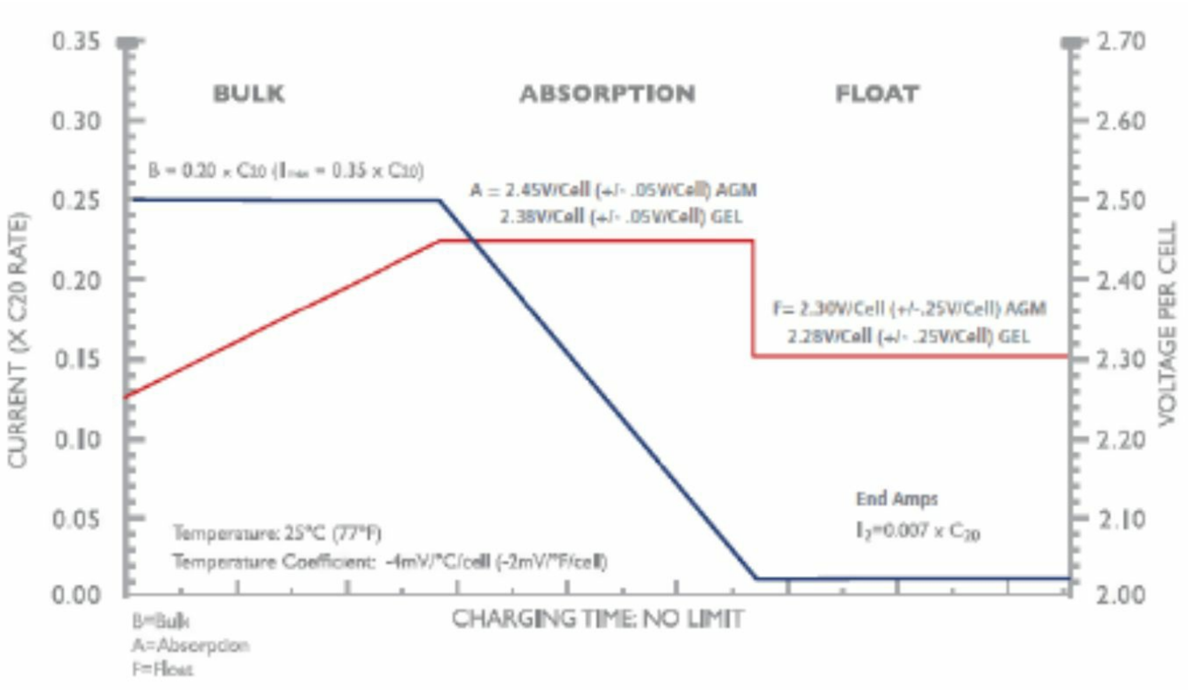
Wiring the solar panel to the charge controller

To do so, during the charging process, the charge controller measures the state of charge (SOC) of the battery. Based on the measured value, the charge controller increases or decreases the electric current to comply with particular stages of charge in the battery.

The principal stages involved in the charging process that every charge controller should comply with are:

- **Bulk:** high electric current charge increases the voltage of the cell.
- **Absorption:** stabilizing voltage requires slowly reducing the charging current.
- **Float:** the final process requires a very low charging current.

The following image shows a sample of the charging process in an AGM battery using a charge controller.



Charging cycle of a VRLA battery
Source: Rolls Battery Manual

The second important option of the charge controller is to efficiently and safely discharge the battery to supply energy to the connected loads.

During this discharging process, the charge controller must be able to prevent drainage of electric current beyond the designed depth of charge to protect the battery life. It must also detect overload and short-circuits, and act to stop the flow of current if necessary — more about connecting loads to the charge controller later in the book.

During the nighttime, the battery's voltage is higher than the solar array, which could make the flow of energy go from the batteries to the panels. An important duty of the charge controller is to control the discharge at night in order to avoid these reverse currents.

The third function of the charge controller is efficiently and safely extracting solar power from the PV modules and adjusting the power output of the solar array to the required voltage for the battery (generally 12V, 24V, or 48V). While connecting solar panels in series and parallel, the voltage of the string can reach voltages higher than the nominal value for the battery bank.

If the solar panels were to be connected to the battery directly without a charge controller, then you would be overcharging the battery and damage or destroy it. The charge controller frees the system designer from closely matching the PV voltage to the battery's voltage and allows to set longer strings than what they could have been without the charge controller.

Different Charge Controllers

Charge controllers can be divided into two main groups according to the operation modes they work with. These two main groups are PWM and MPPT charge controllers.

PWM

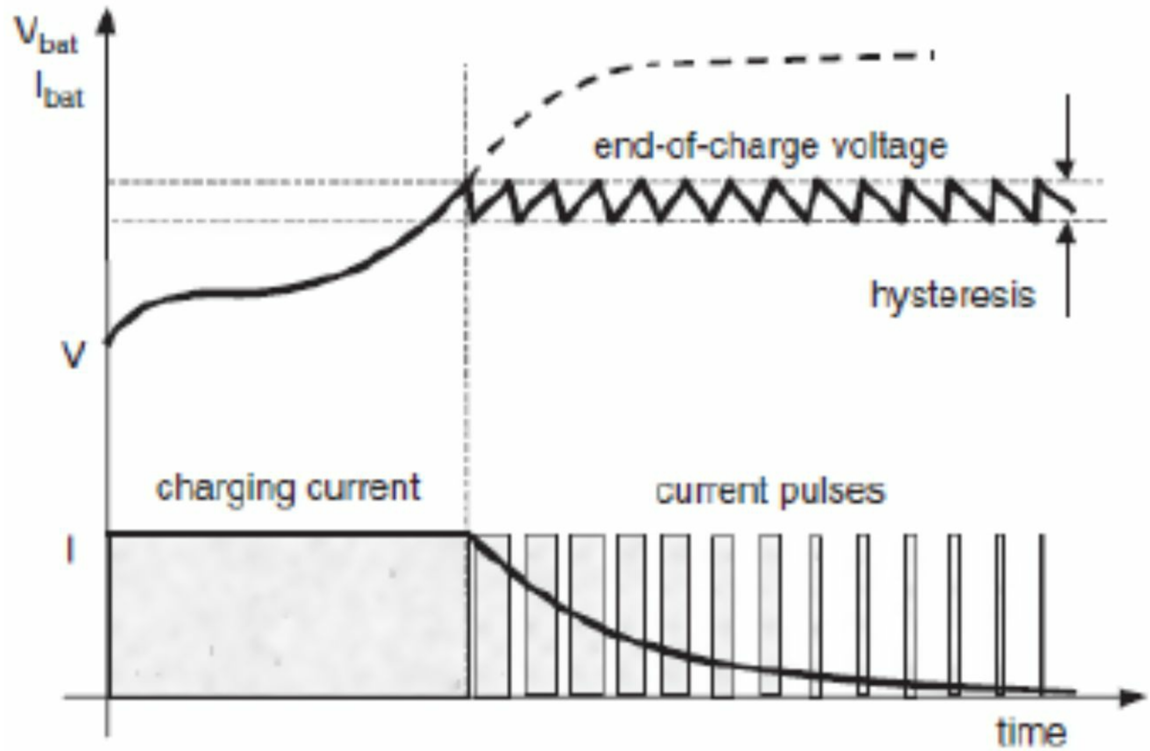
The Pulse-Width Modulated (PWM) charge controller was the first model that appeared in the market and is the most basic (and cheapest) type of controller that you can find.

The PWM charge controller acts like a switch that connects the output of the photovoltaic modules with the battery bank. Once the switch is closed, the voltage in the terminals of the charge controller will be the nominal voltage of the battery.

The charging process of the PWM model consists of closing the switch during the first stage of the process to the maximum possible current value as voltage gradually increases.

When the voltage reaches the absorption voltage value, the current starts decreasing slowly by disconnecting and reconnecting the switch multiple times.

This creates a pattern that has the shape of small pulses until the current drops to zero. The following image shows the charging process of a PWM charge controller.

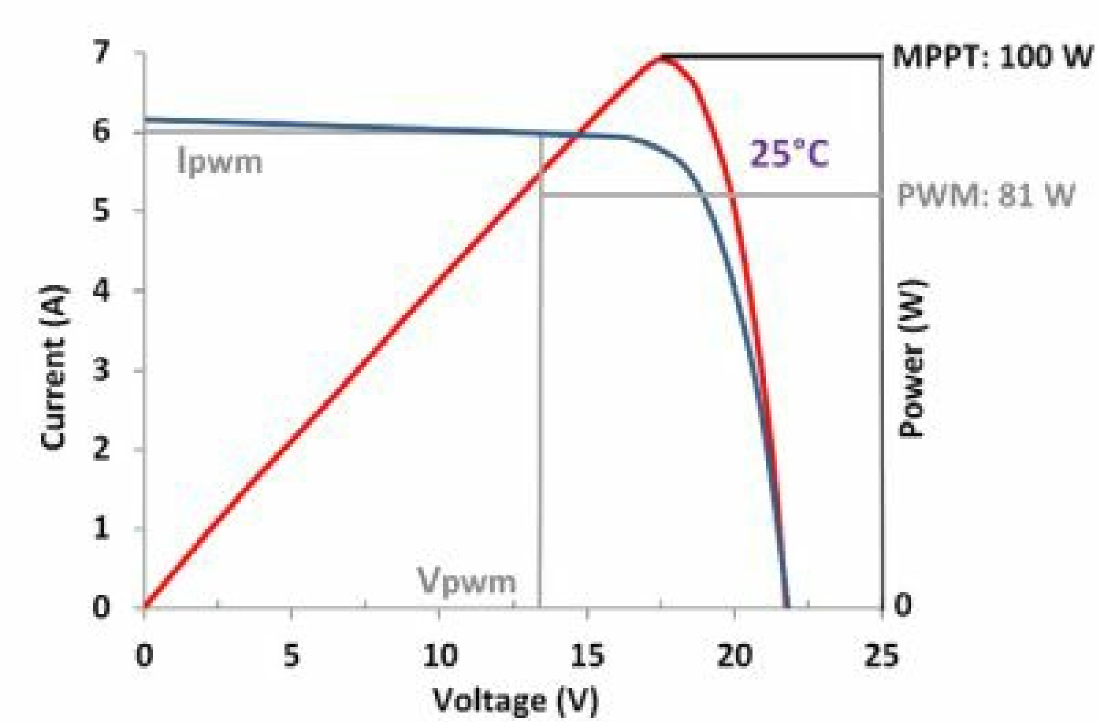


Charging process of a PWM charge controller
Source: A.Luque y S.Hegedus.
“Handbook of Photovoltaic Science and Engineering”

The PWM charge controller always sets the output voltage close to the nominal voltage of the battery bank (generally a little higher to be able to charge it). Then, the regulator will provide the corresponding current in the I/V curve of the solar array.

The next image shows an example of the output of a PWM regulator for a 12V battery. As can be seen, the PWM controller does not operate at the maximum power point.

The PWM charge controller is not as efficient as it can be. Therefore, we will talk about the MPPT charge controller next.



PWM and MPPT charge controller curve comparison
Source: Victron Energy

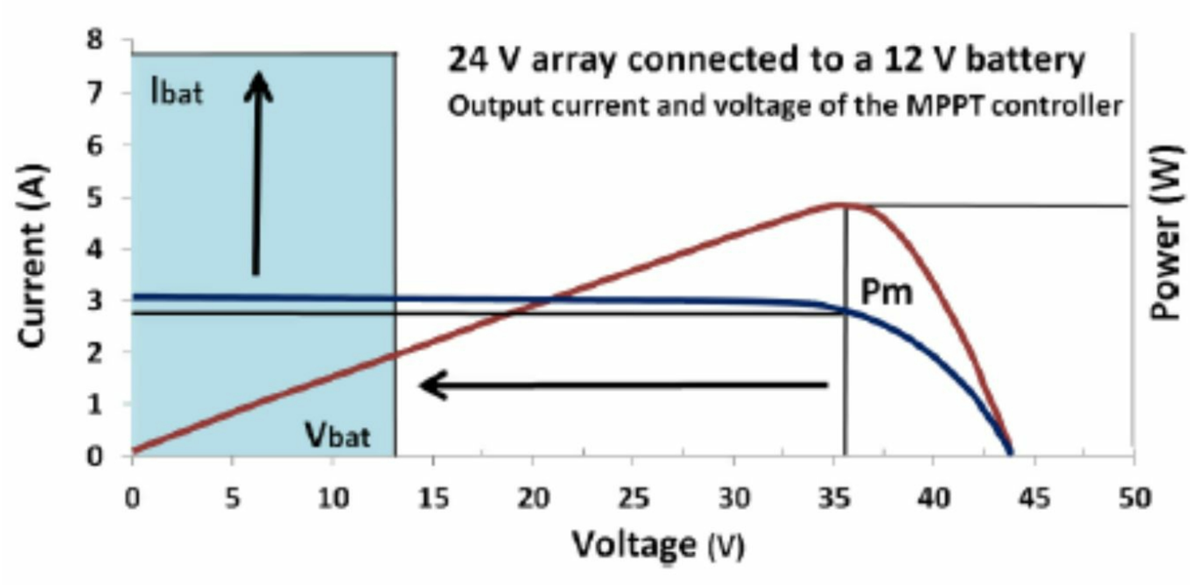
MPPT

The second type of charge controller is the maximum power point tracker (MPPT). This controller is a DC-DC converter (a device that takes a DC signal and transforms it into another DC signal with other parameters).

The operation mode of this type of controller consists of adjusting the voltage in the output terminals according to the voltage required to charge the battery bank.

At the same time, the controller tracks the changes in the solar array across the day in the I/V curve and locates the maximum power point of the curve every time. After locating this point, the controller determines the amount of electric current that would be needed to provide the same amount of power than the MPP would provide, but at the nominal voltage of the battery.
Instead of simply assigning the corresponding electric current in the I/V curve (like the PWM controller does), the MPPT model increases the electric current to reach the maximum power point.

When comparing the two types of charge controllers, you can get over 20% more power with an MPPT than with a PWM charge controller.



Maximum power point in an MPPT
Source: Victron Energy

Selection of Charge Controllers

At the time to choose a charge controller, you must take into account multiple factors. I'm going to explain this by using a datasheet from a widely used charge controller, Rover series, by Renogy.

Electrical Parameters

Model	RVR-20	RVR-30	RVR-40
Nominal system voltage	12V/24V Auto Recognition		
Rated Battery Current	20A	30A	40A
Rated Load Current	20A	20A	20A
Max. Battery Voltage	32V		
Max Solar Input Voltage	100 VDC		
Max. Solar Input Power	12V @ 260W 24V @ 520W	12V @ 400W 24V @ 800W	12V @ 520W 24V @ 1040W
Self-Consumption	≤100mA @ 12V ≤58mA @ 24V		
Charge circuit voltage drop	≤ 0.26V		
Discharge circuit voltage drop	≤ 0.15V		
Temp. Compensation	-3mV/°C/2V (default)		

Renogy Rover series charge controller datasheet

Voltage of the Battery Bank

One of the first things that should be considered when selecting a charge controller is to verify that the nominal output of the charge controller matches the battery. Typical applications will be 12 or 24Volts.

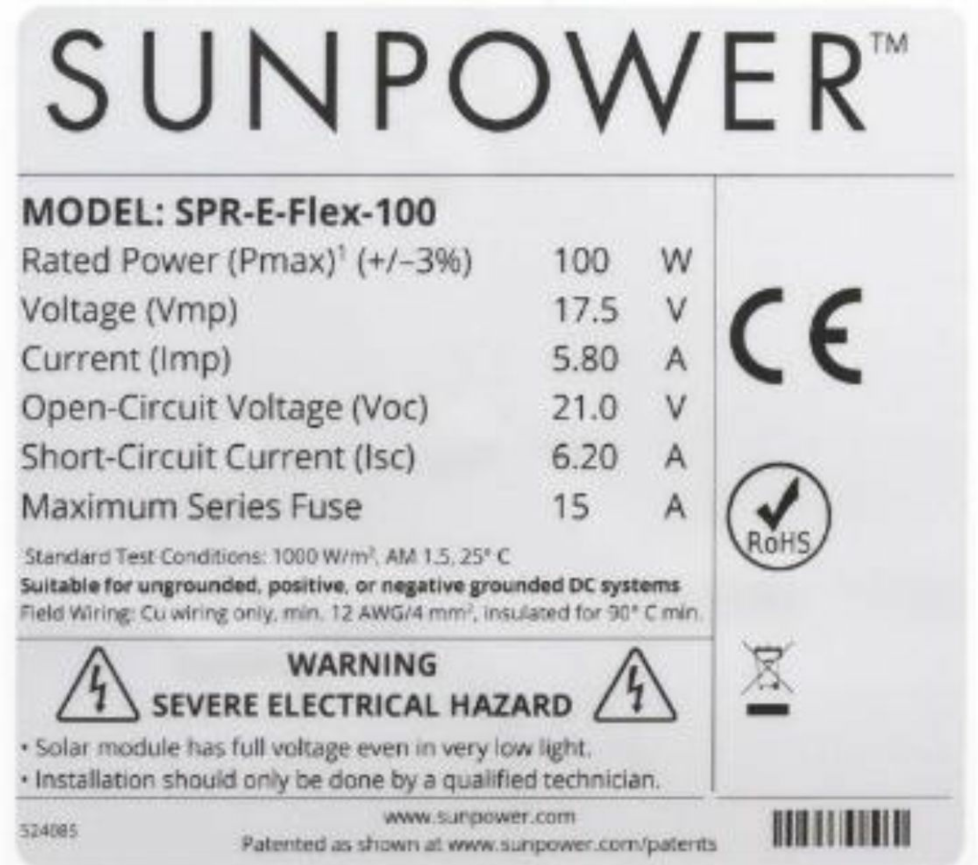
If you intend to do a bigger size nominal battery bank voltage, make sure the charge controller you select is able to set the voltage to that specific value. The charging range must not be a reference for this as voltages may be higher than the nominal value during some stages of the charging process.

Rated Battery Current

This is the value that you will see displayed on the charge controller. It is one of the most important features when choosing your charge controller. This number indicates the amount of current that will go to the battery at the specified system voltage.

Let's explain this with an example.

I have two solar panels with the following specifications:



If I wire both panels in series, I will get one panel of 35 Volts and 5.8 Amps. By using the safety factor of $1.2 \times \text{Impp}$, I would choose a $1.2 \times 5.8 \text{ Amps} = 7 \text{ Amps}$ or 10 Amp solar charge controller to charge the battery.

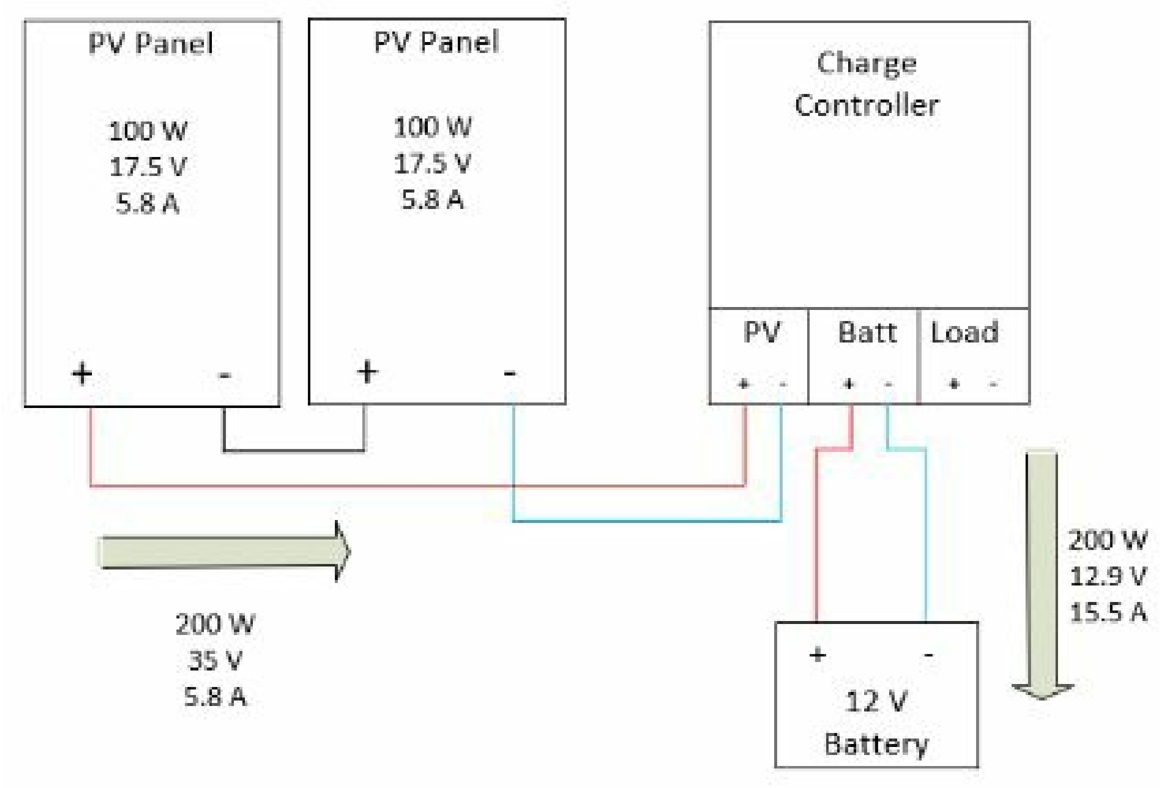
However, we do not charge our batteries at 35 Volts. The charge controller steps down the volts to a range of 12.9 Volts to charge the battery. This conversion increases the current.

The wattage of both panels is 200 Watts. Let's calculate the current at a charging voltage of 12.9 Volts.

$$\text{Charging current} = \frac{200 \text{ Watts}}{12.9 \text{ Volts}} = 15.5 \text{ Amps}$$

$$15.5 \text{ Amps} \times 1.2 = 18.6 \text{ Amps}$$

You can see that the charging current to the batteries is higher than the previously calculated 7 Amps. The new charging current is 18.6 Amps, including the safety factor of 1.2. This means that you would need to get a 20 Amps charge controller.

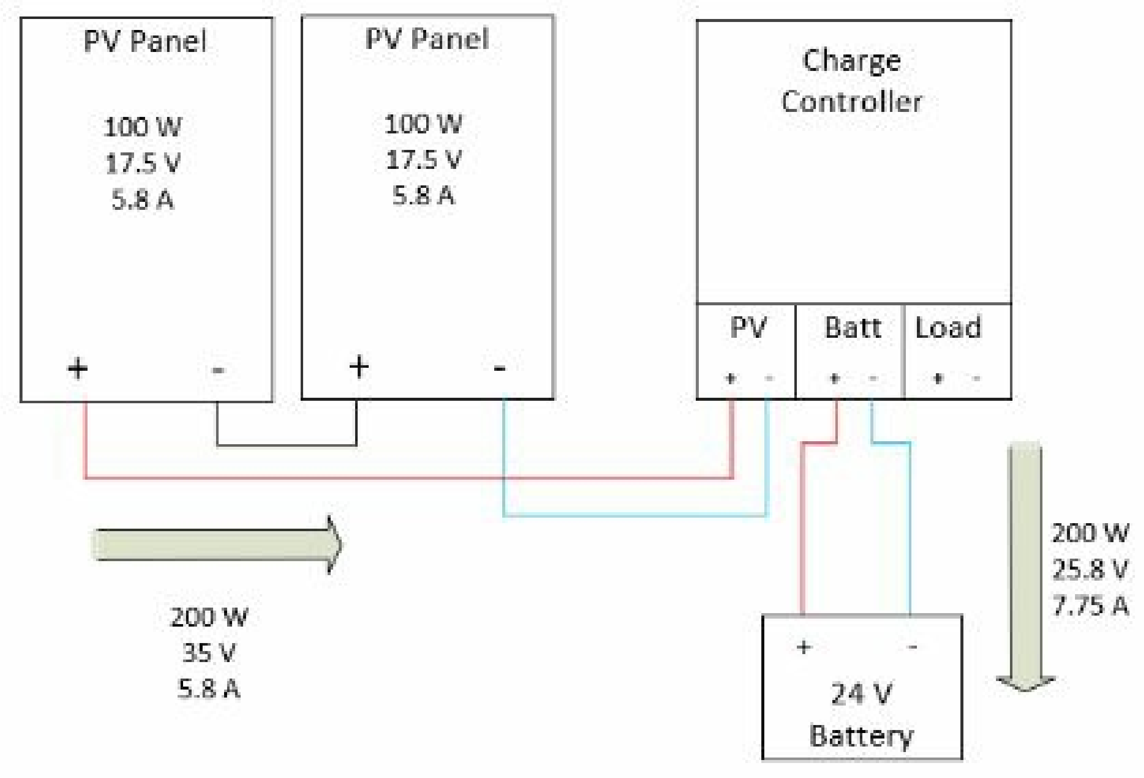


Let’s repeat the calculation with a battery bank of 24 Volts.

$$\text{Charging current} = \frac{200 \text{ Watts}}{25.8 \text{ Volts}} = 7.75 \text{ Amps}$$

$$7.75 \text{ Amps} \times 1.2 = 9.3 \text{ Amps}$$

As you can see, the charging current is reduced because we use a higher battery bank voltage. This will also increase the charge controller’s efficiency. We would now need a 10 Amp charge controller.



Increasing the voltage of the battery bank allows you to use a smaller charge controller because the charging current will be lower.

Load Current

As mentioned before, we generally do not use the load terminals of the charge controller unless it's a small load. It is best to use the battery terminals to power DC loads.

Input Voltage

Another factor that must be considered is related to the estimated operating voltage ranges for the PV array.

As previously discussed, the voltage varies across the day, depending on the temperature of the cell. Moreover, it also changes depending on the number of solar panels connected in series. When sizing a solar array, you need to estimate the number of solar panels that need to be connected in series, the more panels in series, the higher the voltage.

The charge controller that you selected will have both a maximum and a minimum input voltage from the solar array that it can handle. Whenever choosing the charge controller, you must make sure the input voltage does not go over or below that range.

Here, you must consider the effect of temperature on the cell voltage as it was explained in the solar panel section. In other words, the maximum input voltage that the charge controller can accept should be associated with the voltage of the string under minimum temperature conditions. Meanwhile, the minimum input voltage that the charge controller should accept is related to the voltage of the string under the maximum temperature conditions.

Power

Another factor is power. The charge controller is capable of handling a specific amount of power input.

Power is the product of voltage and current. The power of a solar string or array is the same in every configuration (series or parallel).

Max. Solar Input Power	12V @ 260W	12V @ 400W	12V @ 520W
	24V @ 520W	24V @ 800W	24V @ 1040W

Maximum input power is related to battery voltage

Efficiency

Efficiency is also very important to consider. When having to decide between two charge controllers, the model that has a higher efficiency is preferable.

Since charge controllers are electronic devices that are intended to act as intermediaries between the charging source and the load, then charge controllers should transfer as much energy as possible. Therefore, efficiency should always be located above 93%. Efficiency will be higher (96%) when you choose a battery system that is rated for 24 Volts, compared to a battery system of 12 Volts. This means that a charge controller will be more efficient if you match the solar voltage to the battery voltage because it needs less voltage transformation. More transformation means more heat generation, and the less efficient the charge controller will be.

Operating Temperature Range

Each charge controller will also have a permissible operating temperature range. Keep in mind that the cabin or cabinet where you locate the regulator will have the permissible temperature or humidity limit values stated by the charge controller manufacturer.

Also, take into account the enclosure protection rating, typically established according to the IP ratings.

PWM charge controllers operate better with estimated solar cell temperature ranges between 113°F (45°C) and 167°F (75°C).

MPPT charge controllers outperform PWM models under all cell temperature conditions, but especially when they are either below 113°F (45°C) or higher than 167°F (75°C).

PWM or MPPT?

As has been previously explained, a PWM charge controller does not operate at the maximum power point of operation. This means that the power output that can be obtained from a solar panel array when using a PWM model is much lower than the MPPT model.

In commercial-based or residential systems, the MPPT charge controller must always be the preferred choice since the extra amount of energy that can be obtained from the I/V curve exceeds the additional cost of the MPPT model.

There is a particularly important factor to consider when selecting the charge controller. If the solar array has a high number of solar panels in series, then the voltage is higher. As the voltage gets higher, the maximum power point (MPP) distances from the nominal voltage of the battery bank.

Keep in mind that the impact of six solar panels wired in series for a 12V battery bank is not the same as for a 24V battery bank. The extra voltage difference will be bigger in the 12V battery bank (and so will be power losses).

Therefore, if you have multiple solar panels wired in series, then the PWM charge controller would have much more losses than the MPPT model. In this case, it is recommended to choose the MPPT charge controller. Having more solar panels wired in series also reduces the amount of current, and therefore, reduces the cross-sectional area of the wires that would be needed, which translates into cost reductions.

There is no specific voltage at which you should consider switching from a PWM to an MPPT. Nevertheless, keep in mind that you need to have a higher voltage in order to charge the batteries, therefore, if you have a battery bank at 12V, you will need to have at least 14V at the source (panels). PWM charge controllers are, most of the time, limited to an input voltage of 12 or 24 Volts.

Also, keep in mind that voltage can reduce with temperature changes, therefore, it is advisable to have a solar panel setup that provides between 17-19V (maximum power point voltage) for a 12V battery bank. Adding more panels in series over this limit will simply increase voltage losses due to the larger difference in nominal voltages.

In the case of a 24V battery system, it is recommended to use a panel between 32-36V (Vmpp) or use two 18V panels wired in series to reach a similar voltage. Meanwhile, with 48V battery banks, the situation changes a bit since it is unlikely that you use solar panels with 60V as to be wired in parallel, here the most common approach is to wire modules in series to reach string voltages between 54-58V. And, for 48V systems, it is highly recommendable to use an MPPT charge controller.

Despite taking these measures, keep in mind that it is likely that you will lose performance in efficiency by using a PWM charge controller, it is unavoidable due to the structure and functioning of the device.

Another factor to consider is shading. Under shading conditions, the MPPT charge controllers will have a much better performance than the PWM models because the MPPT models can track the maximum power point of the array (which will become affected by the presence of shade). If your solar panel installation is expected to have shading conditions, then you would probably be better choosing an MPPT model.

Despite all of the advantages of MPPT charge controllers, they can be considerably more expensive than PWM models. Therefore, the decision comes down to a balance between costs and performance.

For simple off-grid purposes like RVs, cabins, or boats, a PWM charge controller can become very handy to reduce costs.

If the system that you intend to install is small (below 500 watts) and you are sizing the array in such a way that the voltage of the solar panels slightly matches the voltage of the battery bank (mainly through parallel connections), then going with a PWM charge controller could be a good choice. Otherwise, and especially if there are many solar panels wired in series, then you would do better with an MPPT charge controller.

Temperature Compensation

As it has been explained before in the battery section, batteries can be severely affected by temperature changes. The capacity of the battery can drastically reduce as it approaches 32°F (0°C) and even more if it goes lower. Combining this temperature effect with high load demands can lead to a severely reduced SOC in your battery.

Voltage charging setpoints are usually established for charge controllers assuming 77°F (25°C), which is the standard for batteries. However, as temperature rises, the necessary charging voltage would be lower.

If the temperature reduces, the charging voltage required rises. To avoid overcharged (which can lead to gas expulsion) or undercharged (leading to sulfation in lead-acid) batteries, the charge controller must integrate temperature compensation.

Chargers can either have fixed temperature compensation voltage (e.g., 5mV/°C/cell) or an adjustable setpoint. Having an adjustable setpoint is advantageous since battery manufacturers can recommend different temperature compensation values. For instance, Rolls and Victron Energy Batteries recommend -4mV/°C/cell while Crown and Deka recommend -3mV/°C/cell.

Each charge controller also has a specific temperature compensation range, generally between 32-122°F (0-50°C). If ambient temperature goes beyond the limits, then compensation is set at the nearest value.

The temperature compensation that is made by the charge controller consists of using the nominal system voltage, the nominal charge voltage at 77°F (25°C), the temperature compensation rate, and the battery temperature.

As a reference example, let´s assume a 24V system, with a charge voltage of 28.6V, along with a temperature compensation rate of -5mV/°C/cell and a battery temperature of 113°F (45°C).

Since the system is 24V, it means that it has 12 battery cells (2V per cell). Then,

$$\text{Temp}_{\text{comp}} = [\text{Temp}_{\text{rate}} \times \text{Numb}_{\text{cells}}] \times [\text{Batt}_{\text{temp}} - 25°\text{C}] + \text{Charge}_{\text{voltage}}$$

$$\text{Temp}_{\text{comp}} = \left[-\ 0{,}005\ \text{V}°\frac{\text{C}}{\text{cell}} \times\ 12\text{cells} \right] \times [45°\text{C} - 25°\text{C}]\ + 28.6\text{V}$$

$$\text{Temp}_{\text{comp}} = -0.06V \times 20°C + 28.6V = 27.4V$$

The new charging voltage for that battery bank would be at 27.4V instead of 28.6V. As you can see, the voltage is reduced.

There are two types of charge controllers in this aspect. There are models that already integrate an internal temperature sensor and that are able to perform this function directly. These models are quite useful when the battery bank and the charge controllers are located inside the same enclosure and have similar temperatures.

There may be occasions in which the battery and the charge controller are located in different enclosures. In these cases, it is appropriate to choose a remote temperature sensor. Remote temperature sensors consist of a wire with a terminal pin to be connected to the charge controller and a sensitive probe to be used for testing and measuring temperature. This is also recommended when the temperature changes across the year step over 5°C.

Most of the higher end MPPT charge controllers have a port so you can add a temperature compensator. The charge controller will use the temperature and calculate the ideal charging voltage. You simply put the sensor in the same compartment as your batteries. You can use tape to stick the sensor to the side of your batteries for the most accurate compensation.

Temperature compensation sensor

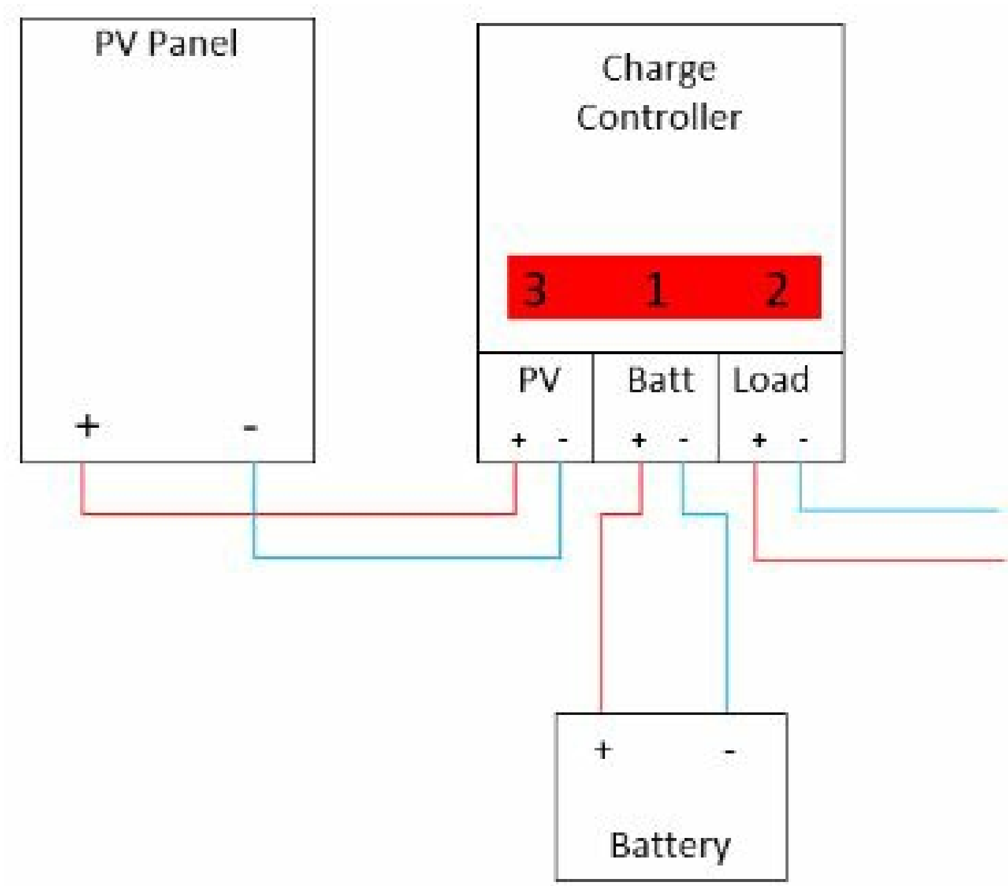
Temperature compensation on the Renogy charge controller

Connecting the Charge Controller

The procedure of wiring a charge controller into the system is very simple.

Charge controllers generally have two output terminal sets: one for the battery (positive and negative lugs), and the other one for the load. Also, charge controllers will have a single input terminal set that must be connected to the solar panels.

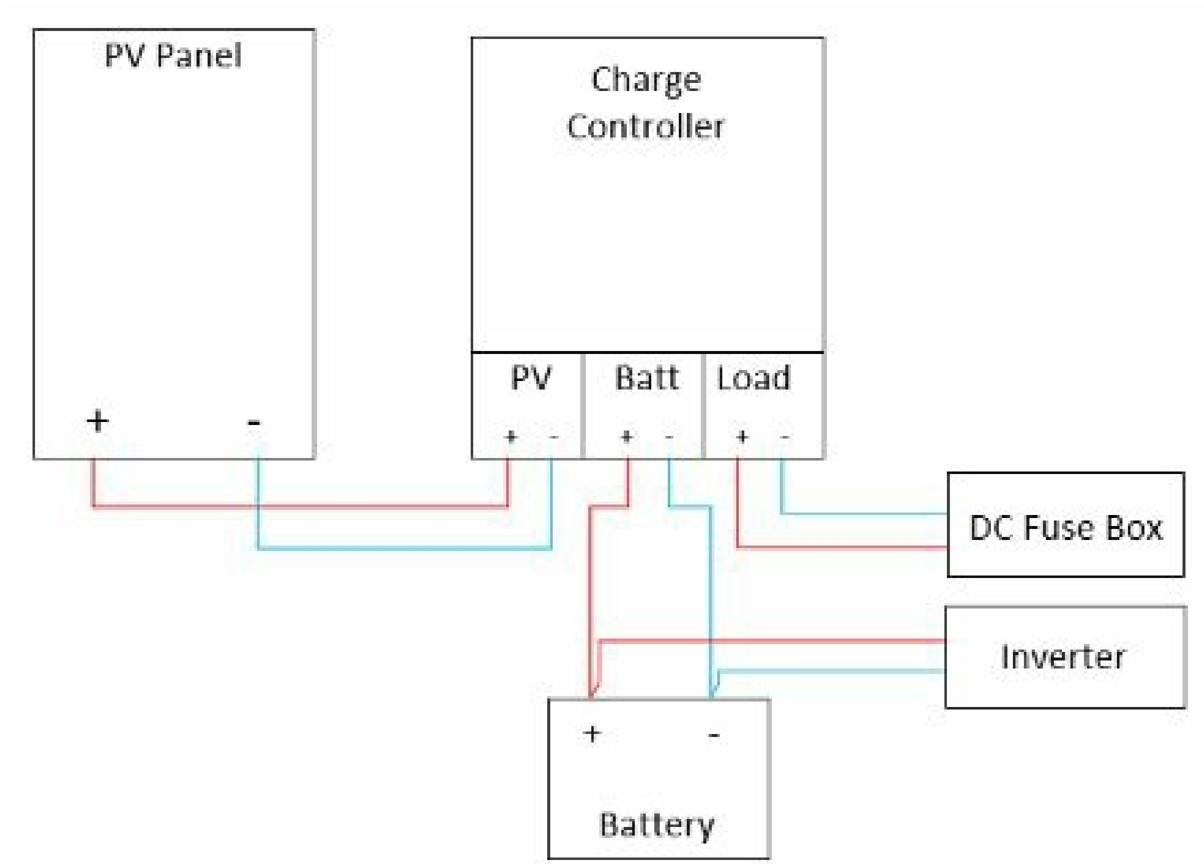
When wiring the charge controller, you must first connect the batteries to their corresponding output terminals. Then, you must connect the loads to the load outputs. Then wire the solar panels to the charge controller, in order to stabilize the generation source with the storage device and avoid the risk of burn out.



Connection sequence for the charge controller

The load terminal on the charge controller is only able to supply a limited amount of current to loads. Therefore, we attach small DC loads to the charge controller, and we connect the inverter straight to the battery terminals. Always keep in mind the maximum load current of the charge controller, which is stated on the datasheet. If the total DC current is higher than the rated output current of the charge controller, then connect the DC fuse box directly to the battery.

The load terminal on the charge controller is not capable of providing surge power. That's why I recommend using the battery terminals for inverters. See the following image for reference.



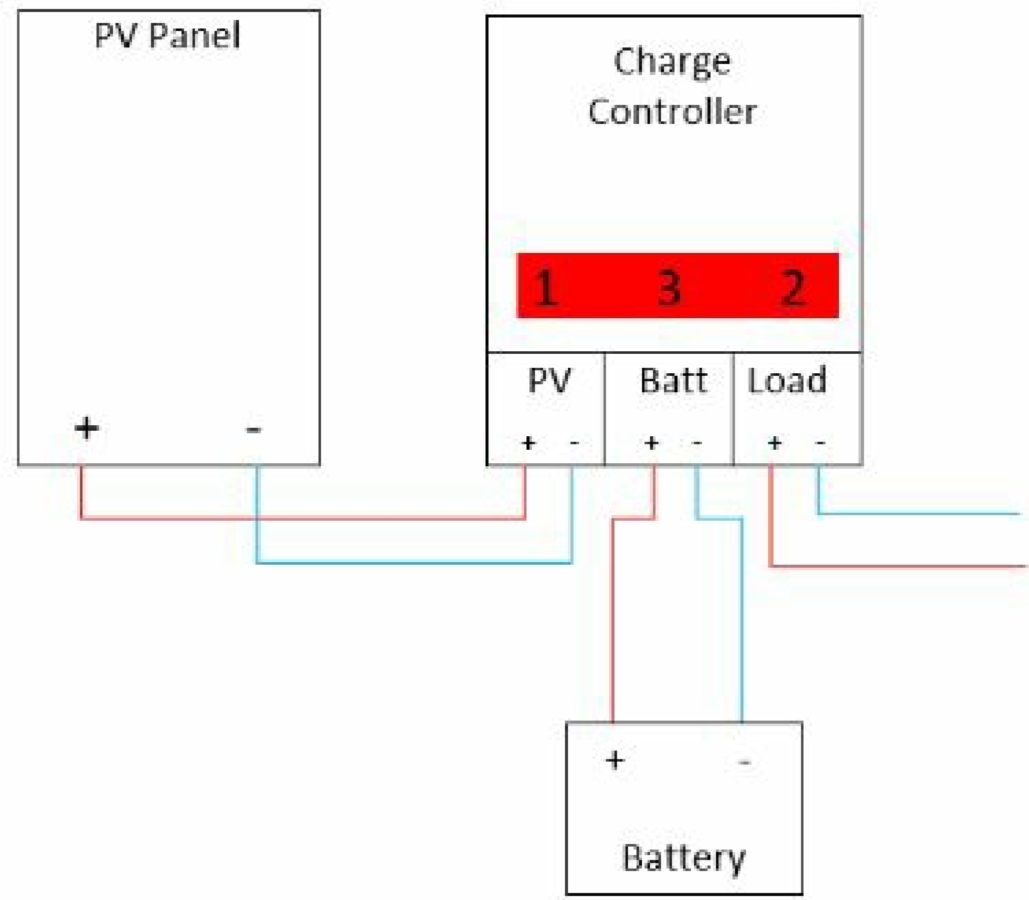
Wiring the charge controller

Always keep in mind that the charge controller input and output will have a maximum gauge size that can be connected to the terminals. This will depend on the electrical current output of the charge controller.

Sometimes a single charge controller will not be able to handle the entire output of the solar panels. If multiple charge controllers need to be used, then you must make sure to use the same brand and model to wire them together with communication cables in order to synchronize their operation.

This will avoid overcharging or malfunctioning. Make sure the manufacturer approves this type of connection.

If you want to do maintenance and want to disconnect the PV system, always remember to disconnect the DC switch between the charge controller and the solar panels first. Once this is done, proceed to remove the load connections before removing the connections of the battery from the charge controller.



Disconnecting sequence

When you connect the wires to the terminals, there might be a spark. This spark originates from the charging of the capacitors in the charge controller. Sparks are more common in higher voltage systems (12 Volts +).

Inverters

What is the Task of an Inverter?

Finally, the last but still an important component of the PV system is the inverter.

The most important task of the inverter is to convert the DC signal that is stored in the batteries into the AC signal that is consumed by most loads in the market. As it was explained at the beginning of this book, there is an important difference between DC and AC signals.

Since solar panels generate DC, and most loads require AC signals, then the inverter acts as a DC-AC converter that can or cannot synchronize with the signal that is obtained from the power grid.

However, there are different types of inverters, and depending on the type, it may also have alternative functions.

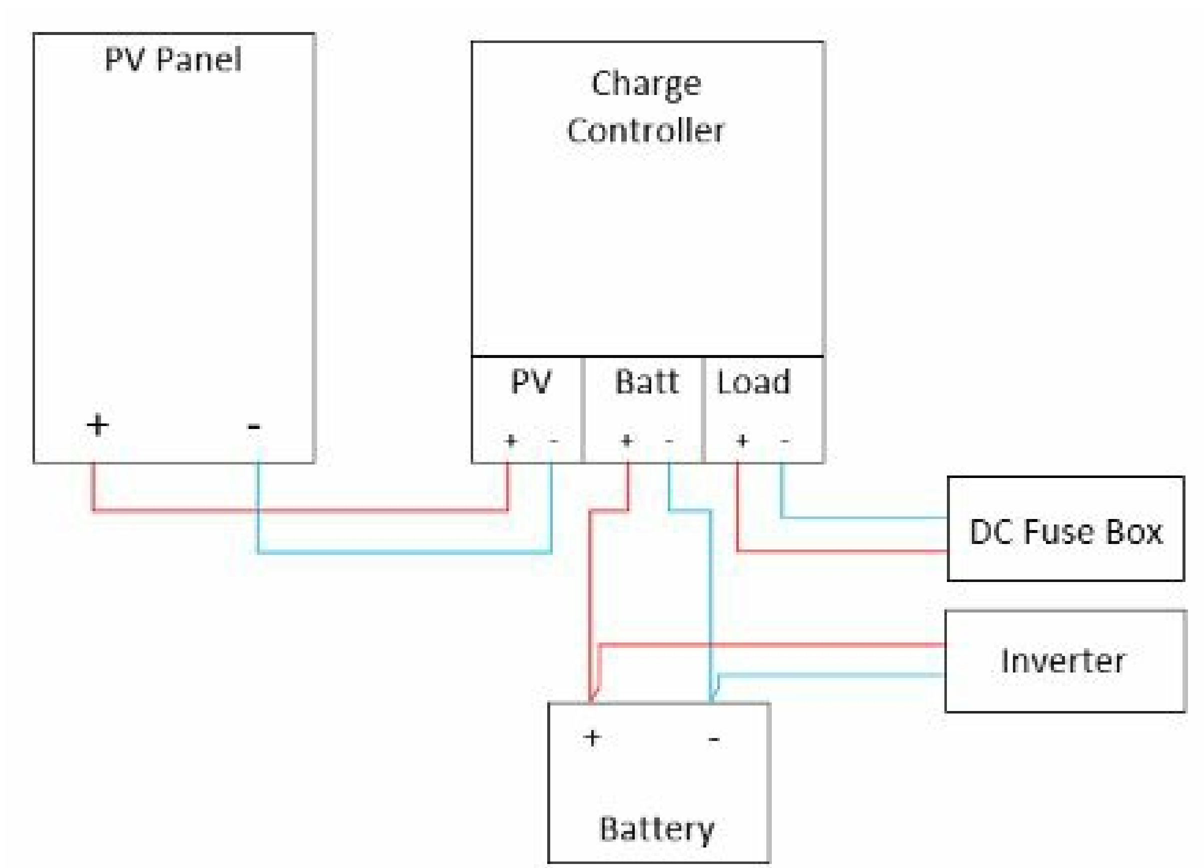
Types of Inverters

Off-grid

For applications in RVs, cabins, and boats, the most common type of inverter that we will be looking at is the battery-based inverter (also applicable for inverter/chargers) suitable for stand-alone setups.

This type of inverter works independently from the power grid and can be synchronized with lead-acid or lithium batteries. It will be connected directly to the batteries and will have a DC input value at the nominal voltage of the battery (generally 12V, 24V, or 48V). This type of inverter will create its own AC signal and is capable of providing overload protection.

Always remember that the AC loads must be connected on the AC side of the inverter, which is in the output terminal. AC loads must never be connected to the charge controller because the charge controller (no matter what type) will always work in DC. The only loads that you can connect to the charge controller must be DC; like small LED lights, smartphones, and other small electronic loads. The setup for this type of inverter can be found in the following image.



Off-grid inverter setup

Grid-Tied

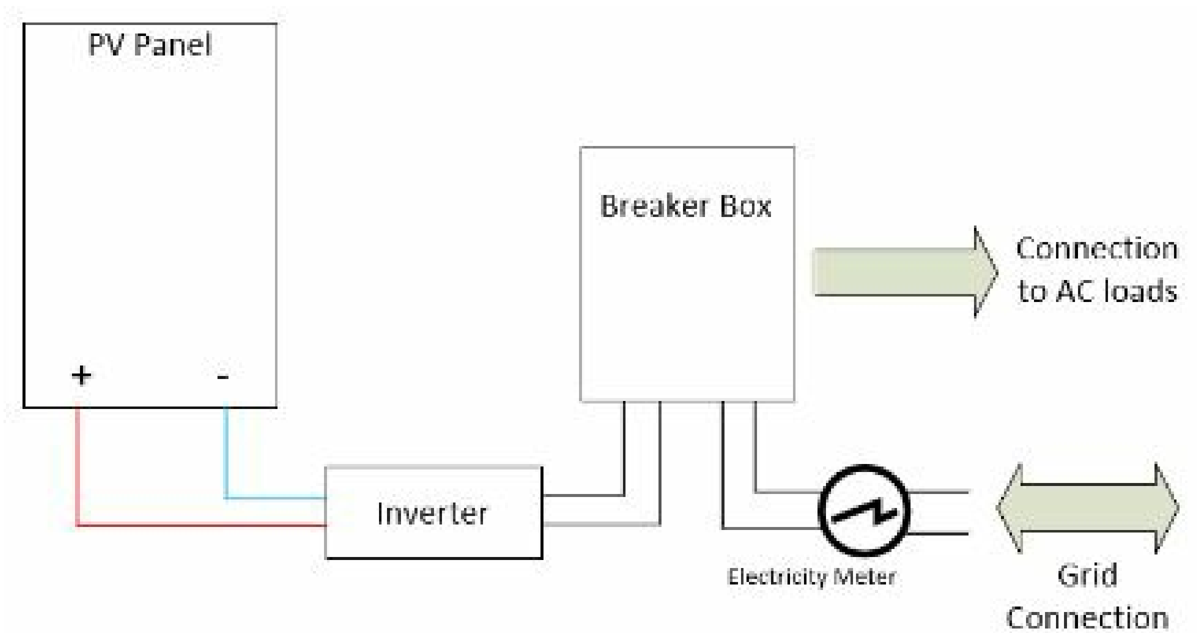
The most common type of inverter available in the market is the grid-tied model. This inverter is used when the power grid is available for connection and when no storage device will be used.

This applies mainly for residential, commercial, and utility-scale applications. This type of inverter needs a signal from the power grid to get synchronized since it cannot create its own AC signal. Therefore, when the power grid goes down, the inverter shuts down. This is also to protect people who are working on fixing the electrical lines in the street from being electrocuted.

The input of this inverter are the solar panels and can perform the maximum power point tracking, while the output is an AC source signal either at 50 or 60Hz. The output signal of the inverter will have a slightly higher voltage than the grid. This is to make the electricity flow from the inverter to your home appliances instead of power from the grid. If the voltage level in the grid rises, the inverter will track the change and increase the voltage level of its output.

If you have an RV, off-grid cabin, or boat, a grid-tied inverter will not work for you. If you are using grid-tied, you need permission from your electrical company to feed electricity back into the grid.

The following image shows a schematic of the connection of a grid-tied inverter.



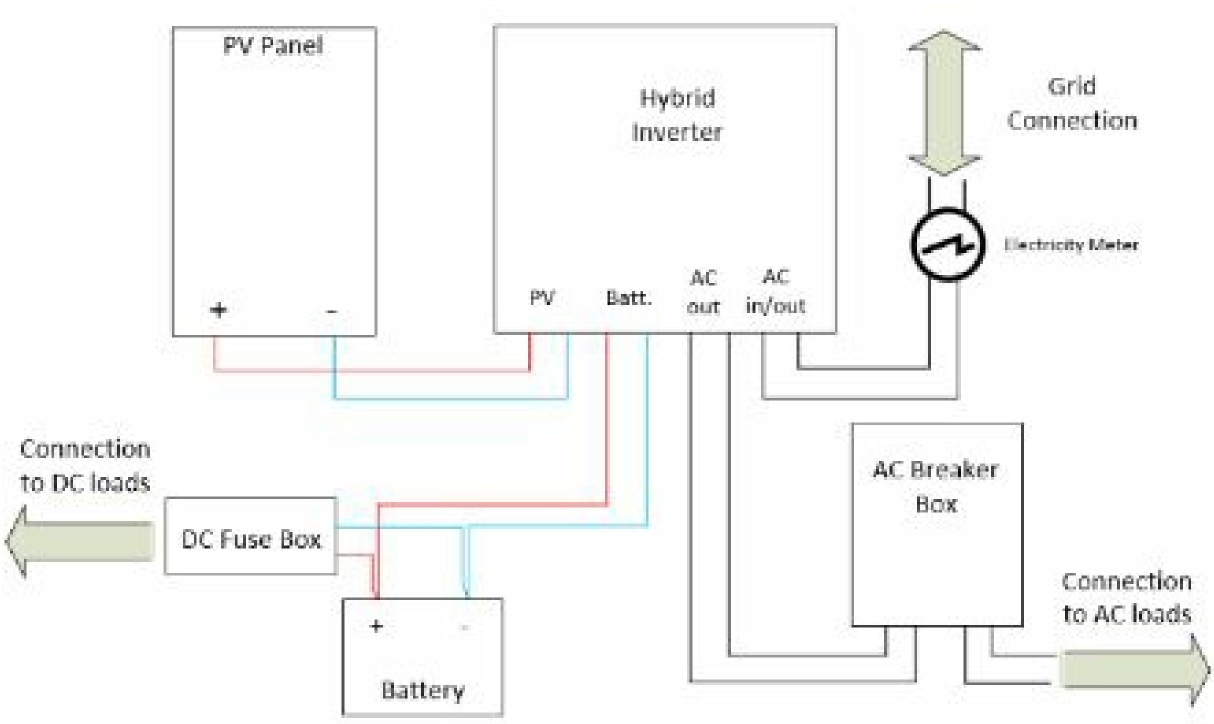
Grid-tied inverter

Hybrid-Inverter

The hybrid inverter is the most advanced and complex inverter available in the market. This device integrates the benefits of both the grid-tied inverter and the battery-based inverter into a single product.

The hybrid-inverter is capable of receiving the signal from the solar panels and track the maximum power point to extract solar energy.

It is capable of using this energy to be stored into a battery, combining the advantages of available power from the grid with energy storage. A unique feature of this type of inverters is that they can synchronize with the grid when it is available, they can also generate their own AC signal when a blackout occurs.



Hybrid-inverter schematic

One of the great advantages of hybrid inverters is that they can charge the batteries without the need of a charge controller and they can use both the wall outlet to charge your batteries as well as solar power. While driving in an RV, you may be wondering if it would be a good choice to wire them to a wall plug.

Technically, you could buy the inverter only with that purpose. However, you would be underestimating its potential as you would still constantly depend on shore power to charge the batteries and power your loads. By installing solar panels, you would be able to move with the RV and travel for days without getting worried about the availability of shore power.

Now, if you live in an RV, you might also consider the fact of the amperage limit of your shore power source. For instance, if it is 20A, you might need more power if you want to run heavy loads, that’s when having an independent source of energy that charges the batteries will be very useful for you. If you live in an RV, your shore power availability is wide enough to charge the batteries and loads, and if you don’t plan to travel for many days when you take the RV out for a drive, then using a hybrid inverter alone might as well suit your needs.

The only question that would remain would be a balance between operational costs of electricity rates vs. installing solar panels for a medium to long-term saving investment. In that case, the system selection would be similar to a grid-tied mode, with the additional factor that when moving from one place to the other, you would be able to take your solar panels with you.

The hybrid inverter will use the battery bank to make an AC signal if there is a blackout or if you are on the road. If it detects that there is power being produced by your solar panels or onshore power (at a campground), it will make use of that power, and charge the batteries.

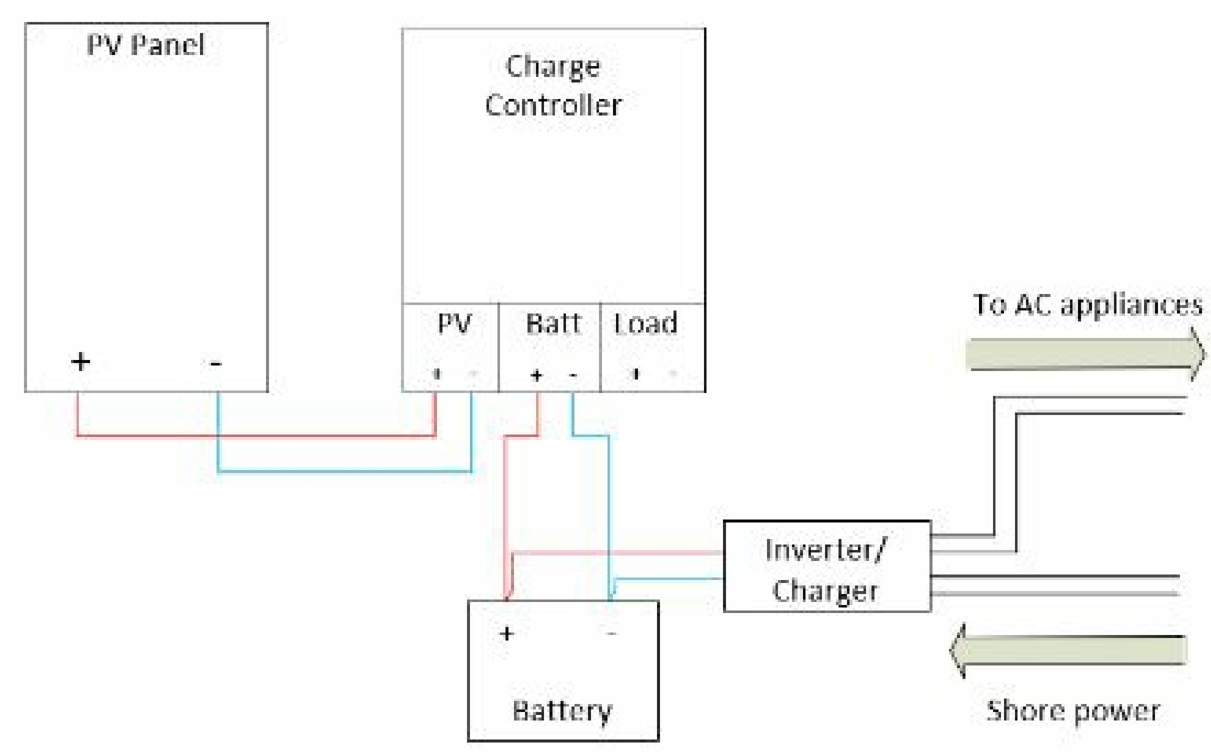
The disadvantage of a hybrid inverter is that they tend to consume quite some power in standby mode. If you are only using DC, the DC to AC inverter is still idling, which consumes power constantly. It might not be much, but you should consider it if you have a small system.

Inverter/Charger

This might be the best solution if you are moving around in a van or boat. This inverter does not only convert DC voltage from the battery to AC loads but is also capable of charging the battery itself. It’s a cost-efficient solution if you want to be able to charge your batteries with shore power while on the road.

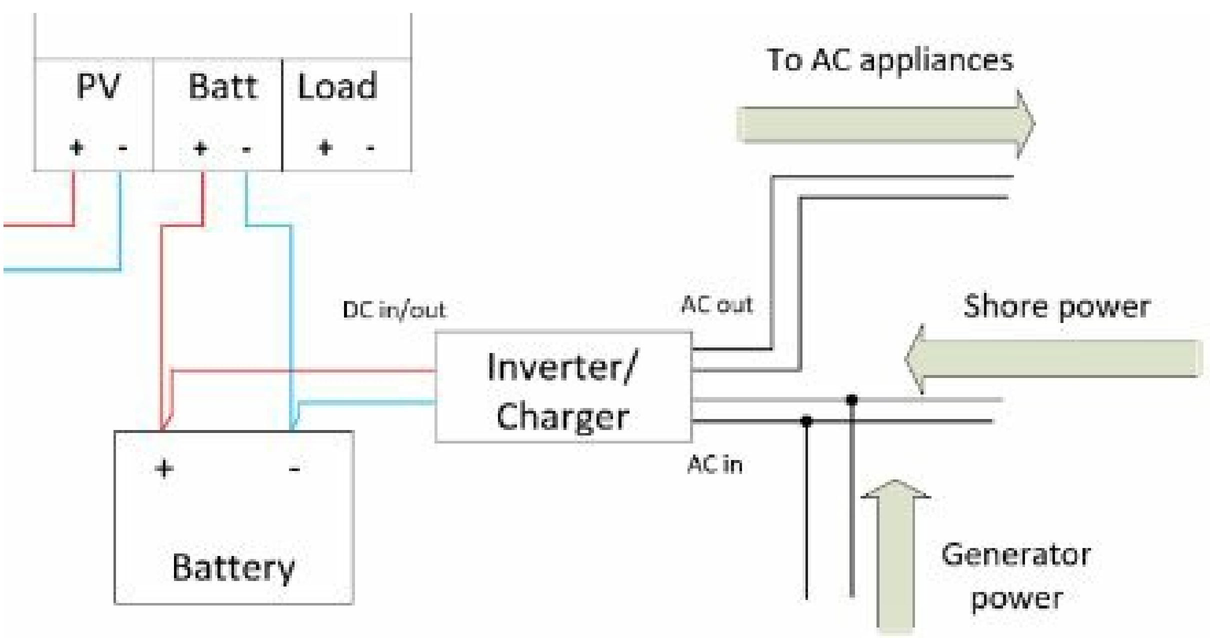
Most of the time, these come with a temperature sensor to adjust the charging of the battery according to ambient temperature. You now have two choices of charging the battery bank, through solar and through shore power.

How to wire the inverter charger can be seen in the following diagram:



Wiring diagram for an inverter charger

Apart from using shore power, you can also use a portable generator to connect to the AC input of the inverter/charger to charge the batteries.



Wiring inverter charger with shore power and a generator

Inverters Output Signal

Besides their configuration type, inverters can also be classified by the shape of the signal wave of their output.

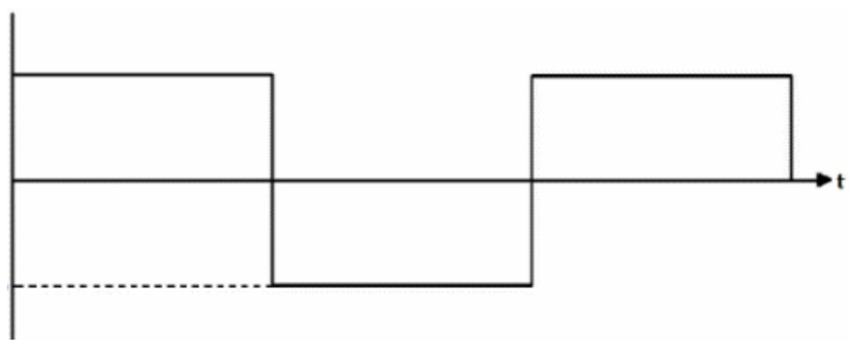
Square Wave

These are considered the oldest technology available for inverters. Their working mechanism tries to resemble the periodic shape of an AC signal by flipping the voltage directly from negative to positive and back again.

Unlike a typical AC signal, there is no pause through zero between the negative and positive voltages. Due to this alternating pattern, they resemble the shape of a square.

As of today, square wave inverters are not considered for many applications because most loads would heat up when using them. The reason is that electronics require smoother signals free of harmonics (noise components).
Square wave inverters have a much higher noise level than a sine wave inverter, which creates a real disturbance. Despite these flaws, square wave inverters can be much more affordable than their sine wave counterparts. This is because the square wave is an older, less complex type of inverter.

Mainly, the only applications where purchasing a square wave inverter might be suitable would be to power lights and fans or small motors.

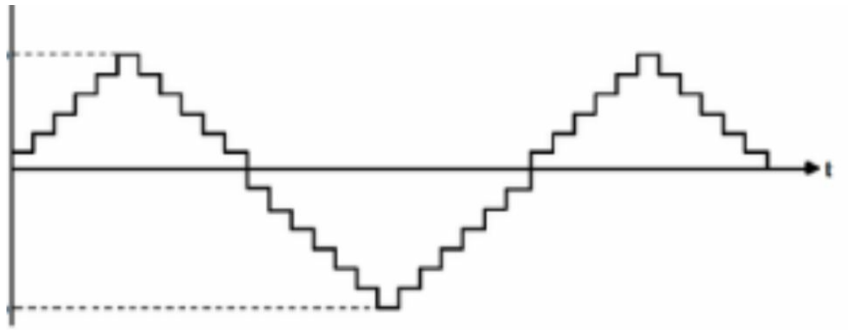


Square sine wave

Modified Sine Wave

The modified sine wave inverter is another version of inverters that came after the square wave type that had better performance and was more similar to an actual AC sine wave signal.

Unlike the square wave type, the modified sine wave adjusted the ups and downs of the output signal to match as closely as possible the shape of an actual AC sine wave signal.



Modified sine wave

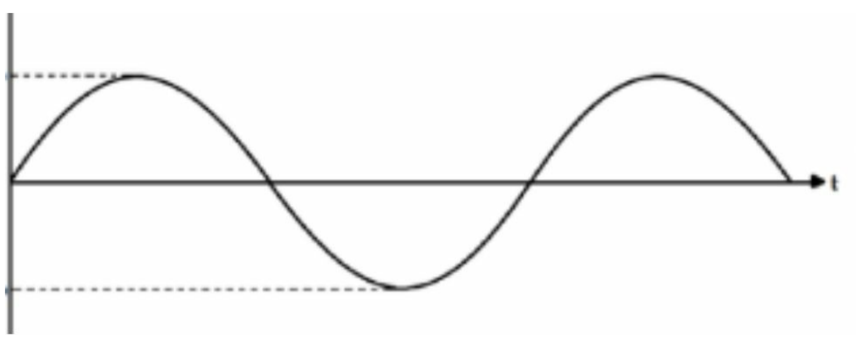
Despite having a better performance than the square shape type inverter, the modified square wave inverter will still have a noticeable harmonic distortion that won't allow it to run sensitive electronics such as laptops. Besides, you are likely to hear a "buzz" when operating it.

Modified sine wave inverters are cheaper than a pure sine wave inverter.

Pure Sine Wave

The most efficient, technological, and certainly an ideal option for any type of load is the pure sine wave inverter. The signal of this inverter resembles exactly the one that could be measured in the power outlet of your house, meaning a perfect sinewave.

Sensitive electronics need the cleanest signal available to work without any risk of damage. Despite that, they will be more expensive. They will not be as noisy as the square wave model, they will not heat your appliances, and they will work better in cases where there is constant use across the day.



Pure sign wave

Utility Interactive for on-grid Connections

Inverters that are connected to the grid (grid-tied or hybrid inverters) have additional features that battery-based models do not need. Due to their connection with the grid, inverters can act under different interactive modes of operation depending on the conditions of the power grid.

The first type of connection available is the simple grid-tied mode, which consists of exporting all the energy generated by the solar panels back to the grid. There are multiple compensation schemes available out there depending on your location. For U.S.-based cases, you will find schemes such as Net Metering and Feed-in tariffs that will compensate you for every kWh injected back to the grid.

Nowadays, inverters are capable of more. Some inverters known as smart inverters are capable of interacting with the power utility operator to guarantee the safest operation of the power grid. Using high-tech communication systems, a network operator is capable of shutting down all inverters within a perimeter in case the solar power injection to the grid exceeds the limits for the stability of the system.

Network operators are also capable of curtailing or adjusting the power factor of smart inverters to reduce or increase solar power injection into the grid. Some networks, such as the Hawaiian power grid, already operate under these mechanisms.

Hybrid inverters have other functionalities as well. Some of them are:

- **Backup:** Isolating operation from the grid when there is a blackout.
- **Grid Zero**: Does not allow selling energy to the utility. The inverter tries to avoid consuming power from the grid, only using the renewable energy source and the batteries.
- **UPS:** Intended to increase the response speed to support specific loads (important for data banks).
- **Mini-Grid:** Operates as an off-grid system, using the utility grid as a backup generator.
- **Time-of-Use:** Inverter is set to take advantage of low-cost electricity rate periods to consume power from the grid and use high-cost electricity rate periods to sell power back.

Efficiency

The efficiency of an inverter as any other conversion device is essential to ensure the proper use of the generated solar power.

Efficiency is referred to as the amount of power of the DC signal that enters the inverter, compared with the amount of power in the AC signal that comes out of the device.
Inverters should generally have efficiency values above 93% to reduce energy losses. The latest inverters will have values above 97%.

Automatic Load Shedding

The term load shedding is a technical term referred to as reducing the amount of load (power) that is connected to a generator, energy source, or electrical system. This is done to ensure that the electrical system can provide power to the most important (critical) loads uninterruptedly.

In a solar power system that is off-grid based, it is important to take into account during low solar radiation days that the availability of power may be lower than expected. That's when an automatic load shedding control mechanism or device becomes handy.

Some inverters already integrate this feature (like the SMA Sunny Island inverter). However, you may also find separate devices that can perform this task. This will allow you to prioritize the loads that you want to keep running in case of increased load demands or low electricity generation. It will also protect your batteries from over-discharge.

Peak Power

The peak power is referred to as the maximum power that the inverter will be able to provide during a short time. Surge power follows a similar concept, although it is under a shorter time frame. It is important to mention that this does not apply as a reference for the power capacity of the inverter when sizing the system. The peak or surge power can be used as a reference for those loads that require extra power during the starting process, such as motors.

Depending on the inverter model and brand, you will be able to find some products that offer different peak power capacities under different time frames. For instance, a 2kW inverter may provide a peak power of 2,500W over 30 minutes (just in case that load demand slightly increases) and may even provide a surge power of 4,500W for 5 seconds (only suitable for starting loads with motors like a fridge or A/C unit).

Power Consumption

Finally, power consumption is another factor to consider since every inverter will demand a small power consumption to keep electronics working, even when there is no load connected.

Despite that power consumptions tend to be small, selecting the inverter with the lowest power consumption is always preferable.

A hybrid inverter is an all in one unit, so it will consume more power.

Charge From car Alternator

Solar energy is entirely dependent on the weather conditions of your location. You may find yourself in a situation where multiple rainy days can keep your solar panels from completely charging your batteries. Or over time, you can also be consuming more power than what your system was originally designed for.

Either one of them, having an alternative backup energy source to charge your auxiliary batteries, is always preferable.

In RVs, there is an additional available source of energy that can be used to charge your batteries. We are talking about the car alternator. Just as the RV moves and charges your starting battery, it can also power an auxiliary battery. There are two ways of doing this.

Battery Isolator Charger

The first option is to use an isolator charger.

The purpose of an isolator charger is to connect your car's alternator to the auxiliary battery to charge it when the car is running. However, when the car stops, the idea is not to draw your starting battery's energy to supply the loads. Therefore, the isolator charger ensures that you *isolate* the starting battery from the auxiliary battery when the engine is not running. This is the lowest cost option.

Direct charging from the alternator can be damaging to the alternator and battery cells. This is because there is no current limitation or regulation for the charging process. Therefore, I do not recommend using an isolator charger.
A car alternator is not made to charge deeply discharged batteries. The current demand from the alternator to the solar battery will be too high for the alternator. This makes the alternator provide more amps than it can safely handle, and will lead to the destruction of your car's alternator.

Battery-to-Battery Charger (B2B)

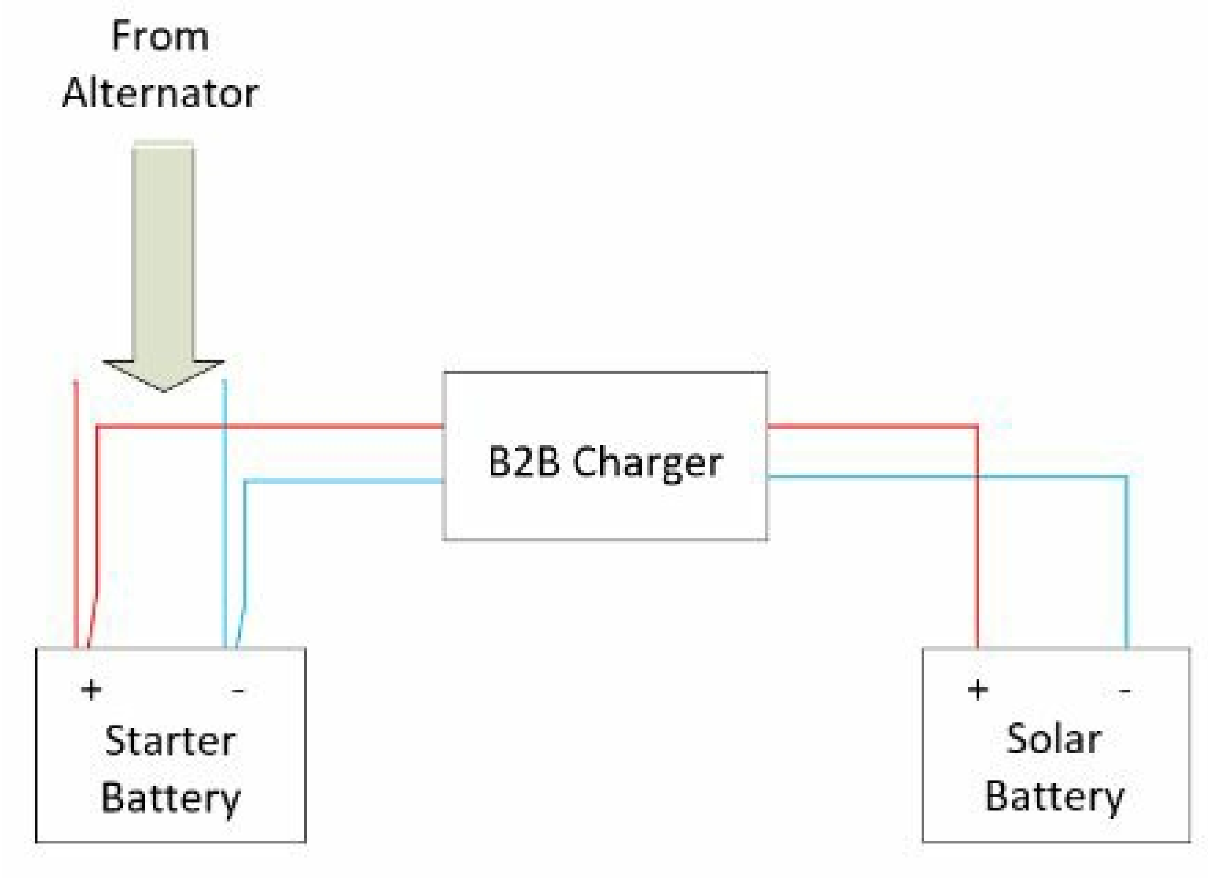
The other option is using a battery-to-battery charger or B2B device, also known as DC-to-DC battery chargers.

These devices are located between the starting battery terminals and the auxiliary battery terminals. Their purpose is to take the car starter battery and boost or reduce it to provide a stable voltage under a multi-stage charging profile. This ensures that the backup batteries are safely charged while keeping the main starter battery full.

Renogy offers a B2B device that connects to your car's ignition. It only runs when the car engine is running. You can select several options like battery type and battery voltage using the switches on the side.

Battery-to-Battery charger from Renogy

The difference between a B2B and an isolator charger is that the B2B is capable of performing a multi-stage charging scheme (the most optimal charging method).



Wiring diagram for a B2B charger

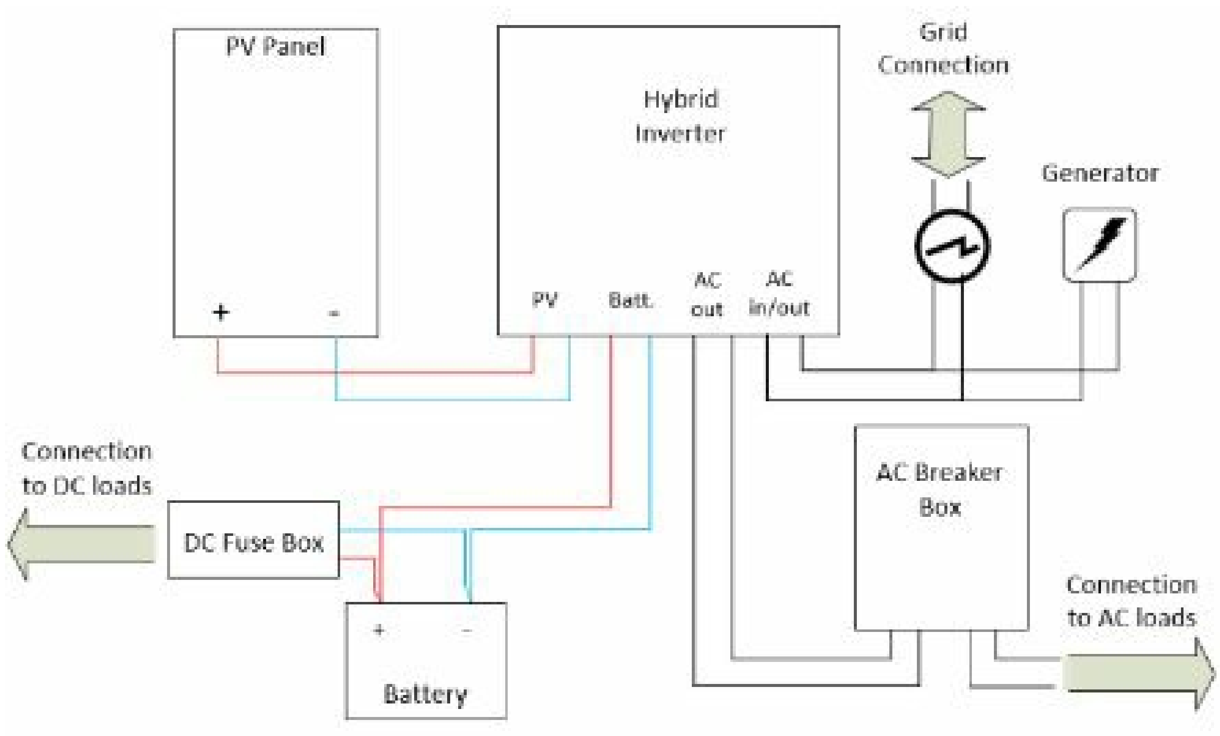
When selecting a B2B charger, you must take a look at the maximum output and input currents, and also at the permissible voltage values. A 10 Amp or 20 Amp B2B charger will suffice in most cases.

Charge From Generator

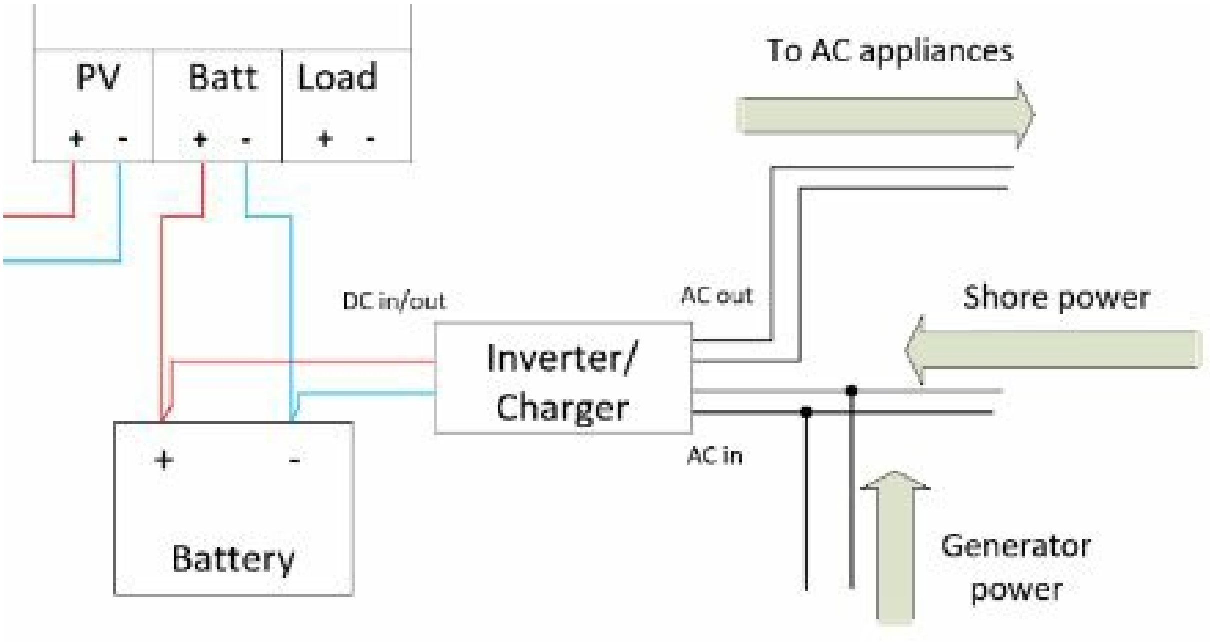
Although less common in solar power applications, another option available is to couple an inverter/charger with a traditional gas or gasoline generator. The backup generator can be connected to an AC input that the inverter has.

Keep in mind that this modality is available for hybrid inverters (through their AC input) and to some inverter/chargers that also integrate an AC input for backup support through a diesel generator.

Not all models have this feature available, so you would need to look in the datasheet or installation manual to see if there is an AC input terminal for such a device. One sample inverter/charger that has this feature available is the Outback Power FXR series that has a 48VDC input that needs to be provided by a charge controller of the brand.



Hybrid inverter with a backup generator



Inverter/charger setup with shore power or generator

DIY Solar Power Setup

The procedure for a solar power system is very simple and can be done by following these steps:

1. **Calculations and schematic**

Before you order components or even consider making a solar system, you need to do the calculations first. Refer to the chapter ‘Sizing your solar system’ for more information.

Drawing out your solar system will make it easy for you to assemble the components later. It will also give you an estimation of the space you need.

2. **Ordering and preparing components**

After you have done the load analysis, it’s time to order your components. Make sure you have read all the chapters in this book before buying your components to avoid unnecessary setbacks.

Remove the components from their boxes and put them roughly where you want them. Using a wooden backboard to mount the components can make it easier to install. Make sure to put them as close together as possible to reduce wire losses and save on wire cost (especially thick wire). Make sure the connections are accessible for future upgrades or maintenance.

3. **Layout**

Look for a space in one of the compartments of the RV to locate the lead-acid or lithium-ion batteries and place them there. Keep in mind to respect the limits and parameters stated in the National Electrical Code section of the book. Make sure the batteries are placed at room temperature.
Place the inverter and the charge controller in an ideal position that is close to the battery bank. This reduces the voltage and ohmic losses and allows a simpler installation.

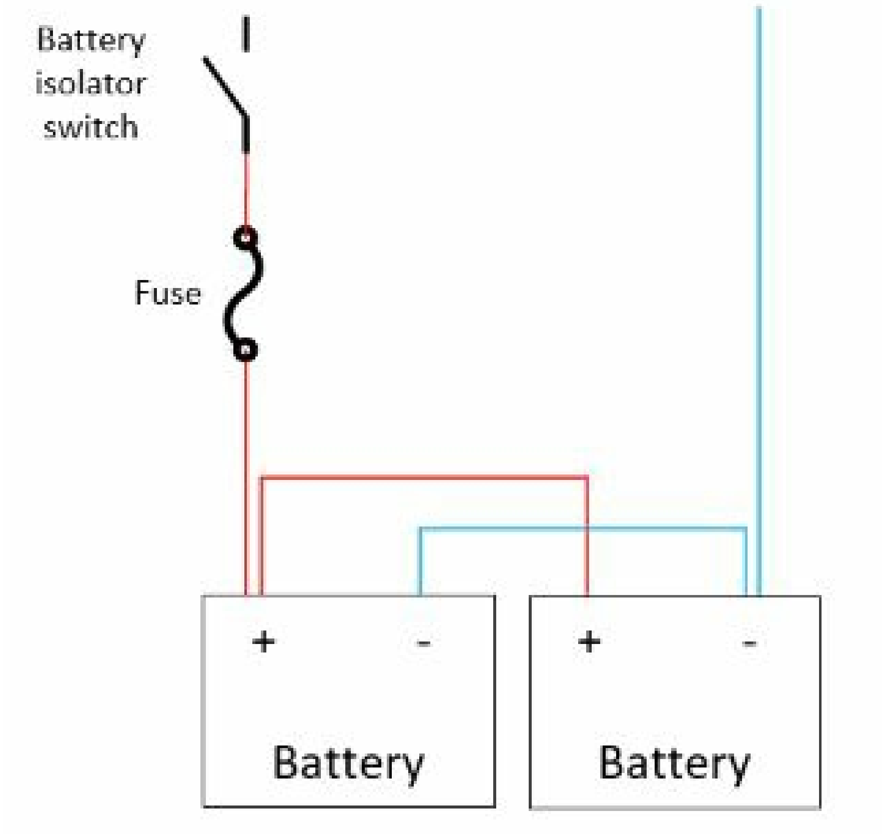
4. **Wiring the batteries**

Remember to review the section related to series and parallel connections in the battery section of this book before wiring your batteries.

Choose your wire gauge size wisely to handle the current that flows from your charge controller to the batteries. Check the ‘Calculating wire sizes’ chapter for further details.

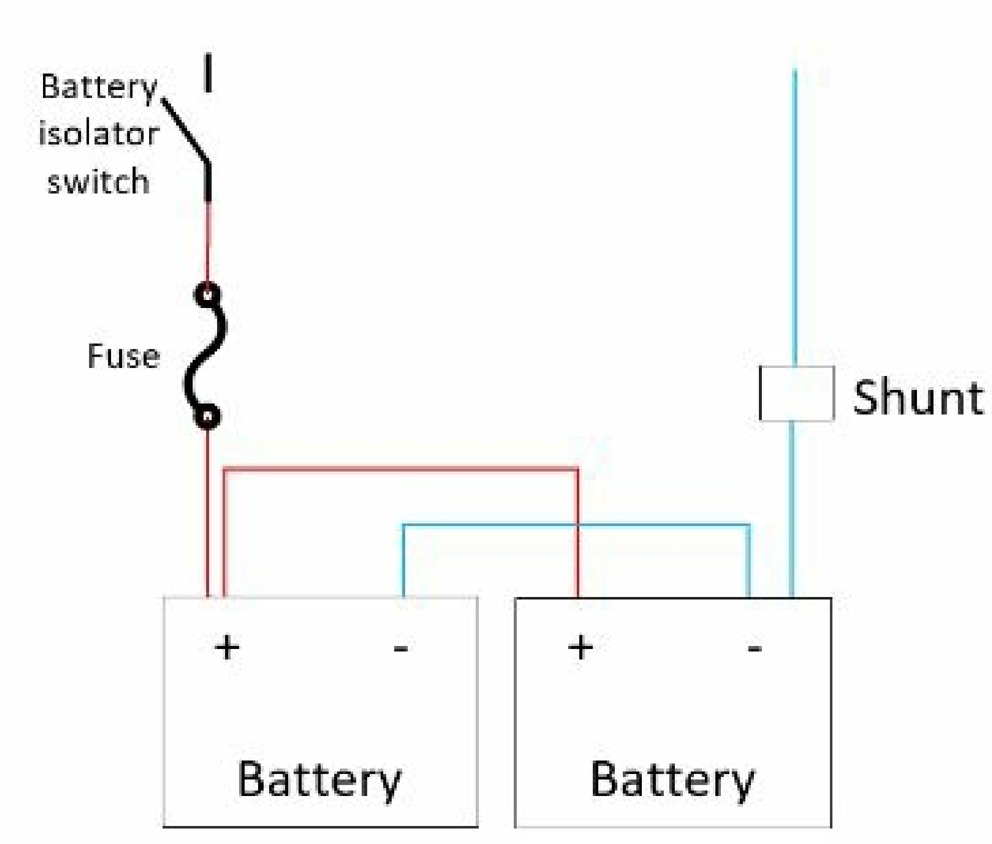
Keep in mind the maximum wire size of the input terminals on the charge controller. Add an inline fuse and a battery bank disconnect switch. The inline fuse should be as close as possible to the positive battery terminal.

Your charge controller will have a maximum charging current. Use this number together with temperature compensation to find out the right wire gauge. Select a fuse size that will protect the diameter of the wire. This should come close to 125% of the charge controller charging current.



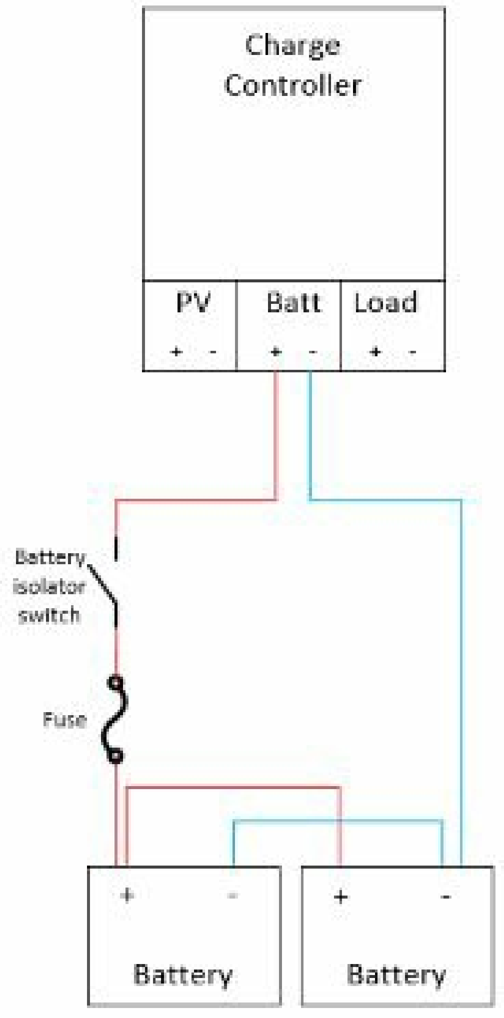
Two batteries in parallel with fuse and switch

If you choose to use a shunt, now is the time to wire it in. The negative terminal of the shunt will act as the negative battery terminal.



Shunt at the negative battery terminal

5. **Wire the battery to the charge controller.**



Wiring the batteries to the charge controller

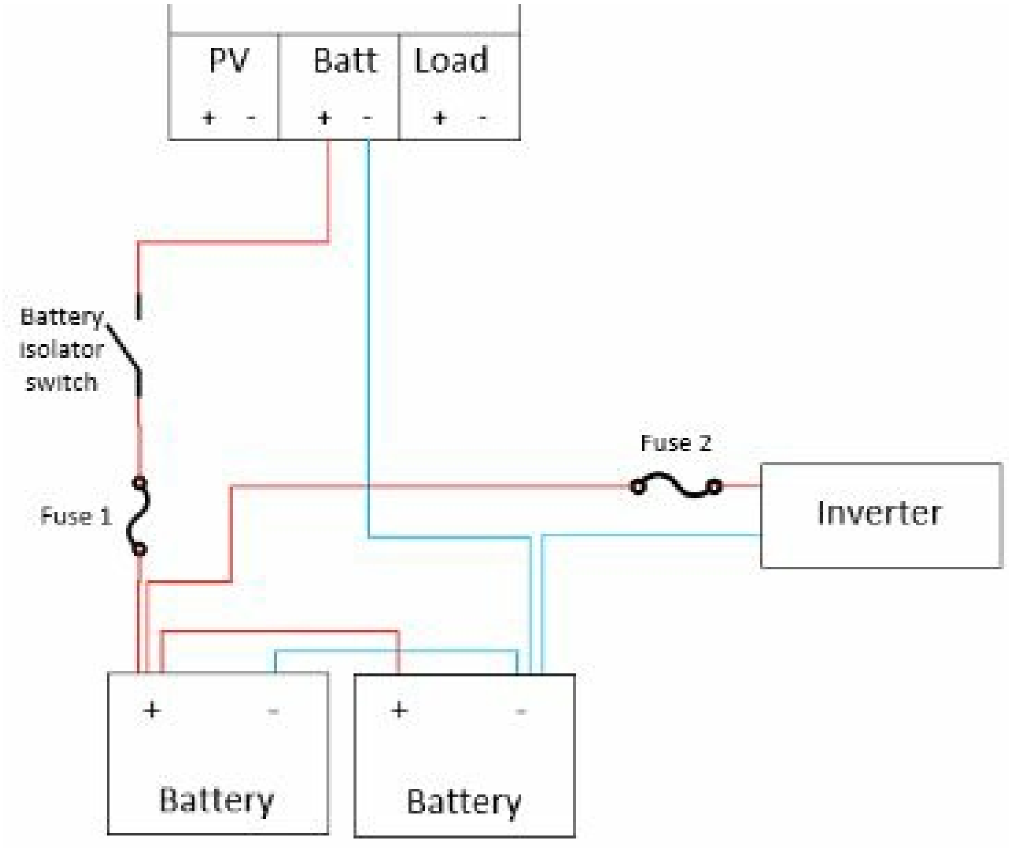
Once wired, the display of the charge controller will light up. Select the battery type you are using. Follow the directions in the manufacturer's manual on how to do this.

6. Install the inverter

You have two choices when installing the inverter:

- Wiring directly to the battery terminals.
- Wiring from a busbar.

Wiring from the battery terminals:
This option is a bit easier than wiring from the busbar because you need fewer fuses. The downside to this setup is that it is harder to expand your setup later.



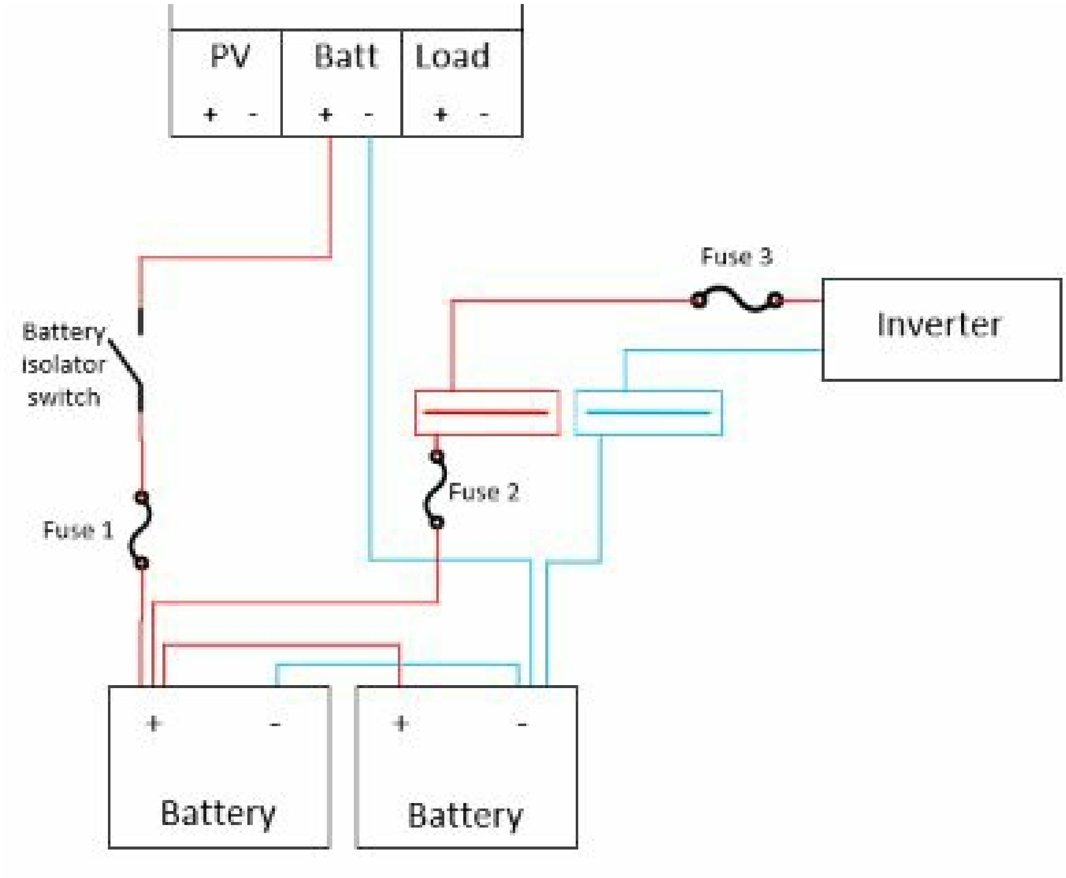
Wiring the inverter or inverter/charger to the batteries

The fuse needs to be able to handle the current that the inverter draws. If the inverter is rated for 2,000Watts, you need to know the amount of current that flows through the wire. For a 12 Volt system:

$$\text{Current} = \frac{2{,}000\text{W}}{12\text{V}} = 166.6 \text{ Amps}$$

There will flow a maximum of 166.6 Amps trough the wire if the inverter uses 2,000 Watts of power. Select the wire diameter and choose the correct fuse that goes together with the wire diameter.

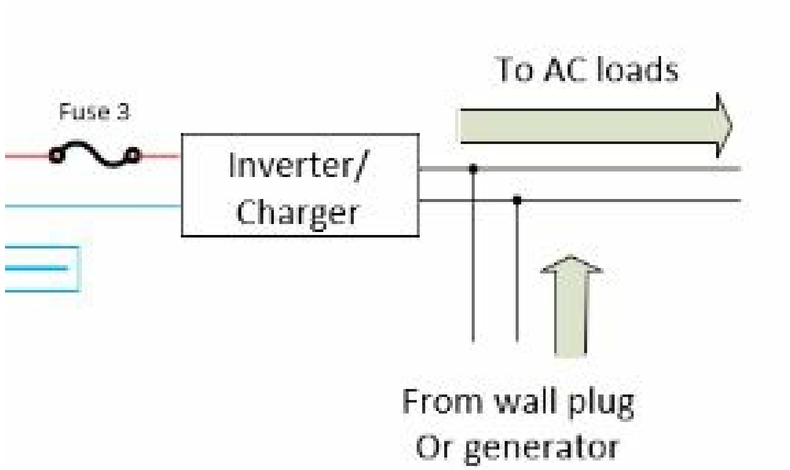
If you do not want to wire directly from the batteries, I recommend installing a busbar. The following image shows how to wire the busbar.



Wiring the inverter to a busbar

In this case, the size of fuse two and three will be the same. If there are no other loads attached, it's enough to use only fuse 2. However, if you are going to expand your system with a DC fuse box, the size of fuses two and three will not be the same.

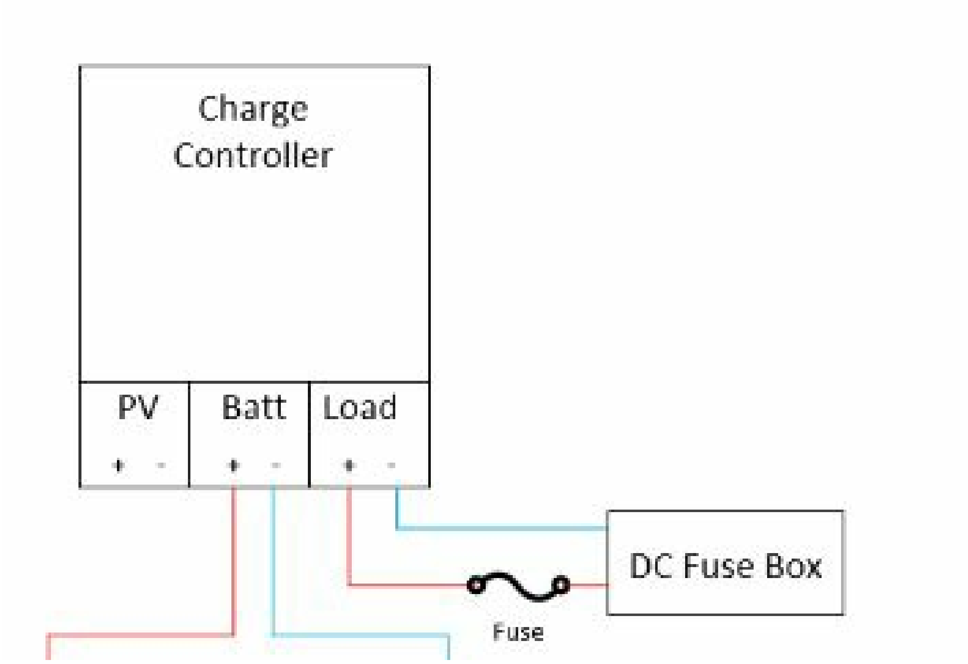
If you choose an inverter/charger, install the AC input plug that can accept shore power or power from a generator.



Installation of inverter/charger

7. **DC fuse box**

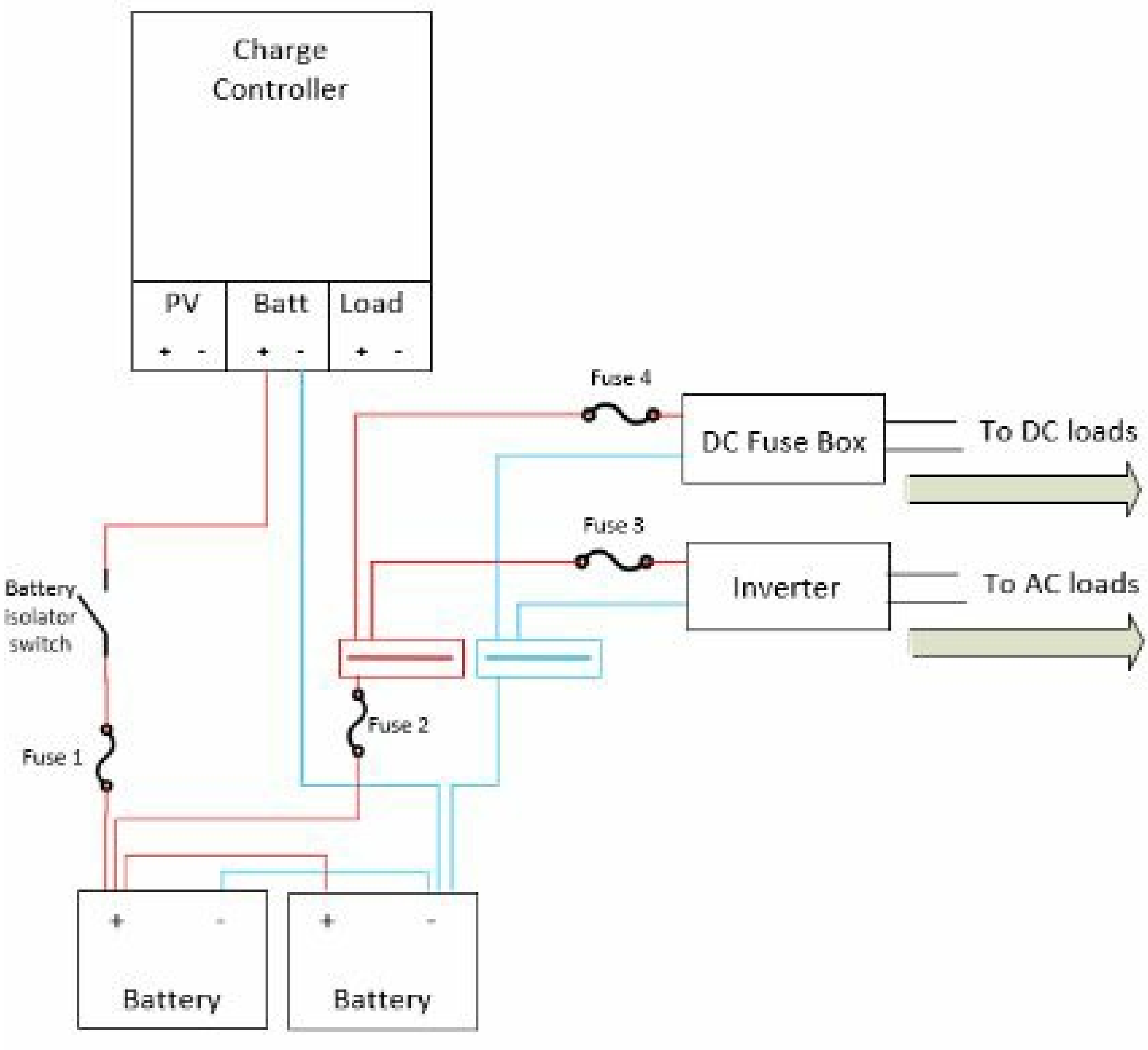
You can connect the DC fuse box using the load terminals of the charge controller.



Connecting the DC fuse box

However, if the output terminals can only supply 20 Amps, you will be limited to $12 \text{ Volts} \times 20 \text{ Amps} = 240 \text{ Watts}$.

This can be a problem, especially if you have a lot of DC loads. Therefore, I recommend connecting the DC fuse box to the previously installed busbar, or the battery terminals.



Connecting the DC fuse box to the busbar

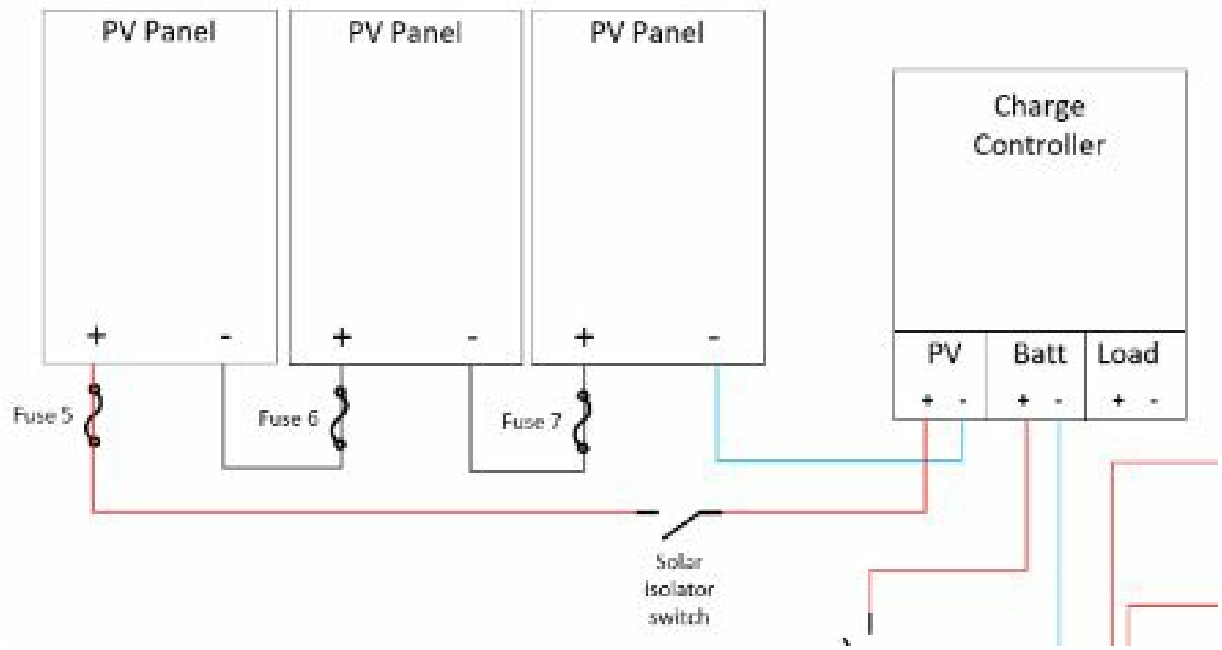
In this case, fuse two and three won't be the same. You must calculate the maximum AC load and DC load using your load estimation and select the correct fuse for each. Add up both fuses three and four to know the value of fuse two.

8. Install the solar panels

Whether you have decided to install rigid or flexible solar panels, you need to secure them to the roof. In case they are rigid solar panels, use the available holes in the back frame to drill the roof and place the screws and bolts to secure the panels. In case you use flexible modules, you can use adhesive materials.

9. Wire the modules

Check the chapter 'Series and parallel connection' of the solar panel section to understand how to wire the modules properly.



Connecting 3 panels in series

In this example, the panels are fused using inline MC-4 fuses (fuse 5, 6, and 7). The solar string can be disconnected using the solar isolator switch if maintenance is required. Try to place the switch in a location where you can easily get to, preferably close to the charge controller.

The cable entry plate is a device that allows you to safely connect the output of the solar panels from the outside to the inside of the RV. Make sure to use enough sealant to protect your roof from leaking water during rain.


Solar cable entry plate

10. Install the B2B charger

If you would like to charge the solar battery using the car battery, install the battery to battery charger. Refer to the wiring scheme given in the ‘B2B charger’ chapter.

11. Testing

Congratulations, you have completed the solar system installation. Now you can run some tests. Testing includes:

- Checking for loose wires.
- Checking for sharp edges that can cut your cables.
- Monitoring the temperature of components.
- Monitoring the temperature of the wires.
- Checking the battery voltage when fully charged.
- Testing loads.

Recommended Brands

Epever

Epever is a Chinese company established in Shenzhen that manufactures charge controllers and off-grid inverters.

Available charge controllers can either be MPPT or PWM based, and their outputs can go from 10A to 60A. On the other hand, the inverters of the brand are pure sine inverters type.

Rich Solar

Rich Solar is a popular American-based company dedicated to supplying off-grid solar equipment for RVs, agriculture, housing, marine, light, and heavy industrial equipment.

The brand manufactures solar panels (both rigid and flexible), charge controllers (both MPPT and PWM), inverters, solar lights, accessories, and sells pre-assembled solar power kits.

Victron Energy

Victron Energy is a company from the Netherlands that is one of the top brands available in the market for off-grid applications. Actually, not only for the off-grid market but also for home-based and commercial systems.

This brand offers multiple component options such as inverters, lithium batteries, charge controllers, solar panels, battery isolators, battery combiners, auto-transformers, and much more.

Batteriesplus

Batteriesplus is another valuable brand with over 20 years in the market that can be used if you are looking for reliable sealed lead-acid RV batteries.

Renogy

Probably the most valuable option in the off-grid market for RVs is Renogy. An American-based company that manufactures charge controllers (PWM and MPPT), pure sine wave inverters, deep cycle, lithium-ion phosphate batteries, and solar panels (flexible and rigid). You can also look for foldable solar suitcases and pre-assembled kits.

Conclusion

This book has the sole purpose of providing you with information to establish your solar power system.

I hope this book has accomplished that purpose.

Never forget that the safety of you and the people around you should be priority number one. Take extreme care when working with tools that are not insulated. A wrench that falls on the battery bank that shorts out the terminals will create a big spark that could hurt you and the people around you.

Having said that, enjoy the process of making your own solar system from scratch. If you are unsure about certain things, contact a licensed electrician for more information.

Take care,
Nick

Can you do me a favor?

Thank you for downloading and reading my book.

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