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MOBILE SOLAR POWER

Design and Install Your Off-Grid Solar Power System for RVs, Vans, Boats and Off-Grid Homes

Mobile Solar Power

Easy Guide for Powering RVs, Vans, Boats, Cabins and Off-grid Homes

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Our current crisis of unsustainability is not an inevitable result of human nature but is culturally driven- a product of particular mental patterns that could conceivably be reshaped.

Our future will possibly see a coming struggle between two contrasting views of humanity: one driving to a technological endgame of artificially enhanced humans, the other enabling a sustainable future arising from our intrinsic connectedness with each other and the natural world.

This struggle is one in which each of us will play a role through the meaning we choose to forge from the lives we lead.

- *Jeremy Lent*

Dedicated to my family and friends for their unending love, support, and wisdom

Disclaimer

This book is intended for educational purposes, to introduce beginners and enthusiasts to solar power systems and provide knowledge for planning and installing their own solar power systems. It is imperative to maintain all safety standards, local regulations, permits, and electric code for design and installation. Solar power systems just like any electrical system can present several risks during or after installation- so, safety should be the absolute priority for yourself and others around. Improper use or handling of electrical components or tools may be injurious or even fatal. Therefore, make sure you take the time to fully understand all the aspects, safety practices, and complexities of a solar power system before thinking of installing your system. The authors have presented all the information to the best of their knowledge and experience but it is ultimately up to the readers to pragmatically put this into practice. So, the authors disclaim liability for any risks, losses, or damage in connection with the book. Any action that the readers may take upon the information contained in this book shall be entirely at the readers' own risk. Note that each location or site may present unique issues that are beyond the scope of the book- but needs to be addressed. If you have no prior experience or face doubts, we recommend you to consult with an expert or professional before performing design and installation work. The author, Sitav Bhadra, will also be available for consultation and design services (see About the Authors section).

Table of Contents

1 Introduction

We are truly in the midst of entering the Solar Age. With rapidly advancing technology followed by monumental drops in prices- solar photovoltaics (PV) have made their mark across the world over the last decade. In several countries, the price of solar power has dropped even below that of coal, oil, and gas. This means solar power should be favored above dirty fossil fuels not only for environmental reasons- but also because it is cheaper and more profitable to use solar power!

Solar power systems come in various shapes and sizes. Broadly speaking, there are two types of solar PV systems: **on-grid** and **off-grid** . On-grid solar systems work together with the grid. While off-grid systems work independently from the grid but include a battery to supply power at night.

This book focuses on two types of off-grid systems:

Mobile Solar Systems : Solar panels can be placed on your vehicle's roof to power the electrical appliances inside. You could install these systems on a wide range of vehicles including cars, vans, recreational vehicles (RVs), and boats.

What are the benefits?

✓ *Significant savings!* Since solar power is cheaper than gasoline and grid electricity, you could make long-term savings on energy costs.

✓ *Get power anywhere!* All you need is some sunshine on your solar panels and you're good to go. You no longer have to keep running to a fuel station or charging point to get your power back.

Off-grid Solar Home Systems: These systems are ideal for homes and cabins which have no access to the grid. You will be able to power your holiday home in the woods, up on a mountain, or in any remote location. These systems are also the top choice for urban homeowners who wish to be independent of the grid.

What are the benefits?

✓ *Start living a self-sufficient life!* By producing your own *power* , you no longer need to depend on the grid or fuel for your electricity needs.

✓ *Skip the generator!* With solar power around, you don't need a loud and dirty generator running all the time. You also skip traveling long

distances to buy generator fuel.

- ✓ ... *And of course* savings*!* Say goodbye to costly fuel and electricity bills.

This book will provide you with step by step instructions on how to build your own mobile solar or off-grid solar home system. You will learn about the design and installation processes, equipment, and tools needed. Supporting images and charts are presented at every step to make sure you have a smooth and hassle-free installation. The book requires no prior knowledge on solar- so even a complete beginner can enjoy learning and install their own solar system within a week!

2 Electricity Basics

Generating electricity is ultimately the point of having a solar PV system. But what really is electricity? If your answer is something along the lines of magic- you're not very far off! In fact, the first people to be called '*Electricians* ' were 18th century street magicians and conjurers. They travelled around Europe mesmerizing crowds with their ingenious tricks that involved electricity.

So, before we dive into solar power, it would be useful to understand the basics of electricity. We will learn essential concepts like voltage, current, resistance and polarity. We will also learn about polarity and the types of electricity.

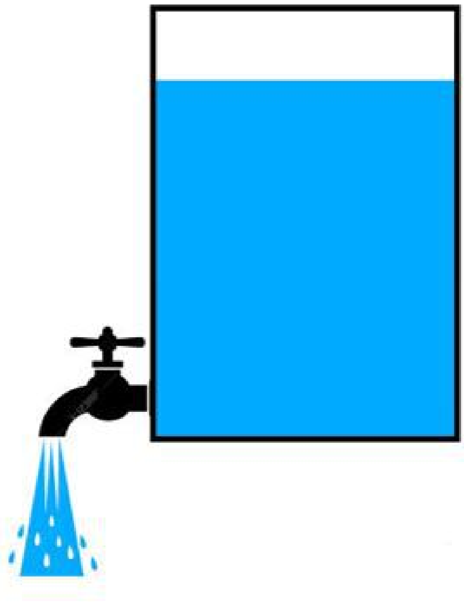
2.1 What is Electricity?

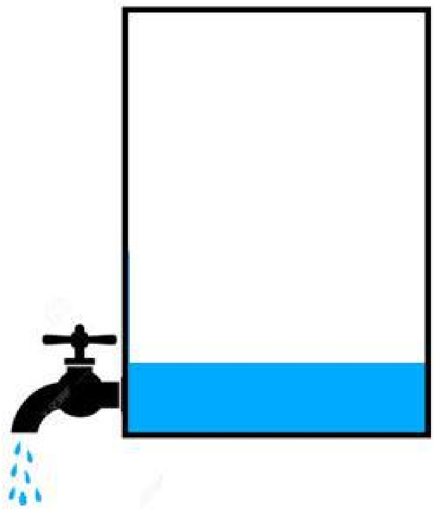
To understand electricity, let's imagine water flowing in a pipe. *Now* , just change one thing in the imagined picture- instead of water think of electric sparks flowing. That's it! Just like water, tiny sparkly electrons flow through cables to power up your lights and fans. That's electricity in a nutshell. Simple right?

Let's go through some important concepts to get a deeper understanding of electricity.

Voltage is simply the force that pushes the electricity around. In other words, it is the force that causes electrons to move from one point to another.

To picture voltage, let's think of a water container with a tap attached. As you can see in the illustrations, the higher the water level- the more water will be pushed out of the tap. And vice versa. Voltage is similar to the water level in the container- *i.e. voltage pushes out electricity, and a higher voltage level pushes out more electricity.*





Current is the amount of electricity (electrons) flowing through a material. Current flows through a conductor whenever there is a voltage present across two points of the conductor.

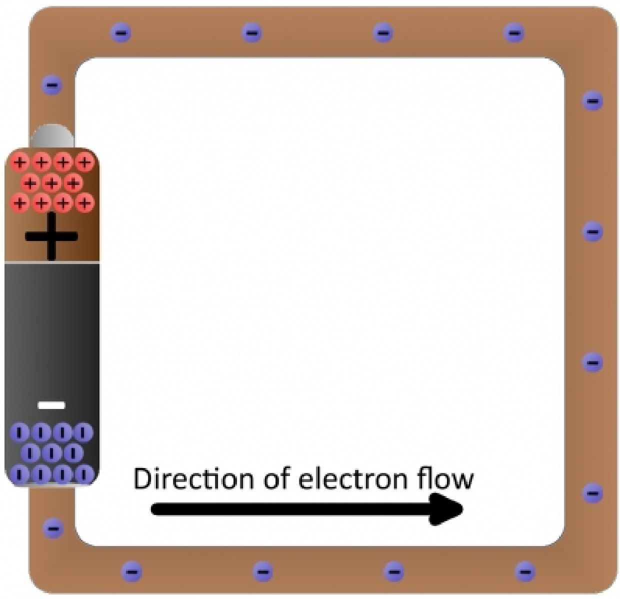
Let's again look at the water tank example. Electric current is similar to the *amount* of water flowing out of the tap. We can also infer that higher voltage leads to higher current.

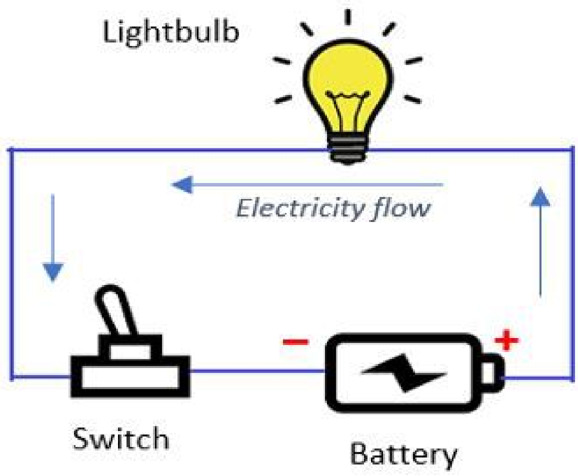
Resistance is the opposition to the flow of electricity. To understand resistance, let us think of the tap attached to the water tank. When we open the tap fully, water splashes out in large amounts. However, when we start closing the tap slowly, there is more opposition to the flow. This results in less water flowing out. That's how resistance works. A material

with higher resistance will oppose the flow of electricity, and reduce the amount of electric current flowing through that material.

What is Polarity?

There are two types of electric poles- positive (+) and negative (-). The – pole has more electrons and is in a negative state of electric charge. While the + pole has a lack of electrons making it have a positive state of electric charge. This difference in electric potential causes the electric current to flow from the + pole to the – pole. Electric potential difference is just another term to describe voltage. In other words, there is a voltage between the + and – poles.





Source: Spark Fun

Let us take an example of a battery to understand this. As you can see in the illustrations, electrons flow from the – pole of the battery to the +

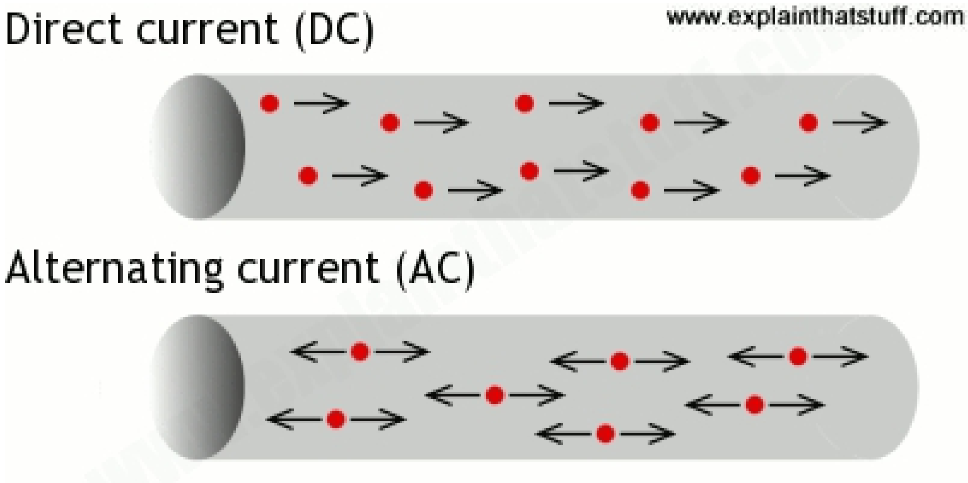
pole.

2.2 What are the types of electricity?

Let's quickly go through the two types of electricity since both are usually present in solar systems. At the same time, you will learn where the famous rock band **AC⚡DC** gets its name.

Direct current (DC) flows in one direction- like a river flowing down a mountain.

Alternating current (AC) does not flow in one direction but instead oscillates back and forth.



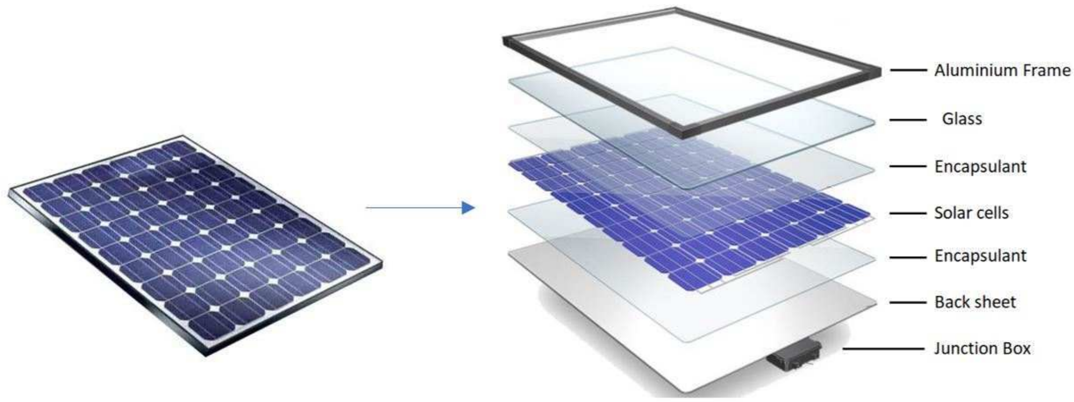
DC and AC Electricity Flow- *you can see the direction of flow of the electrons (red blobs). DC flows in one direction; while AC oscillates back and forth.*

Source: Explain That Stuff

3 Solar Power Fundamentals

Now that you're well acquainted with electricity and how it works, you are ready to be introduced to the world of solar power! In this chapter, we present the major components of a solar power system and their working principle. We will take a look at what's inside a solar panel, how a solar panel works and how a solar power system works.

3.1 What are solar panels made of?



Source: Trina Solar

In the illustration above we see the different layers that make up a solar panel. Each layer serves a special purpose-

Solar Cells: Solar cells are the heart of the solar panel. These little devices are made of special semiconductor materials that convert light energy directly into electricity. Commonly, silicon crystals are used to make solar cells. They can also be made from other materials such as cadmium, indium, and gallium.

Aluminum Frame: The aluminum frame holds all the layers of the solar panel together and helps protect the edges.

Glass: The glass protects the panel from the weather, dust, debris, and other pollutants. The glass is made of highly transparent and anti-reflective material to make sure the maximum amount of sunlight can pass through to the solar cells.

Encapsulant: The encapsulant holds the solar cells intact together in one place. It also serves as a layer of protection from moisture and dirt.

Back sheet: The back sheet is the rearmost layer of the solar panel. It acts as a final line of defense from moisture, dirt, and damage. It also provides electrical insulation for the panel.

Junction Box: The junction box is a small weatherproof enclosure located on the back of the panel. This is where cables are connected to get the electricity output.

3.2 How do solar panels work?

Simply put, when sunlight falls on solar panels- they convert it into electricity. Solar cells inside the panel are responsible for this conversion.

Let us take a deeper look at how this awesome technology works.

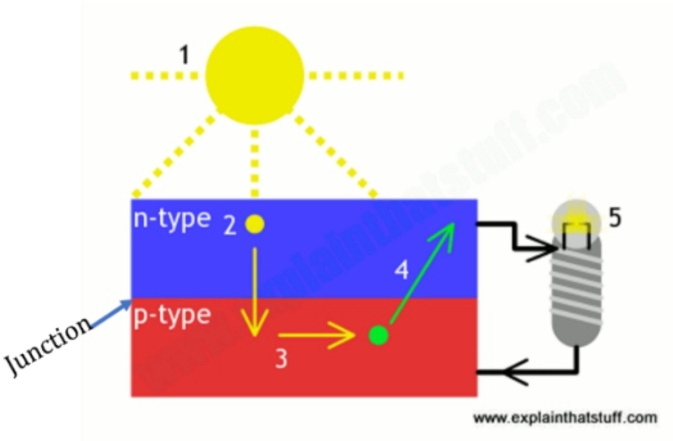
A solar cell is like a sandwich of two layers: n-type silicon (blue) and p-type silicon (red). Between the p-type and n-type layers, there is a junction. The n-type layer has an excess of negatively charged electrons. While the p-type layer has an excess of positively charged holes. This difference in electric charge, along with the energy from sunlight, creates a potential for the flow of electrons, explained as follows[1] :

1. When sunlight shines on the solar cell, light particles known as photons fall on the upper layer (n-type).

1. Explain That Stuff

2. The photons (yellow blobs) travel down to the lower layer (p-type).

3. The photons release their energy to electrons (green blobs) present in the p-type layer.



Source: Explain that Stuff

4. The electrons use this energy to jump across the junction into the upper n-type layer and move out into the output circuit.

5. Electrons flow around the output circuit giving us electricity for our usage.

3.3 Can we directly connect solar panels to our appliances?

Solar panels produce electricity but it’s not in a stable form. So, we should <u>not</u> connect solar panels directly to our appliances. We need a couple of components in between to make the electricity usable for our appliances throughout the day, as we will see next.

3.4 How does a solar power system work?

We’ve discussed how solar panels work. Now, we can look into how an overall solar power system works. We will also go through the other essential components involved.

So, let’s look at how an off-grid solar power system works in ***5 simple steps*** -

1. Solar panels produce electricity

The solar panels produce electricity during sunlight hours as we have discussed earlier in this chapter.

2. Batteries to store electricity

The electric grid is not available for off-grid solar systems. So how do we get power at night when there is no sun? You guessed it- batteries!

During the day, some of the electricity produced by the solar panels is stored in the batteries. The batteries then supply this stored power to our appliances in the evening and at night.

3. Charge controller to protect batteries

Solar panels produce a high electric current when the sun is shining in all its glory. This excess electricity can damage our batteries. For this reason, we need a nifty little device called a charge controller to make the electricity safe for the batteries.

4. Inverter for AC appliances

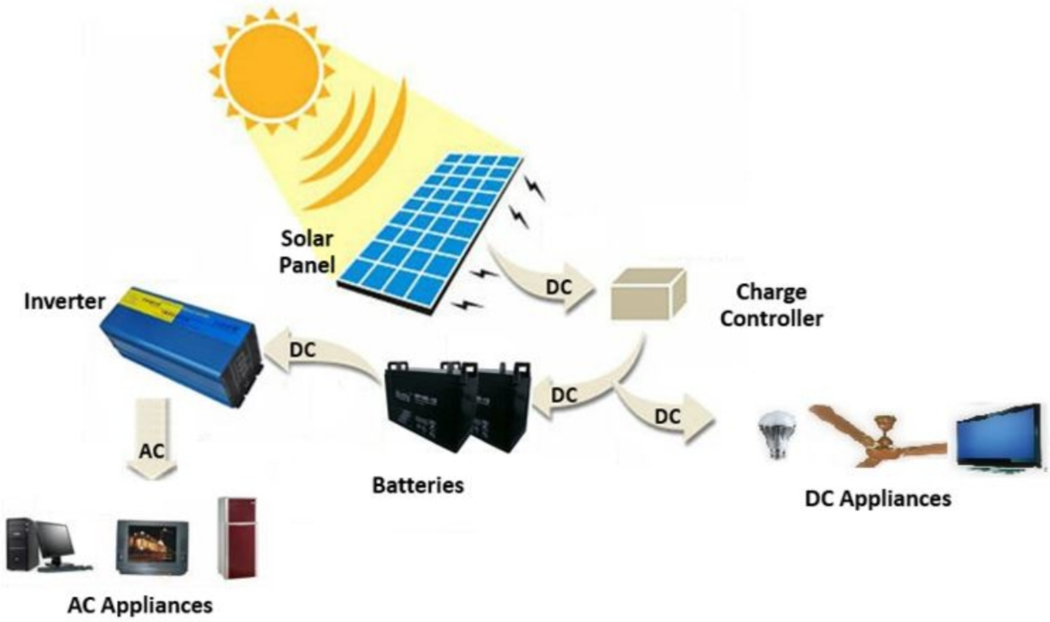
Remember AC⚡DC? Well, solar panels (and batteries) produce DC electricity while our common appliances need AC to work. Now how do we make our AC appliances use this DC electricity? The answer is a wonderful device called an inverter! An inverter can instantly convert DC to AC and feed it to our appliances.

5. What if I have DC appliances?

With solar power becoming more and more popular, we have various DC appliances hitting the market. Unlike AC appliances, we don’t connect

DC appliances to the inverter. Instead, we connect them between the charge controller and batteries.

Now, let's put the 5 simple steps together… and we get an off-grid solar system! –



Source (modified): Medium

4 Off-grid Solar: Applications, Challenges and Solutions

In the last chapter, we saw how off-grid solar works as well as the different components involved in such systems. In this chapter, we will look further into off-grid systems and their applications. We will also review the unique challenges of off-grid systems and how we can overcome them.

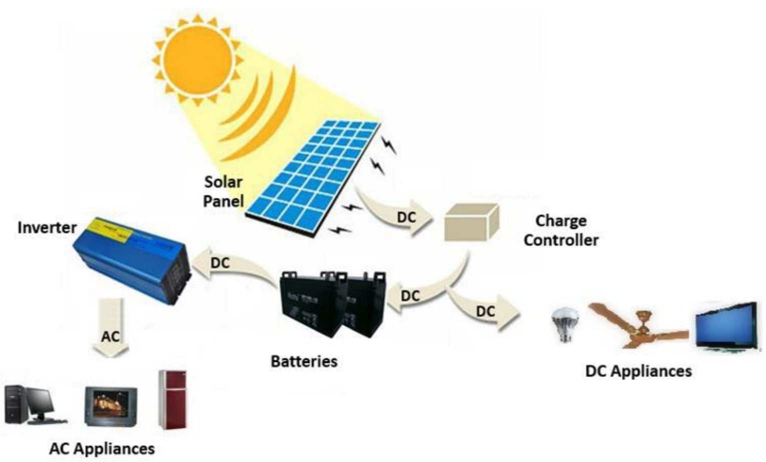
Before we dive right in, let us understand how off-grid systems are different from their on-grid counterparts.

4.1 How are off-grid systems different from on-grid systems?

On-grid means your solar system is connected to the electric utility grid. When the solar system is not producing enough energy (e.g. on cloudy days or at night), electricity from the grid is used.

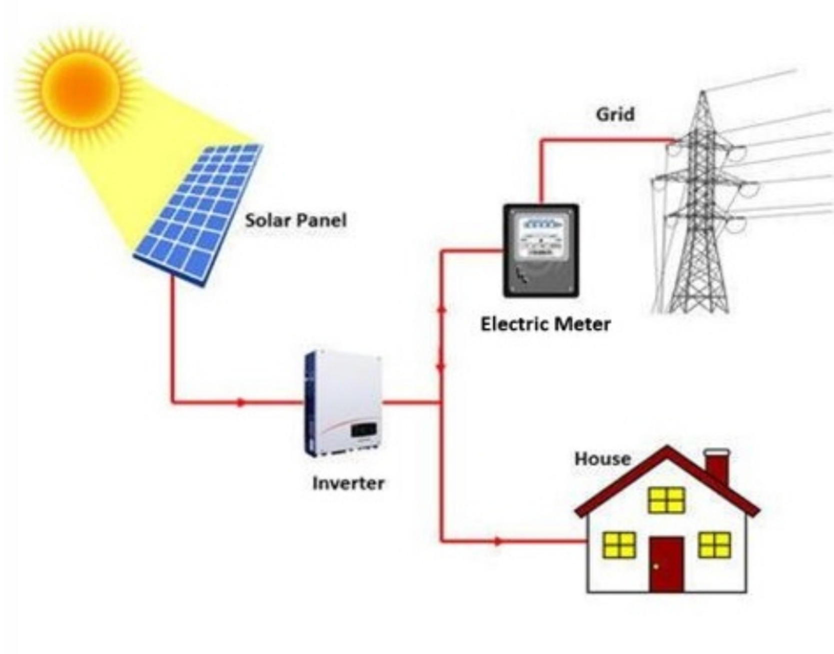
Being off-grid means you are not connected to the electric grid in any way. All your electricity needs are supplied by the solar system. This is great because you are fully self-sufficient for your electricity needs. However, being off the grid means we need batteries to supply electricity during cloudy days and at night.

We can see the types of connections and components involved in the two types of systems in the illustrations below.



On-grid Solar System

Source: Engineering Dost



Off-grid Solar System
Source: (modified): Medium

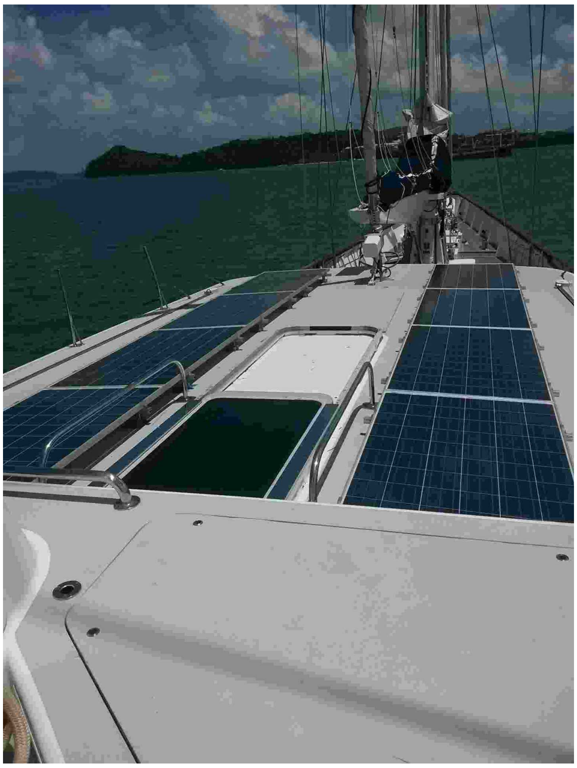
4.2 Off-grid Solar Applications

We can benefit from off-grid solar systems in a variety of applications. Recreational vehicles (RVs), campers, vans, cars, and boats are examples of mobile systems. Off-grid solar is also useful for powering cabins and homes located in remote off-the-grid locations. Other applications include solar street lights, solar water pumping and irrigation, electrification of rural or remote settlements, and emergency power supply after natural disasters.

RVs, Campers and Vans!

Source (clockwise): Northern Arizona Wind & Sun; Precision RV;
The Homestead Survival; Ruhls of the Road; Xconomy

Boats!



Source: Soel Yachts; Aequus Boats; Monosun Technology

Homes and Cabins!

Source: Green Mountain Energy; Mark Landry; Eco Home

4.3 Benefits of Off-Grid Solar

Going solar can have a wide range of benefits ranging from financial gains, to health, wellbeing, and environmental benefits. Let us look in more detail at what exactly makes energy from the sun so wonderful.

- ✓ ***Savings!:*** First, of course, is the significant money saving. A solar system requires us to invest money upfront, but once it's up and running- it generates free electricity for over 25 years. Alternative means such as gasoline engines and diesel *generators* have an upfront cost and ongoing costs of purchasing fuel. Along with this, the prices of both grid electricity and fuels are ever-rising. The maintenance costs for diesel generators are much higher than solar systems. Going solar will make sure you cut down on all these expenses for the next 25+ years!
- ✓ ***Self-sufficiency!*** By choosing to go solar, you will start leading a self-sufficient and sustainable life with regards to energy. Producing your own power means you no longer have to depend on the public electricity grid or fuel suppliers. You are safe from power outages, unreliable grid supply, and rising costs. Solar power unlocks a host of other opportunities such as being able to power your own farm or business at cheaper electricity prices. Going solar can truly be an essential step to achieving economic freedom!

- ✓ ***Quiet operation!*** Peace and quiet are vital for our health and well-being. It can even help boost our productivity and creativity. Whether you are at your home, relaxing in your mountain cabin, *sailing* your boat, or lounging in your RV- having a loud generator running is really the last thing you would want. One can entirely skip this noise and find solace in a silent solar power system!
- ✓ ***Clean surroundings!*** Generators and engines are not only loud but they are *dirty* too! They will keep spewing out harmful and polluting gases the whole time they are running. Again, why would one even consider having toxic gases around their home or vehicle? Switching to solar would mean you have clean air and a pollution-free space. Of course, using renewable and emission-free energy has even wider benefits towards climate change and the planet's environment.
- ✓ ***Get power anywhere, anytime!*** By having a solar system around, you can get power virtually anywhere where there is sunshine. You don't have to keep running to a fuel station or charging point every time your generator runs out of fuel. Who really wants to lose power (and sleep) in the middle of the night? Also, if you happen to be in a remote location, this could mean traveling for hours and hours trying to find fuel. Secondly, you can also safely generate electricity and charge your battery with solar power while you're away from your weekend getaway cabin or boat. This isn't possible with generators – running a generator requires manual operation and monitoring. With solar panels, you can produce usable electricity during the week and then use it for your weekend adventures.

4.4 Main challenges and how to succeed?

Off-grid systems might present some challenges related to initial costs, space limitations, and energy availability. The good news is all these challenges can be easily addressed if we are mindful of a few best practices. As we will see, we really don't need to sacrifice our energy use, lose our comfort or spend obscene amounts of money for off-grid living.

Let us first understand the challenges.

Challenge 1- Initial Costs: As we discussed earlier in this chapter, off-grid systems have to fully supply your electricity needs. Thus, the amount of electricity you use on a daily basis will determine the required size of the solar system (solar panels, batteries, inverters, etc.). So, the

size of the system and therefore its cost will depend on the amount of electricity it needs to supply. We can keep these costs low as we will see in detail in the solutions.

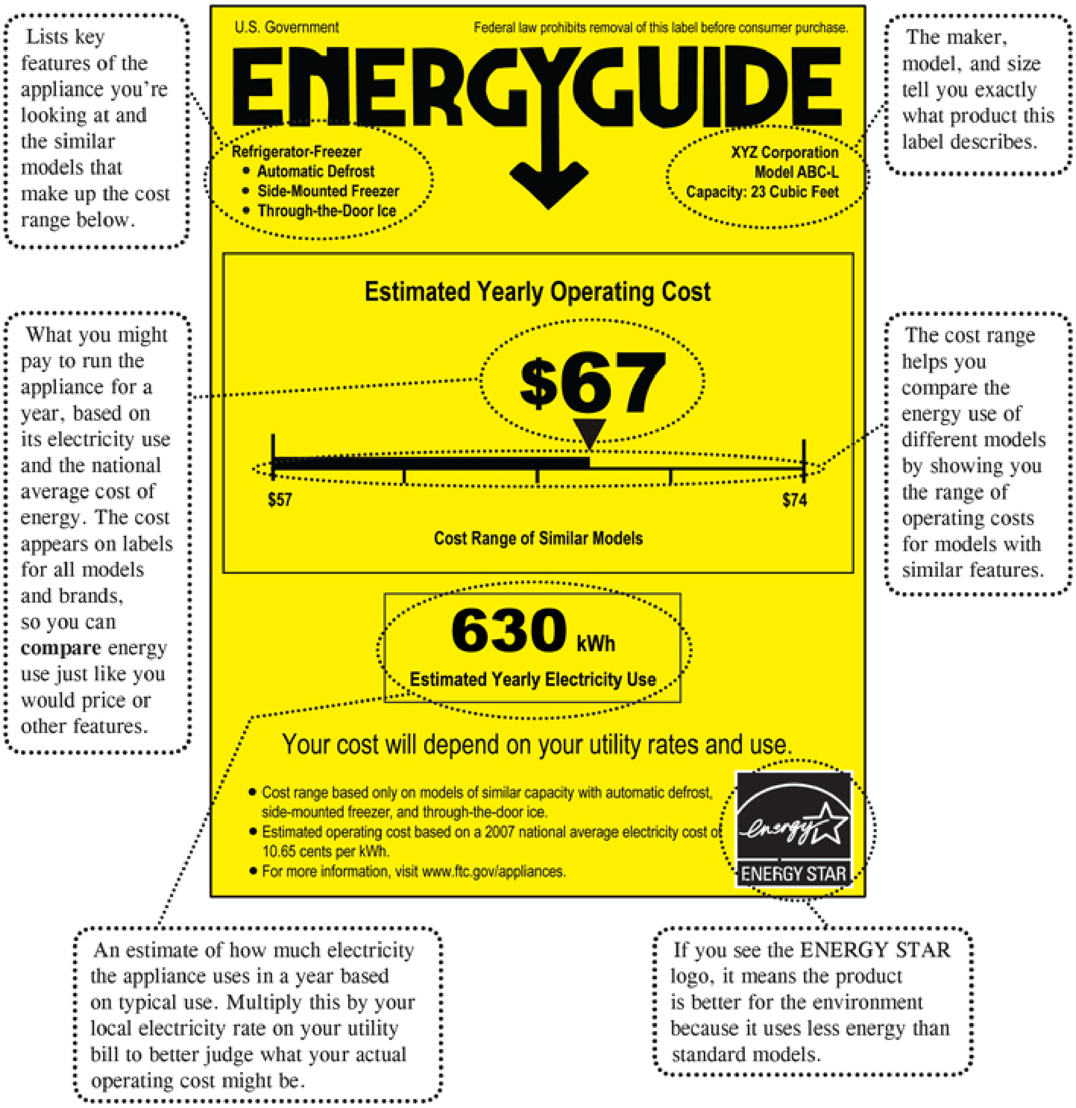
Challenge 2- Space Limitations: The maximum number of solar panels you can accommodate depends on the space available on the roof of your vehicle or home. So, the available space you have will define how much solar electricity you can produce. This issue needs more attention when it comes to mobile solar systems as we cannot go beyond the vehicle's roof. For homes and cabins, we could potentially place solar panels in the surrounding land. We will look at how we can easily get a system that fits in the solutions.

Challenge 3- Energy Availability: We all want energy to be available when we need it- whether it is for essential activities or for entertainment. As you can imagine, being out of power can make life difficult and uncomfortable. By being smart about our energy use, we will never have to worry about being out of power as we shall see next.

Now, let's look at the **solutions** which can smartly address the above challenges.

Solution 1- Switch to Energy Efficient Appliances: Energy efficient appliances can get the job done by using comparatively less energy. In the USA, energy efficient appliances have an ENERGY STAR rating on their Energy Guide Label. Similar ratings are provided in several other countries as well.

Replacing old TVs, fridges and other appliances with high efficiency ones can work wonders. They can bring down our energy use and therefore the size of the solar system. This obviously means our solar system will be cheaper and likely to fit on your roof!



Reading the Energy Guide Label of an Appliance
Source: US Federal Trade Commission

Solution 2- Switch to LED Lights: Traditional incandescent light bulbs are horrible when it comes to energy use, wasting lots of energy as heat. Using LED lights instead can save up to *75%* energy! This is huge considering we use lights daily for several hours. You can already guess that these energy savings translate to a smaller and cheaper solar system! Moreover, LED lights don't need to be replaced often- they last much longer than incandescent lights and CFLs.

Incandescent light (left) vs LED light (right)

Solution 3- Make the Most of Daylight: Why switch the lights on when we can have beautiful sunlight coming in through the windows and skylights? Daylighting is simply the use of natural sunlight to illuminate your space in the daytime. As simple as it sounds, using daylight instead of electric lights can lead to significant savings in energy and costs.

Solution 4- Use Energy Smartly: There are several simple ways to use energy in a smart and planned manner. The following practices will ensure savings in *energy, costs, and space* ! -

✓ *Stick to the plan!* Off-grid solar systems are designed to power a planned list of appliances for a particular amount of time every day. We should not add new appliances or use existing appliances for more time than they were planned for. This could lead to power unavailability unless we cut down on energy use elsewhere.

✓ *Always remember to switch off and unplug!* This simple mantra cannot be emphasized enough. Always switch off lights, fans, TVs, computers, and other appliances when they are not being used. Chargers for laptops and cellphones should be kept unplugged.

✓ *Keep refrigerators away from heat!* Refrigerators and freezers should not be located near the stove, exposed to direct sunlight or other heating elements. Exposing refrigerators to heat will force them to use more energy to remain cool.

✓ *Go for efficient shower heads and toilets!* This is useful when a water pump is connected or planned to be connected to the solar system. By installing low-flow shower heads and toilets, we can reduce our water consumption by up to *40%* ! This means the pump has to operate for shorter times *(= savings!)*.

- ✓ *Manage your water pump!* The pump operation can be controlled with a level switch in the storage tank and possibly with a time switch to limit pumping to certain hours. This will make sure the energy-guzzling pump does not run more than it has to.
- ✓ *Go for timer switches!* Timer switches can automatically switch off lights and appliances during a preset time or period to make sure no energy is wasted.

5 Solar System Components: Overview and Buying Guide

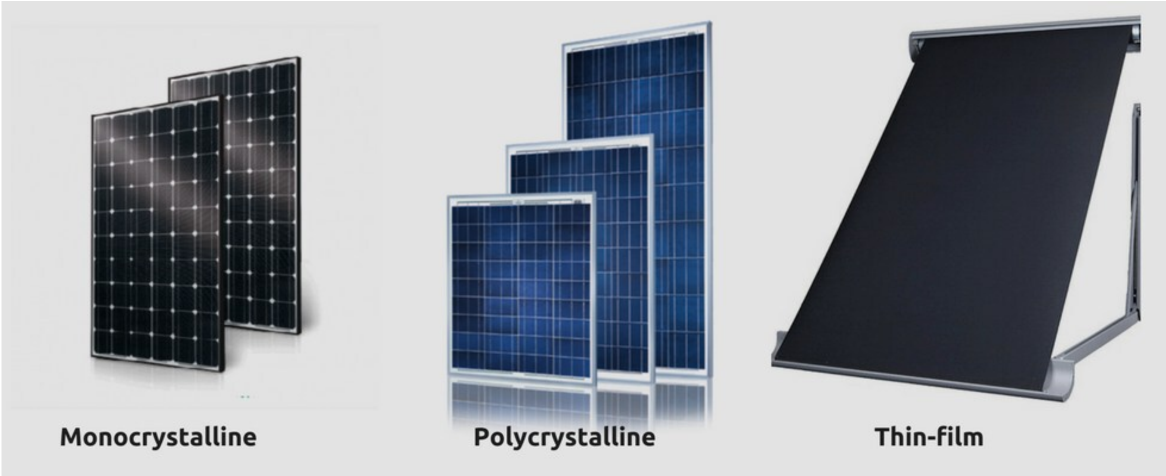
By now we are well versed in the working mechanism, applications, challenges, and best practices of off-grid solar systems. To fully prepare us for planning and installing solar systems, it would help to look in a bit more detail at the components involved. We will also provide tips on how to choose and buy the right components for your system.

5.1 Solar Panels

We've seen how solar panels are the powerhouses of solar systems. Here, we will go into more details about the available panel technologies and which ones to buy.

There are mainly two types of solar panel technologies available on the market- crystalline silicon and thin film.

- **Crystalline Silicon Panels:** So far, crystalline silicon panels are the most common, making up about 90% of the panels we see. Crystalline panels are available in two forms- monocrystalline and polycrystalline (also known as multi-crystalline). Monocrystalline panels are more efficient and therefore more expensive. Since they can produce more power per panel- they are particularly useful when space is limited. For all other cases, polycrystalline panels will do just fine.
- **Thin Film Panels:** Thin film panels are generally less efficient than crystalline panels. However, these panels are well suited for low lit or shaded areas. They would work well on a cabin heavily shaded by trees for instance. There are several thin film technology options available on the market, including cadmium telluride (CdTe), copper indium gallium diselenide (CIGS), and amorphous thin film silicon (a-Si, TF-Si).



Source: Save Geo

There are a few pointers to keep in mind before we buy solar panels (or any component for that matter). It always helps to do a bit of research online on reputed brands. It’s also a good idea to create a shortlist of panels before running to the store or ordering online.

Warranties for the product and performance are also key points to consider for panels. A solar panel’s performance warranty typically guarantees 90% production after 10 years and 80% at 25 years of use. Product warranty will typically guarantee 10-12 years without failing.

Certifications are also a good measure to make us confident about our choice. There are international institutions that test and certify solar components based on performance, durability, reliability, and safety. These certifications will be available on manufacturer websites, brochures, or can be requested from the shop. Below is a list of the main panel certifications to look out for -

IEC 61215 – Durability testing for crystalline silicon panels.

IEC 61646 – Durability testing for thin film panels.

IEC 61853 – Performance and energy testing.

IEC 61701 – Salt mist resistance test. Required for solar panels being installed near the coast.

5.2 Mounting System

How do we make sure your solar panels don’t get blown away by strong winds or fall off the roof as you drive your RV or boat? Well with the mounting system of course!

Mounting systems are used to hold solar panels in place and fix them to surfaces. Mounting kits consist of rails, structures, and other hardware

that hold and attach the panel. They are typically made of aluminum or steel but other materials such as wood can also be used.

The choice of the mounting structure depends on the surface on which you want to mount your panels- on your vehicle, roof of your house or cabin, or on the ground.

Choosing mounting structures is comparatively less involved. We just need to ensure that they are of good quality, made of sturdy materials, and have a decent warranty. There are also some weather and structural considerations to be looked at- more on that later.

Let us look at some examples of mounting structures for vehicles and homes.

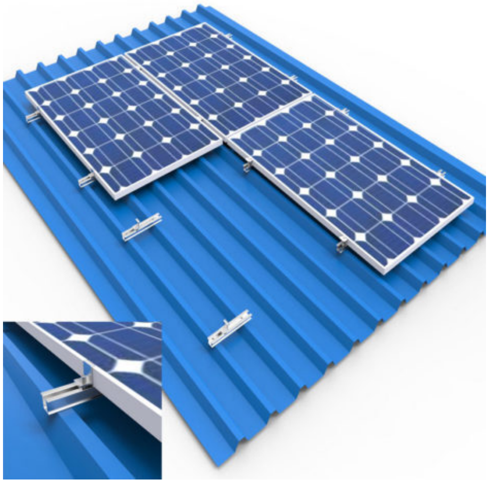
RVs, Campers and Vans!

Source: Wanhos Solar; Build A Green RV

Boats!

Source: Coastal Climate Control; Teal Tales

Roof-mount!



Source: Wanhos Solar; Solar Parts Components

Ground-mount!

Source: Shift Energy Group

5.3 Batteries

We know by now that batteries are very important for off-grid systems as they store power for the periods with no sunshine.

There are commonly two types of batteries used with solar- lithium-ion batteries and lead acid batteries.

- **Lithium Ion Batteries** are the current state-of-the-art battery technology for solar applications. They are superior to lead acid batteries when it comes to efficiency, capacity, and lifespan. Lithium ion batteries are also smaller in size and weight and require no maintenance. For these reasons, they are more expensive. However, this extra cost is justified by their longer lifespan and other benefits. Lithium ion batteries can last for over 10 years while lead acid batteries last for 3 to 5 years.

- **Lead Acid Batteries** can further be of two types- **Flooded Lead Acid (FLA)** and **Sealed Lead Acid (SLA)** . FLA batteries are cheaper compared to SLA. But the drawback is that FLA batteries require regular maintenance while SLA are maintenance-free. SLA batteries are also known as valve regulated lead acid (VRLA)

Lastly, *SLA* batteries themselves can be of two types- **Absorbed Glass Mat (AGM)** and **Gel.** The main difference is that *gel batteries* cannot handle as much current, which means they output less power and take longer to charge.

Which type of battery should I choose?

- For regular and heavy use applications such as full-time off-grid residences or mobile homes, lithium-ion batteries are recommended. If you are looking for less expensive options and you're fine with the lower lifespan and high maintenance, flooded lead acid batteries can be used instead.
- For smaller systems that aren't used regularly such as off-grid cabins, vacation homes, or campers, sealed lead acid batteries will do just fine.

IEC 61427 and **IEC 62093** certifications are the ones to look for while choosing reliable batteries tested for solar applications.

Lithium ion batteries (left to right) by Tesvolt, LG and Tesla

Lead acid batteries (left to right) by Champion, Exide and Ritar

5.4 Charge Controllers

As we briefly discussed in chapter 3, charge controllers are essential electronic devices that protect the battery. They prevent the battery from overcharging or over-discharging by regulating the electric current entering or leaving the battery. Without a charge controller, a battery’s lifespan can be severely shortened.

Charge controllers also perform other essential duties. They are responsible for efficiently extracting power from solar panels. They also prevent any harmful reverse flow of current from batteries to the solar panels that may occur at night.

There are two types of charge controllers- PWM and MPPT explained as follows...

- **Pulse Width Modulation (PWM)** charge controllers are simpler and cheaper compared to MPPT. They work by slowly reducing the amount of power flowing into the battery as it approaches full charge. Typically, the choice of solar panels that are compatible with PWM controllers is usually limited to low power and low voltage solar panels.
- **Maximum Power Point Tracking (MPPT)** charge controllers have added advantages and hence, are more expensive compared to PWM. MPPT controllers can adjust their input to ensure the maximum possible power is extracted from the solar panels. This makes MPPT controllers 10-20% more efficient and effective compared to PWM. We can also use higher voltage and higher power solar panels with MPPT controllers.

Which type of charge controller should I choose?

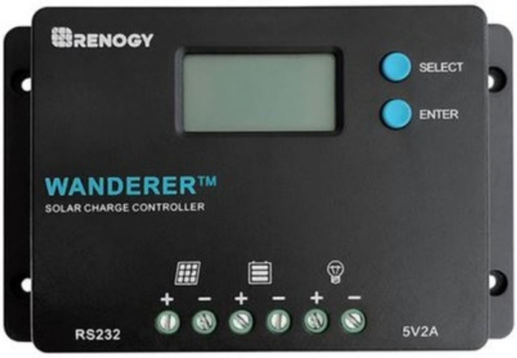
- With PWM controllers, the solar panel system and the battery need to have matching voltages. This is usually the case for small solar systems. So PWM controllers are more

suited for small solar systems with a couple of solar panels and a small battery.

- In larger solar systems such as for a home or an RV, the panel and battery voltages won't be the same usually. For this reason, MPPT controllers are preferred for larger systems.

Sometimes, charge controllers are integrated with the battery or inverter. Otherwise, they need to be bought separately. When choosing a charge controller, make sure to ask your supplier if it is compatible with your chosen battery or inverter.

IEC 62509 and **IEC 62093** are the international certifications for the design and performance of solar charge controllers.



PWM Controller by Renazogy
MPPT Controller by Victron Energy

5.5 Battery Monitor

Battery monitors are very useful little devices that tell us the state of charge of the battery. They can show us the remaining solar battery charge percentage just like a cellphone displays the phone battery's remaining charge.

Battery monitors are sometimes included with the battery system or charge controller depending on the brand. Otherwise they need to be purchased separately. So, when you go to buy, confirm the following points with your supplier or from websites-

1. Is a battery monitor included with the battery system, charge controller, or inverter?
2. If it is to be bought separately, confirm the compatibility of the battery monitor with the battery you purchased or planning to purchase. If possible, choose the same brand of battery monitor as that of the battery or charge controller.

Battery Monitor by Simarine

5.6 Inverters

Let's look at another important component used in solar systems- the inverter. The main job of the inverter is to convert DC electricity into AC electricity which is used by common appliances.

As we discussed in the first chapter, AC and DC are rather different and cannot be mixed with one another. So, inverters have a separate DC side and an AC side. The DC side connects with the solar panels, battery, charge controller, and DC appliances. While the AC side connects to AC appliances.

There are different types of inverters based on the functions they serve. Let us have a look at the different types of inverters.

- **Off-grid or Stand-alone Inverter:** As the name suggests, these inverters work independently from the grid and can be connected to batteries. They are suitable for both vehicle and home applications.
  Many off-grid inverters include the **Inverter/Charger** function.

With an inverter/charger you can charge your batteries using AC sources such as shore power or backup generators (in addition to charging batteries from solar).

- **On-grid or Grid-tie Inverter:** This type of inverter works in parallel with the electric grid. They are the most common type of inverters found on the market and used in residential, commercial, and utility-scale solar systems. However, they are not suitable for off-grid applications as they cannot function without a grid connection.
- **Hybrid Inverter:** Hybrid inverters combine the advantages of both off-grid and on-grid inverters. They can function both with and without the grid. For this reason, they are more expensive than the other two types.

Hybrid inverters are useful for homes or other buildings wishing to use solar power together with the grid and batteries.

IEC 62109 and **EN 61000** are certifications to look for in inverters.

Inverters by (left to right) SMA, Solax Power, Victron Energy and Alpha ESS

5.7 Cables and Wiring

It’s safe to say that we cannot have an electrical system without cabling. We need cables to connect one component to another to allow electricity to flow between them. As solar systems are exposed to outdoor conditions, special attention is required for cables.

Cables can come with different types of wiring- single-core, multicore, and multi-strand. We recommend you use multi-strand cables for solar systems as they are more flexible and easier to work with.

In terms of materials, wires are made of either copper or aluminum. Copper wires are recommended as they are comparatively more efficient and thinner for any application.

Let us explore the types of cables used in solar systems.

- **Solar Cables:** Solar cables (also known as PV wires) are used to connect solar panels to the rest of the system via the DC Combiner Box. They are extension cables with one end

connecting to the solar output cable (built-in with solar panels) and the other end with the rest of the system.

What makes solar cables special? Well, they are weather-resistant and UV proof- meaning they can withstand the forces of nature. They can also endure a wide range of temperatures and have flame-retardant insulation.

Solar Cables
Source: Om Industries

- **THW Cables:** THW stands for Thermoplastic Heat and Water Resistant. They are suitable for indoor cabling.

These cables are used between the following components-

(i) DC Combiner box and Charge Controller

(ii) Charge Controller and DC Loads

(iii) Inverter and AC Distribution Box

(iv) Internal Wiring to the Loads

- **THWN-2 Cables:** The full name of THWN-2 is Thermoplastic Heat and Water-Resistant Nylon Coated. These cables are used to connect batteries to the system. Battery cables may be exposed to high temperatures and moisture as well as gases emitted by the batteries. Therefore, we need a more protected type of cable.

The nylon coating of THWN-2 cables provides added heat and moisture resistance, flame retardancy as well as protection from gases and chemicals.

These cables should be used in the following connections-

(i) Battery to Charge Controller

(ii) Battery to DC Junction Box

(iii) Battery to Inverter

(iv) Interconnections between batteries (when there is more than one battery involved)

Alternatively, *THHN* (Thermoplastic High-Heat Resistant Nylon Coated) or *XHHW-2* (Cross-Linked Polyethylene High-Heat and Water Resistance) cables may be used for the above battery connections.

Multi-strand cables
Source: Electrician Central

5.8 Cable Connectors

Cable connectors are vital to make proper cable connections between components. They ensure protection and safety for the exposed ends of the cable. When buying cable connectors, you must ensure the size of the cable connector matches the size of the cable you are planning to use it with.

Let us walk through the various cable connectors used in solar systems.

- **MC4 Connectors:** MC4 connectors are unique connectors used in solar systems. They are fitted on the solar cables and connected with the solar panel output cables. As solar panels always have a live voltage, MC4 connectors simplify the installation by allowing a safe and touch-proof connection. They also protect the wire from dirt, dust, moisture, and rain. MC4 connectors come in pairs of male and female.

We will go through how to install MC4 connectors in the Installation chapter. In case you are not keen on fitting these connectors yourself,

there are solar cables available that are already fitted with MC4 connectors called “MC4 connector cables”.

MC4 connectors

Source: Safelink; Prom

- **MC4 Branch Connectors:** MC4 branch connectors (also known as Y-connectors and MC4 combiners) are used to combine solar panels into parallel connections. We will see later on what parallel connections are and how exactly branch connectors are used. The size of the branch connector must be matched with the size of the cables on which they will be used.

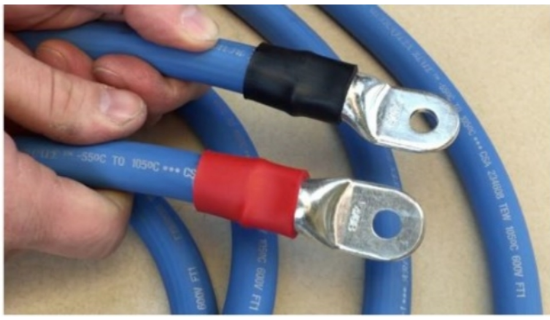
MC4 Branch Connectors
Source: Tomtop; Home Depot; Lelong

- **Cable Lugs:** Cable lugs ensure a solid connection at the device terminals. They also prevent heat buildup and corrosion of the exposed wires. When it comes to off-grid solar systems, cable lugs are mainly used on the ends of big cables such as those connecting the batteries and for the main inverter output cable. They can handle high amounts of current. Like other connectors, the size of the cable lug must match the cable it will be fitted with.

There are two material options available for cable lugs- copper and tin-plated copper. Tin-plated copper lugs are recommended as they offer better protection against corrosion.

Cable lugs will be marked with two numbers- the first number indicates the cable size and the second number is the hole size. The cable size will depend on the cable it will be used with, while the hole size will depend on the battery terminal. If the cable lug at the other end of the cable has to be fitted onto a busbar- we will need nuts and bolts the same size as the lug’s hole.

We will go through how to install cable lugs and the tools required in the later chapters. However, you can also buy cables that are already fitted with cable lugs.



Cable Lugs
Source: Polar Wire; Nivash

- **Crimp Connectors:** We have already seen how cable lugs are used for big cables such as those used for batteries and inverters. For small cables connecting the rest of the devices, we use crimp connectors. Like the other connectors, the size of the crimp connector has to be matched to the size of the cable.

There are several types of crimp connectors. For solar systems, we usually use three types of crimp connectors- ferrule, ring, and spade. Ferrules are used to connect cables at device terminals. Whereas, ring and spade type crimp connectors are used to connect cables to

busbars. We will look into busbars and how to install crimp connectors later.

Crimp connectors are marked with two numbers- the first number indicates the cable size and the second number is the hole size. The cable size will depend on the cable it will be used with, while the hole size will depend on the terminal size of the component it will be connected to. If the connector at the other end has to be fitted onto a busbar- we will need nuts and bolts the same size as the lug's hole.

Ferrule

Ring

Spade

Source: Fastech; OOXX; Misumi

5.9 DC Isolator Switches

DC Isolator switches can isolate specific parts of the system. They ensure a safe disconnection of power sources when we need to perform maintenance on our solar system.

DC isolator switches are placed in two locations for off-grid systems-

1. Between the solar panels and charge controller
2. Between batteries and the rest of the system

The current and voltage ratings will very likely be different for your solar panels and batteries. Thus, it is important to match the correct voltage and current ratings of the DC isolator switch depending on its location. Some isolator switches meant for solar panels come with MC4 compatibility, meaning we will be able to directly connect the solar cables fitted with MC4 connectors.

DC Isolator Switches for solar panels (left) and batteries (right)
Source: BLUSUNSOLAR; The Battery Cell

5.10 Protection Devices: Fuses, Circuit Breakers, Surge Arrestors and Grounding

Protection devices are our saviors when it comes to electrical installations. They offer protection from faults and prevent unfavorable events such as damaged equipment, electric shock, and fire. Although such risks are unlikely with a well-designed system, it is always better to be on the safe side. Besides, protection devices are typically mandatory by law.

When choosing protection devices, it is very important to confirm the electricity type compatibility of the protection device- AC or DC. An AC protection device will not be effective when placed in a DC circuit and vice versa. We will look more into where the different protection devices should be placed in the planning and design chapter.

Firstly, we look at the devices which protect the system from overcurrent. Overcurrent can occur due to:

(i) *Short-circuits* which happen when there is unintended contact between the two poles of a circuit;

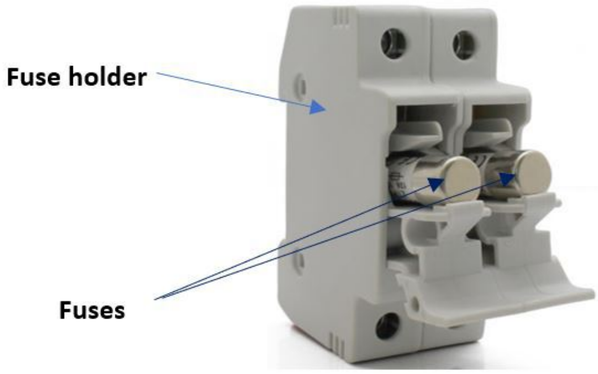
(ii) *Ground-faults* that are caused by accidental contact between a live circuit and the ground; and

(iii) *Overloads* that occur when there is an excess draw of current by an appliance above the design limit of the circuit.

- **Fuses:** Fuses protect the system from overcurrent. They contain a metal filament through which current flows. When a current higher than the fuse's rating flows through it, the filament heats up and melts. This causes the circuit to disconnect, preventing any further flow of current. After such an event, the fuse must be replaced to re-establish the connection.

There are many types of fuses out there on the market. Fuses for solar panels should be of the type **gPV** .

Recently, solar inline fuses have hit the market which can be easily connected next to solar panels. Inline fuses are placed within a special MC4 fuse holder which is connected to the solar cable fitted with MC4 connectors. They are becoming more and more popular with solar installations due to their convenience.



Fuse holder with fuses
Source: BLUSUNSOLAR; Enclosure Climate Control

Solar Inline Fuse
Source: Leader

- **Miniature Circuit Breakers (MCB):** Miniature circuit breakers are another option for overcurrent protection. They are automatically operated electrical switches that contain a magnetic mechanism. When a current above the breaker's rating flows through it, the magnetic mechanism forces it to switch off automatically. Unlike fuses, circuit breakers don't have to be replaced after an overcurrent event. You simply need to put the switch back to ''ON''. Circuit breakers are more expensive than fuses.

There are various types of circuit breakers according to their sensitivity. Typically, Class C MCBs are adequate for residential and mobile solar systems. For circuits with water pumps we use Class D or Class K MCBs, Class D for pumps with high starting currents and Class K for pumps with high inrush currents.

Miniature Circuit Breakers
Source: c3controls

Next, we shall look into devices that protect from overvoltage situations. Overvoltage can occur due to lightning strikes. Without proper protection, overvoltages can break down conductors and components, often leading to very expensive repair work.

- **Surge Protection Device (SPD):** Surge protection devices (also known as surge arrestors) are our line of defense against overvoltages. They are connected in parallel with the circuit and have a connection to the ground. They safely conduct excess voltages to the ground, thereby protecting your valuable components.

When buying surge arrestors, ensure they are Type 2 surge arrestors. We need both AC and DC surge arrestors to be placed on either side of the inverter. Sometimes, surge arrestors are already included inside the inverter. However, if they are not of Type 2- they need to be separately purchased and installed. It is always good to confirm with the supplier beforehand.

Surge Protection Device
Source: Schneider Electric

- **Residual Current Device (RCD):** Residual current devices can go by other names such as Residual Current Circuit Breaker (RCCB), Earth Leakage Device, and Earth Leakage Circuit Breaker (ELCB).

These devices provide supplementary protection from electric shock. When an unlucky person happens to come in contact with a live electric wire, the electricity passes through the person and into the ground instead of flowing back through the circuit. The residual current device can sense this and disconnect the circuit.

RCDs are placed after the inverter. There are a few types of RCDs on the market. For solar installations, we require Type A or Type B. Type B provides added protection against leakage currents but are very expensive. In that case, Type A will suffice as they provide adequate protection. Some inverters have built-in residual current devices. So, if they are of Type A or B, there is no need to buy new ones.

There are some 2-in-1 devices called RCBO (Residual Current Circuit Breaker with Overcurrent). These nifty little devices combine a residual current device and the previously discussed miniature circuit breaker into one device.

Residual current devices
Source: ABB

- **Grounding:** Grounding (also known as earthing) refers to the connecting of certain parts of an electric system to the ground. This is needed for safety reasons. Electrical faults may cause metallic parts or enclosures to become live, which presents risks of electric shock. Grounding systems prevent this risk by safely directing fault currents to the ground.

We need to apply grounding to solar panel frames, mounting systems, inverter, charge controller, junction boxes, metal conduits, and any other metallic parts.

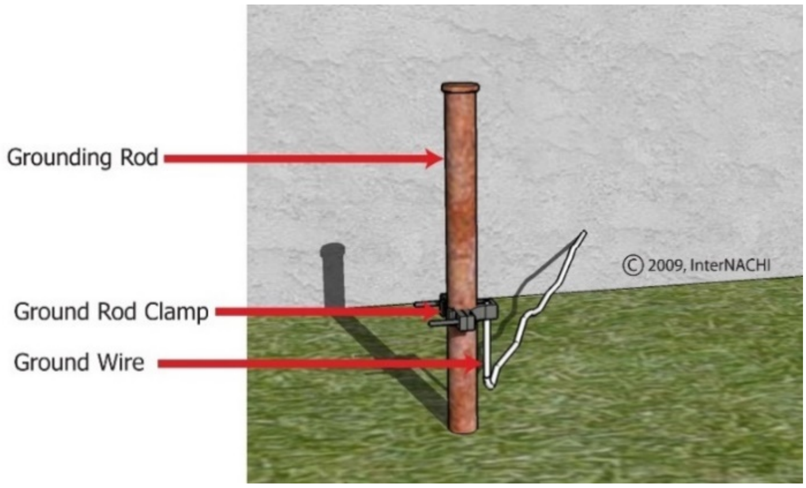
Grounding for solar panel frames typically requires grounding clips. Grounding clips are used to electrically bond solar panel frames with the mounting system. The mounting system is then grounded through

the grounding point (to be confirmed with the mounting system supplier). This creates effective grounding for both the solar panels and mounting systems.

Grounding clips for solar panels
Source: Wanhos Solar

For the rest of the equipment (inverters, charge controllers, junction boxes etc.) we don’t need grounding clips. They are simply grounded by connecting the grounding cable to its grounding point. The grounding requirements and recommended cable sizes are typically noted in the equipment manuals and datasheets.

For homes or buildings, grounding systems consist of grounding cables that are connected to grounding rods. Grounding rods are dug into the ground near the building. For mobile solar systems, the grounding cables are simply connected to the chassis of the vehicle.



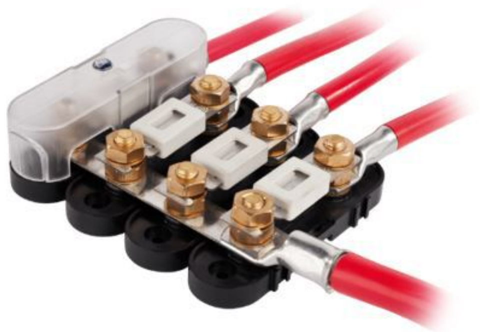
Grounding rod
Source: InterNACHI

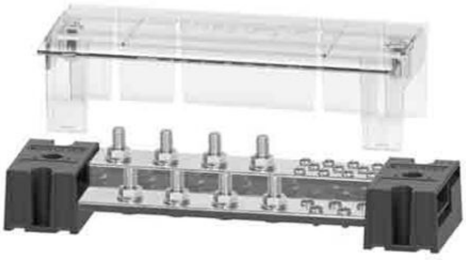
5.11 Busbars

The busbar is yet another important component of electrical installations. They are metallic bars or strips made of copper or aluminum, on which cables are attached. Busbars act as a point where electricity from two or more cables is combined and/or distributed. Cables are connected to the busbar with cable lugs or crimp connectors, along with nuts and bolts. You can see this in the illustrations below.

The size of the busbar is chosen depending on the number of cables that need to be attached to it.

Let us take a practical example to understand busbars. The electricity comes into our house through a single main cable. This cable is connected to a busbar together with the cables coming from the different rooms of the house. Thus, the busbar acts as a point where all these cables are connected, thereby allowing electricity to flow from the main cable to the different circuits in the house.





Busbars of different sizes

Source: Craftsman Marine; Del City; 123RF; Instrumentation Tools

5.12 Junction Boxes

We are all bound to have seen junction boxes at some point. There is one or more in every house. Junction boxes (also known as junction boxes) are where we place our protection devices (remember circuit breakers, fuses, surge arrestors…?), DC isolator switch, busbars, and so on. These devices are usually first mounted on a DIN rail and on to the junction box.

Each solar system will usually have more than one junction box. They are located in different parts of the system as we will see later. The size of the junction box needed will depend on the number of cable connections and devices it will contain.

Junction boxes may have pre-drilled holes or holes may need to be drilled in the box to enter the cables into. *Cable glands* are attached at the entry hole for the cables to ensure sealing and protection from moisture and foreign particles.

When choosing junction boxes, we need to keep in mind its IP Rating. IP Rating (Ingress Protection Rating) defines how well the box is sealed against intrusions from dust, dirt, moisture, water etc. The following IP ratings are applicable for junction boxes used in solar systems-

- **IP65-** dust-tight and protected against water projected from a nozzle.
- **IP66-** dust-tight and protected against heavy seas or powerful jets of water.
- **IP 67-** dust-tight and protected against immersion for 30 minutes at depths 150mm -1000mm.
- **IP 68-** dust-tight and protected against complete, continuous submersion in water.

Depending on the location, IP65 and IP66 are adequate for indoor use, while outdoor boxes must be rated IP67 or IP68.

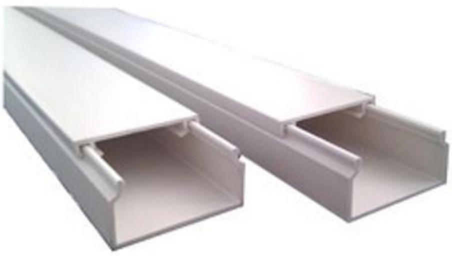
Source: Eco-Worthy; Changsong Electric

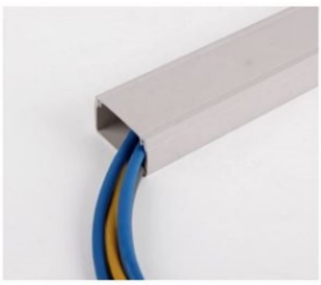
5.13 Installation Materials for Cables: Conduits, Ducts, Ties and Clamps

Let us quickly introduce the cable materials required in solar power installations. These materials help to mount, lay, direct, and protect cables from dust, liquids, and physical damage, etc.

- Cable Conduits and Ducts
- Cable Ties
- Cable Clamps

Cable Conduits
Source: Hellermann Tyton





Cable Ducts
Source: Anshu Houseware; Phoenix Controls; Wiremold

Cable Ties
Source: Velleman; Wenzhou Zhechi; Florian Solar; Hellermann Tyton

Cable Clamps (left) and Nail Clamps (right) (right)
Source: Heyco; Yueqing Jiuhong Electric

6 Site Survey and Locating the Components

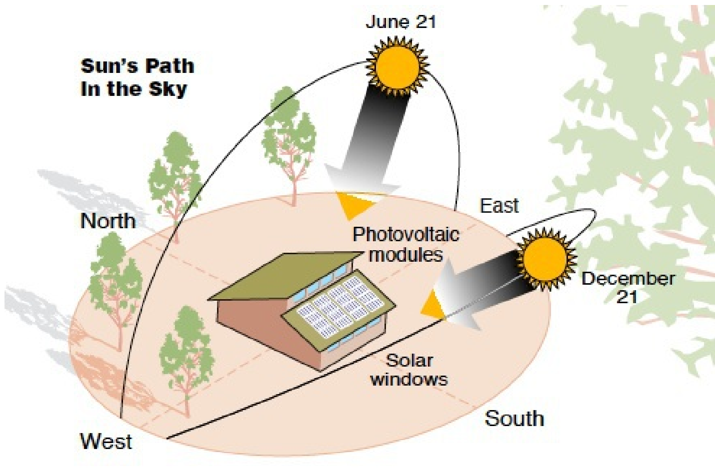
First of all- congratulations! You are now fully prepared to start planning your very own solar power system. A site survey is the first real step in the planning process. We will gather valuable information needed to size your system. In particular, you will learn how to position your panels, measure the available area for solar panels, and understand potential shading issues. We will learn how to plan the locations for placing the various solar components.

6.1 Which direction should my panels face?

Movement of the Sun

Before we answer the above question, let us try to understand the relative movement of the sun across the sky. We know that the sun rises in the east and sets in the west. A somewhat lesser-known fact is the gradual north-south shift of the sun throughout the year. Don't worry if you haven't noticed it. This movement is rather slow. All you need to know is that the sun moves a little to the north or south each day depending on the time of year.

As we can see in the illustration below, when we go from December to June, the sun slowly shifts northwards day by day. Then, as we go from June to December the sun gradually moves southwards. The sun reaches the extreme south position on the summer solstice (21^{st} June) and extreme north on the winter solstice (21^{st} December).



Movement of the Sun
Source: Department of Energy (USA)

The best direction for solar panels

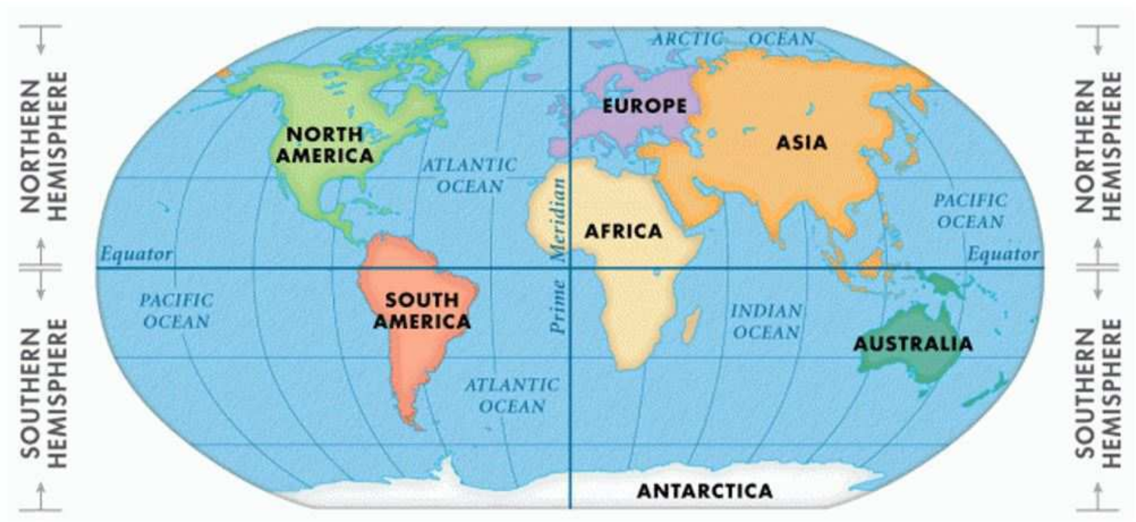
The azimuth angle is the technical measurement for the direction of the solar panels. The reference points for azimuth angle are 0° for the north, 90° for the east, 180° for the south, and 270° for the west.

Based on where you are located and the movement of the sun, we can figure out the best direction our solar panels should be facing for maximum power production.

- ❖ If you are located in the **Northern Hemisphere** , panels produce the best results when facing south.
- ❖ While for those of us in the **Southern Hemisphere,** north-facing panels would be best.

What if I can't position them in the best direction for some reason?

It might not always be possible to position the panels facing the best direction. In that case, we simply choose the roof that is closest to facing the best direction. Generally, east or west-facing panels are acceptable. But, placing the panels opposite of the best direction is a big no-no! That is to say- <u>never</u> face the panels north if you are in the Northern Hemisphere. Similarly, <u>never</u> go with south-facing panels in the Southern Hemisphere.



Source: Geography Name

Panel direction in homes and cabins

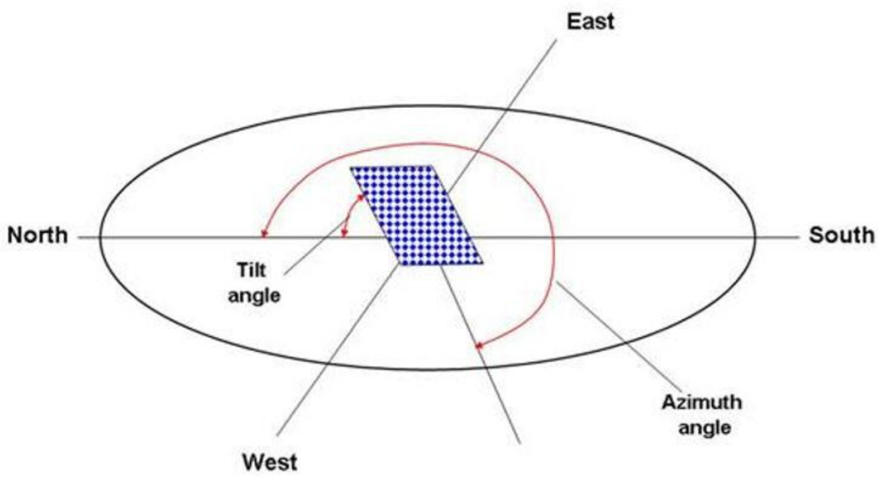
The direction concept is more applicable to solar systems for homes and cabins. This is because the position of the solar panels will usually be fixed in one direction during installation. For sloped roofs of homes or cabins the direction that the roof is facing is also important. Solar panels placed on the sloped roof will face the same direction the roof is facing.

Parking your vehicle for best solar production

For mobile systems, the directions will change depending on how you park your vehicle or which direction you're driving. The trick here is to park your vehicle in such a way that your solar panels face the best direction (that is facing south if you are in the Northern Hemisphere, or facing north if you are in the Southern Hemisphere). This small trick will maximize your power production!

6.2 Should I place my solar panels at an angle?

Tilt Angle is another important angle we should know about. It is simply the angle between the panel and the horizontal surface of the ground or roof.



Tilt Angle and Azimuth Angle
Source: Solar Panels Venue

Tilt angle is applicable mainly for **ground mounted** or **flat roof systems** - as in these cases we have the freedom to choose the tilt angle by using special mounting systems. On the other hand, panels placed on **sloped roofs** will have the same tilt angle as that of the roof. While for **mobile solar systems** the panels are generally placed flat on the roof of the vehicle.

Ground-mount

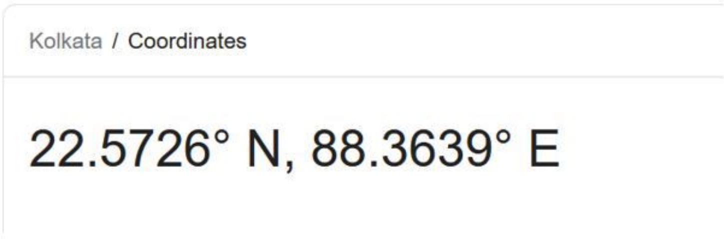
Sloped-roof

Flat-roof
Source: NJRE; Green Tumble; Solar UK

Which tilt angle should I choose?

Now, to the boiling question- what tilt angle should you choose for your solar angles? Well, the choice of tilt angle depends on your **latitude** . You can find the latitude of your city or town by simply searching for it

on Google or any search engine. An example search result is shown below for the city of Kolkata. The first number (22.5726° N) is the latitude, while the second number is the longitude.



For most cases- we choose the latitude of our location as the tilt angle. This results in good performance of the solar system throughout the year.

Tilt Angle for Seasonal Use

If you plan to use the solar system only during a particular season of the year, for instance an RV used only in the summer vacation or a mountain cabin for the winter. In these cases, it is best to set the tilt angle according to the season.

For systems designed for exclusive winter use, we find the optimum tilt angle by simply adding 15° to the latitude of your location

Winter optimum tilt angle = Latitude + 15°

For systems planned to be used in the summer, we do this by subtracting 15° from the latitude of your location

Summer optimum tilt angle = Latitude - 15°

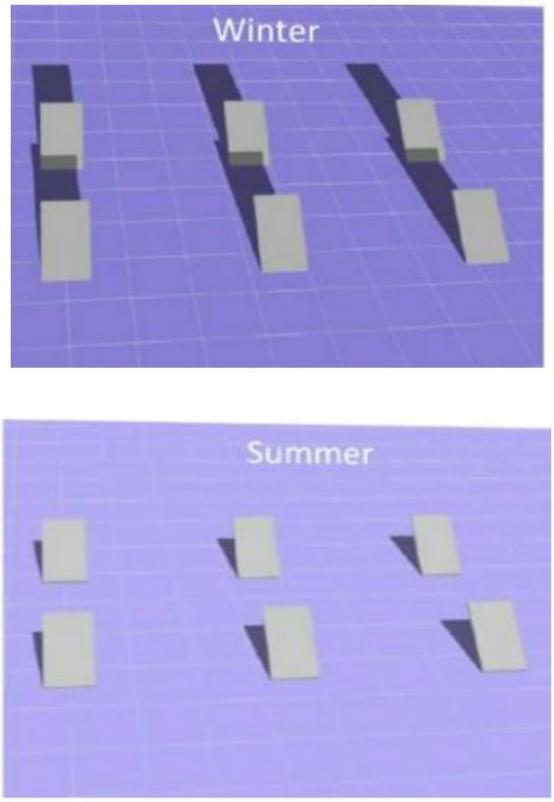
Adjustable Tilt

Moreover, if you're planning on a **ground-mount** or **flat-roof** solar system that will be used throughout the year, you can maximize the seasonal production by simply adjusting the tilt angle. Just by loosening and tightening the nuts of the mounting system and using a protractor or angle meter, you can change the tilt angle of the panels. This way, you can adjust the tilt angle to the optimum angle (according to the season) for maximum production!

6.3 Inter-row Spacing

Another thing to keep in mind for **ground-mount** or **flat-roof** systems with more than one row of panels is the inter-row spacing. If the distance between the two rows is not chosen properly, the rows can shade other

rows. We can see in the illustration below the shading between rows in winter and summer for the same location and same time of the day.

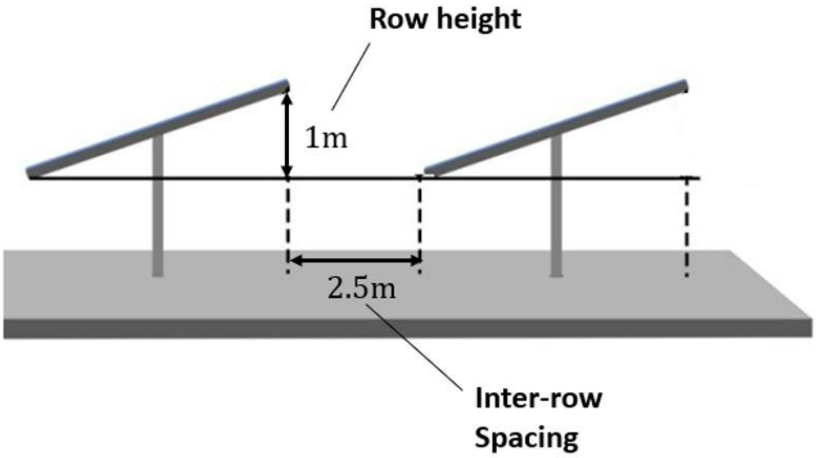


Shading between rows without proper inter-row spacing
Source: TU Delft

We can set the inter-row spacing using the rule of thumb of 2.5 times the row height.

Inter-row spacing = 2.5 x Row height

In the example below, we can see the row height is 1 meter. Note here that the row height is the height from the bottom tip to the top tip of the panel (not from the ground). So, the inter-row spacing is *2.5 x 1m = 2.5m* .



6.4 Measuring the Available Space

Finally, the time has come for you to get up there on the roof of your vehicle or home! Or in the case of ground-mount systems you just need to go out to the area where you want to place your solar panels. Having another person with you makes the measuring job a lot easier.

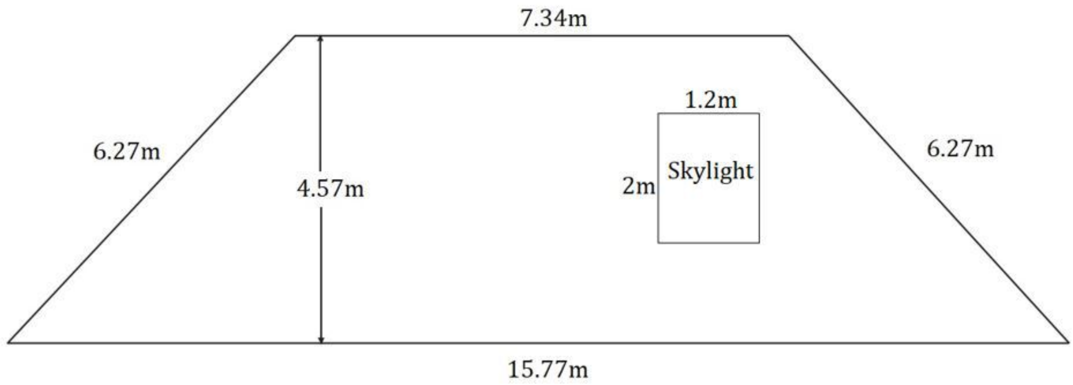
Which tools do I need?

Before getting up on the roof of your vehicle or home, don't forget to take your **tape measure** and **notebook** . Taking pictures of the site using your **camera** or **smartphone** can be of great help for later reference. Take your **compass** as well, to plan the solar panel directions.

To measure the tilt angle of sloped roofs, you can use a **protractor** or better yet, download an **angle finder/measurement app** on your smartphone.

Make a sketch!

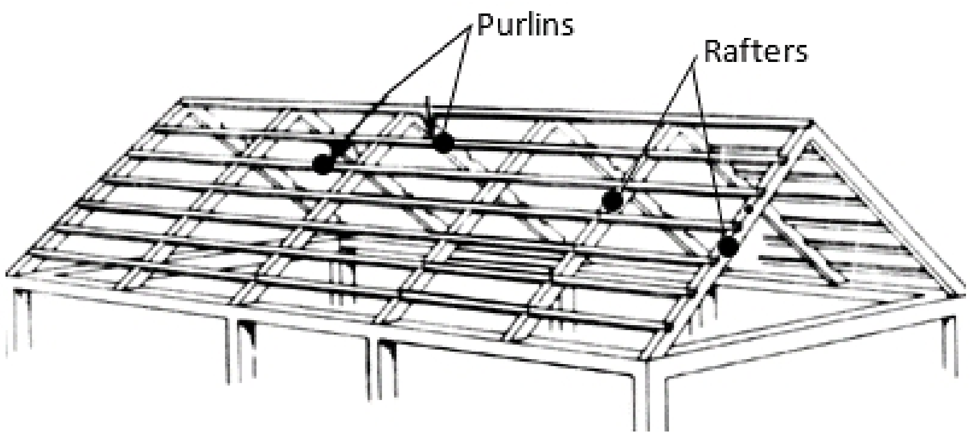
Firstly, it is useful to make a simple sketch of the outline of the area or roof you are working with. After that, use the tape measure to measure the perimeter of the available space. Make a note of any obstructions such as air vents, chimneys, skylights, rails, and other equipment. We need to exclude the area taken up by obstructions as we cannot place solar panels there.

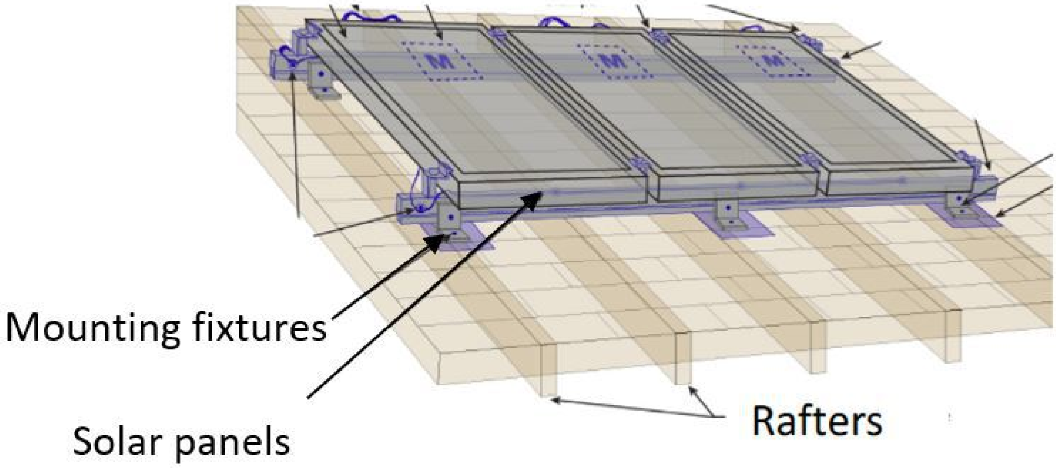


Example measurement for a roof

A couple more measurements for sloped roofs

If you are planning to build a solar system on a sloped roof, there are a couple more measurements that need to be taken. For sloped roofs, the solar panel mounting systems will usually be drilled and attached to the rafters and/or purlins in the roof (as shown in the illustrations below). Thus, we need to measure the length of the rafters and purlins. Along with that, we need to measure the distance from purlin to purlin, and the distance from rafter to rafter. These measurements will guide us as to how many solar panels we can fit in.





What if I have a curved roof?

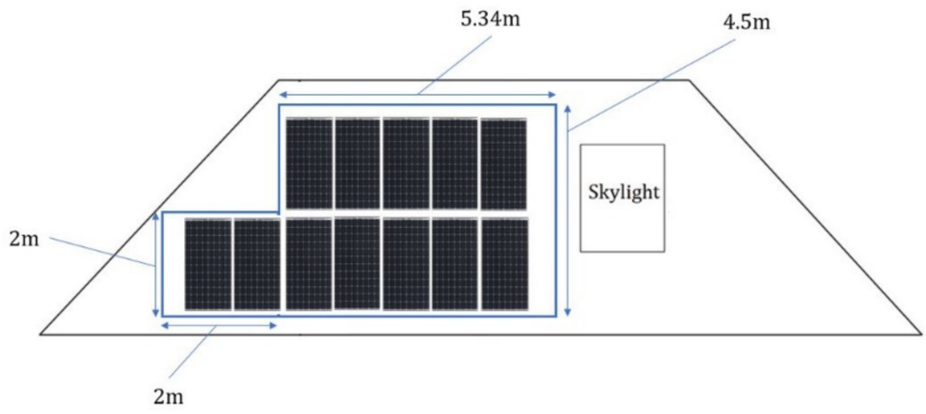
If your vehicle or home has a curved roof you may need to use flexible solar panels. These types of panels are bendable and hence can be easily mounted on irregular surfaces.

Source: Semprius

How many solar panels can I fit in?

After measuring the dimensions of the site, we can work out the available space. Using this information, we can estimate how many solar panels can fit in. Solar panels have an area between 1.5 m^2 to 2 m^2 for power ranging from 250 W to 400 W per panel.

Let us take an example of a roof to see how we can estimate the number of panels we can fit in.



For our calculations at this stage, we can use solar panel dimensions of 1.70 m x 1 m- which gives us an area of 1.7 m^2 . However, the wattage of solar panels can vary from 250 W to 400 W per panel.

By taking into account the dimensions as well as the area of the available space, we can fit a maximum of 12 panels. (Remember we are considering the dimensions of each panel to be 1.7 m x 1 m.)

Thus, for 12 panels we can get total solar power within 3 kW to 4.8 kW depending on the wattage of the solar panel we choose. Remember solar panels available on the market can range from 250 W to 400 W per panel.

6.5 Shading Issues

We all like to bask in the shade of a tree on a warm day. However, solar panels don't share the same relationship with shadows. As you may have already guessed, shading on solar panels leads to a loss in power production. Remember how photons in light lead to electricity production in solar panels? Well, shading blocks the photons from reaching the panel. The amount of power loss due to shading will depend on the extent of shading.

Near Shading and Far Shading

There are generally two types of shading, near shading and far shading. Near shading can be caused by trees, vents, antennas, poles, chimneys, walls, and so on. Whereas, far shading is associated with high buildings or mountains. The size and shape of the shadow changes as the sun moves throughout the day and throughout the year as we discussed earlier.

The Effect Of Shadow and its Solutions

The effect of shading can be widespread. When we have more than one solar panel in the system, the panels are usually interconnected into what is called a *string* . Even if one panel is shaded, the output of all the panels within the string is affected. The electricity production of the whole string will be limited to the current generated by the shaded panel.

Luckily, there are ways to tackle the negative effects of shading. First and foremost, our aim should be to place the panels in a **shade-free or a minimally shaded area** . We can position the panels **vertically or horizontally** to avoid shading.

However, sometimes shading is just unavoidable. Even then, there are ways to reduce shading losses, as follows-

✓ **Bypass diodes- 3 or more:** Bypass diodes are in-built in the solar panel to counter the shading losses. Use solar panels with three or more bypass diodes. You can check this information from the solar panel datasheet or confirm it with your supplier.

✓ **Half-cell crystalline solar panels for partial shading:** Half-cell crystalline solar panels are effective in partial shading conditions. This technology uses half-cut solar cells which divide the solar panel into two halves. If one half is shaded the other is unaffected.

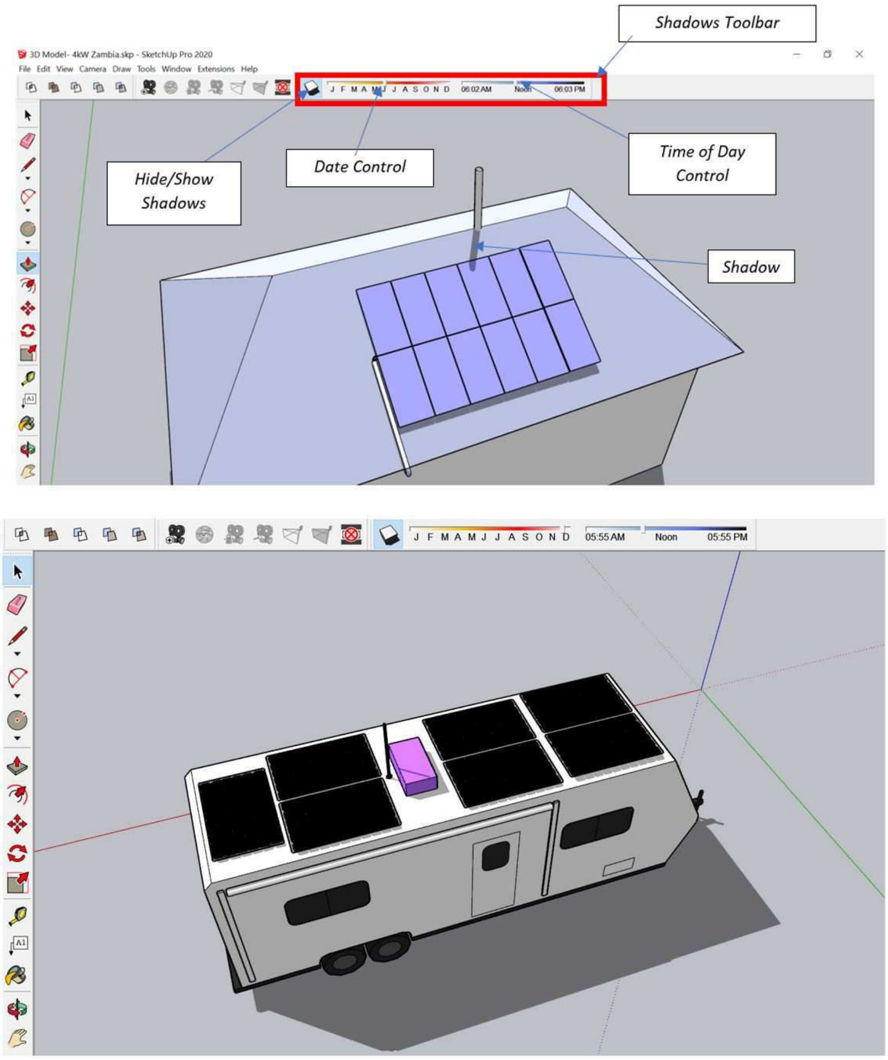
✓ **Thin film solar panels for heavy shading:** For heavily shaded sites such as a house surrounded by trees it is best to use thin film solar panels. This technology has a good response even in heavy shading.

How can I accurately determine shading?

For those of us who are really interested to know the extent of shading throughout the year, shading can be simulated using simple computer software like SketchUp. SketchUp is also great for just creating a model of your system, e.g. to figure out how many panels fit on your roof.

1. Using the measurements of your vehicle or building, create a model of your site along with the shading elements in SketchUp.
2. You can download ready made solar panels at this stage from the *3D Warehouse* option in the *Window* menu in SketchUp. Place the panels on the roof.
3. The shading can then be analyzed by activating the *Shadows* toolbar from the *Tools* menu. You can move the sliders in the

Date Control and *Time of Day Control* to observe the shadow behavior. This is shown in the illustrations below.



Analyzing the shadow behavior in Sketchup software

6.6 Structural Considerations

When we survey the site to plan a solar system for a home, cabin, or vehicle, it is important to observe the condition of the site. We need to look out for any signs of damage, rust, weakness, and so on. Even simple acts like knocking on surfaces or gently shaking the structure can give us an idea of its condition. Adding solar panels on a roof will add extra weight to the roof as well as more wind load, snow load, and so on. So, the roof must be in good condition to handle these. If you have any doubts about the condition of your site or the climate factors such as wind and snow loads, consult an expert structural engineer.

6.7 Locating Solar Components

It is always handy to plan the locations of all the solar components well beforehand. We have already discussed quite a bit about positioning your solar panels earlier in this chapter. We also learned how to measure the roof, estimate the number of panels we can fit, and analyze shadows.

Similarly, make some sketches, lists, and notes of where you plan to place the remaining components- **Batteries** , **Inverter** , **Charge Controller, Junction Boxes (DC Combiner Box, Battery Junction Box, and AC Distribution Box)** at the minimum. It will also help to make some measurements of your space.

In general, it is best to locate batteries, inverter, charger controller, and other electrical components in non-occupied or rarely-occupied areas. They should be placed in cool, well ventilated, and dry spaces. They must be kept away from heat, fire, or wet areas. It is important to keep some space around the components to allow for cooling and improved functioning.

One of the main guiding factors for choosing suitable locations is to keep the components as close together as possible in order to minimize cable runs. This way you save money on cables and also keep the system efficiency high by reducing electrical losses in cables. This must be done in a logical manner, however.

Typically, RVs and some vans will have a battery bank compartment. While other vehicles require us to build a separate compartment. It makes sense to place the batteries between the front and back tires of the vehicles for better balancing of the weight *(batteries can be heavy!)* .

The inverter and charge controller are mounted on the wall surface. It is necessary to keep the inverter and charge controller within 3 m (10 feet) of the batteries.

6.8 Cable Paths And Lengths

It is also a very good idea to plan the paths and routes of **cables** . We should also take measurements of the prospective cable lengths. It is again helpful to make some drawings and notes for this.

These are the cables we need to plan for at the minimum-

✓ Solar panels to DC Combiner Box

✓ DC Combiner Box to charge controller

✓ Cables connecting the battery, battery junction box, charge controller, and inverter

- ✓ Cables from the inverter to AC Distribution Box
- ✓ …*And if not installed already*- AC Distribution Box to loads (i.e. lights, appliances, sockets, etc.)

7 Calculating Your Energy Needs

By now, you know how to do a site survey and plan the locations of the components. The next essential step in the planning stage is to calculate your energy needs. This energy calculation will determine the required size of your solar system. Thus, it is necessary to do this as accurately and comprehensively as possible

7.1 The Basics

We need to familiarize ourselves with the concepts of energy and power before we get down to calculating your energy needs.

Power: In simple terms, power is the rate of work done by electricity at any moment. Electricity performs work to make your appliances function. The rate at which electricity performs work at any instant is known as power. Power can be generated (e.g. by solar panels). Or power can be used up (e.g. by your lights and fans).

Power is measured in Watts (W). The amount of Watts or the Wattage of an appliance or component will be mentioned on its label, user manual, or other technical documents. For instance, a 10W LED light consumes 10 watts of power to operate.

If for some reason, you don't have information on the wattage or power rating of an appliance. You can calculate it from its current and voltage rating using the following formula-

Power (Watts) = Voltage (Volts) x Current (Amps)

Energy: Electricity provides electrical energy to appliances in order for them to function. That's right- the electrons carry around a certain amount of energy that they pass on to your lights, fans, and so on. Energy is simply a measure of the amount of power generated or consumed over a specific amount of time.

Energy is measured in Watt-hours (Wh). 1000 Wh makes 1 kilo-watt hour (kWh). We calculate energy using the following equation.

Energy (Watt-hours) = Power (Watts) x Time (hours)

7.2 How to calculate your energy needs?

We need to make a table to calculate your energy needs. You can simply make the table in your notebook or better yet in spreadsheet software like Microsoft Excel. Here, we will need the list of your loads and the amount of time they will be used each day.

If you have both AC and DC loads, you need to make two separate tables- one for AC loads and another for DC loads. We must keep these separate to work out details like the inverter size as we will see later.

Examples of Energy Calculation Tables are shown below.

Daily AC Load Consumption					
AC Load	**Rated Power (W)**	**No. of Units**	**Subtotal Power (W)**	**Working Hours (h)**	**Energy (Wh)**
LED Lights	15	4	60	6	360
Fans	30	2	60	10	600
Small TV	50	1	50	4	200
Small Fridge	70	1	70	12	840
Air Conditioner	1000	1	500	6.5	6500
Home water pump	200	1	200	1	200
TOTAL			940		8700

Daily DC Load Consumption					
DC Load	**Rated Power (W)**	**No. of Units**	**Subtotal Power (W)**	**Working Hours (h)**	**Energy (Wh)**
DC lights	5	3	15	6	90
DC fans	15	2	30	4	120
RV Water Pump	36	1	36	4	144
TOTAL			81		354

The tables have the following columns-

✓ **Load-** Load is something that consumes electricity. In our case, load is used to define AC or DC appliances such as light, fan, TV, or fridge.

✓ **Rated Power-** This is the power rating or wattage of the load.

✓ **No. of Units-** The quantities of each load you are planning to use (e.g. the number of lights, fans, and so on).

✓ **Subtotal Power-** Subtotal Power is calculated by multiplying the two previous columns- "Rated Power" and "No. of Units" for each load type.

Subtotal Power (W)= Rated Power (Watts) x No. of Units.

- ✓ **Working Hours-** This is the number of hours you plan to use a particular load.
- ✓ **Energy-** Energy is calculated by multiplying the two columns- "Subtotal Power" with the "Working Hours".

Energy (Wh)= Subtotal Power (Watts) x Working Hours (Hours)

- ✓ **Total-** Finally, we simply add the Energy of each load (in the "Energy" column) to get our daily total energy use. We also add up the numbers in the "Subtotal Power" column to get the Total Power.

So, there you have it, this is how you calculate your energy needs. Easy, isn't it?

7.3 Load Considerations for Refrigerators, Air conditioners and Water Pumps

There are a couple of things to keep in mind for loads that have a motor, pump, or compressor. Examples of such loads include refrigerators, air conditioners, and water pumps. In order to properly size our solar components, we need to consider the starting surge power and compressor operation time of these loads.

Starting surge power results from the extra current drawn by these loads to start the pump or compressor. This usually lasts for a few seconds. However, it must be checked with the maximum output current and surge current ratings of the inverter (more on that later). Typical surge power for these loads are as follows-

- **Refrigerator:** Four times the nominal or rated power and current.
- **Air conditioners:** Three times the nominal power and current.
- **Water pumps:** Six times the nominal power and current.

Compressor operation time is related to the compressor present in refrigerators and air conditioners in our case. The compressor is the main power drawing equipment in these loads. The thing to keep in mind is the compressor does not operate the whole time a refrigerator or air conditioner is running. The operation time depends on the surrounding air temperature, the number of times they are exposed to outside air, and so on.

We can consider the following patterns in our calculations-

- **Refrigerator:** We can consider the refrigerator compressor draws power for **50%** of the time it remains on. For example, if a 100 W refrigerator is kept on for 24 hours each day, we can say the compressor runs for *50% x 24h = 12 hours.* Thus, the energy drawn per day by the refrigerator will be *100 W x 12 hours = 1.2 kWh.*
- **Air conditioners:** On the other hand, an air conditioner will draw its rated power for the first 5 hours of operation. After the first 5 hours, we can consider 50% compressor operation time. For example, if we operate a 1000 W air conditioner for 8 hours, we can estimate the total energy draw as

(1000 W x 5 h) + (1000 W x [8 h-5 h] x 50%) = 5000 Wh + 1500 Wh = 6.5 kWh

- **Water pumps:** Water pumps on the other hand operate for the entire time they are kept on. They must be switched off manually or by a level switch.

8 Understanding Connections for Solar Panels and Batteries

Series and parallel are the two techniques for connecting two or more electrical components. We look into how these connections are done with solar panels and batteries. We will also see how to calculate the output voltage and current characteristics arising from such connections.

The key thing to remember is voltage increases with increasing series connections, while the current increases with more parallel connections.

When making parallel connections, the number of components in series within each parallel string must be the same. In other words, the total voltage of each parallel string must be the same.

8.1 Solar Panel Connections

Low power applications such as a solar power system designed for a light and fan may be satisfied using a single solar panel. However, most mobile or home solar systems will need to satisfy a greater number of appliances. Therefore, we will need to connect together two or more solar panels. Next, we will learn the two connection techniques for solar panels.

Only identical solar panels (i.e. Same brand, model, ratings, etc.) can be connected together in series and/or parallel.

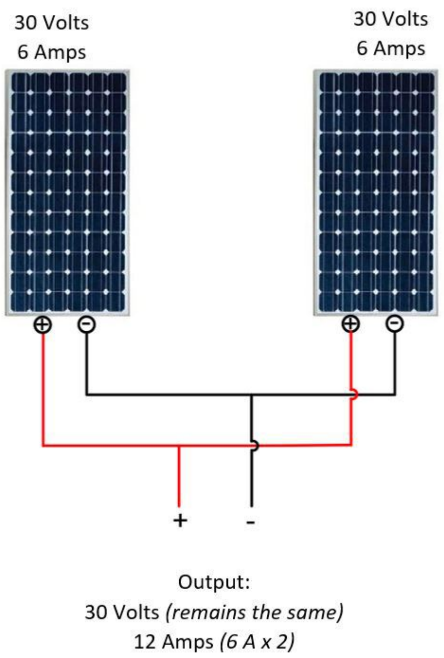
Where possible go for more series connections rather than parallel (depending on charge controller or inverter limits as we will see later). More parallel strings mean more cabling which means more costs and electrical losses.

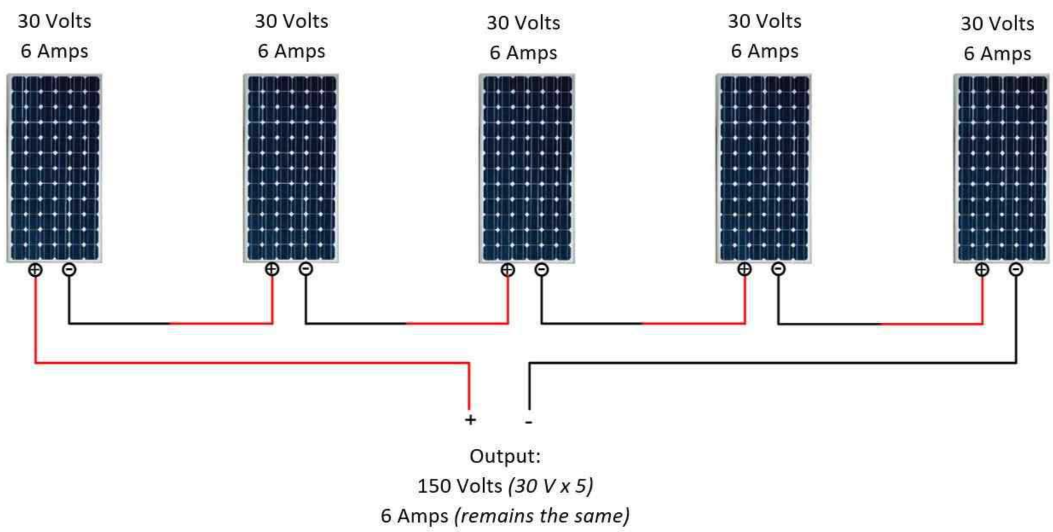
Series Connection

A series connection is done by connecting the negative lead of one component to the positive lead of another component. The output leads are obtained from a positive and a negative output lead coming out from the first and last components respectively.

At the output of a series connection- voltages of all connected components are added up, but the current (amps) remains the same as that of one component.

The wiring diagrams below represent series connections of solar panels rated at 30 Volts and 6 Amps each.





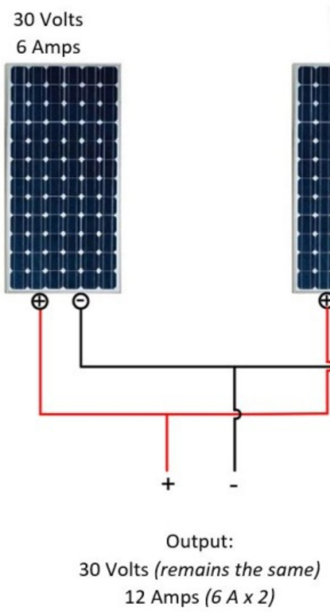
Parallel Connection

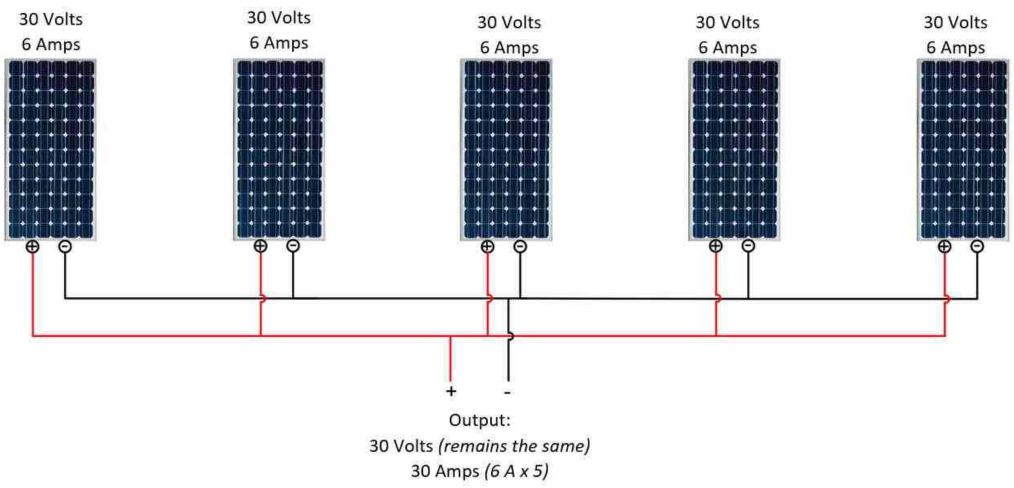
Parallel connections follow a different approach. The positive lead of a component is connected to the positive lead of another component, while the negative lead of one component is connected to the negative lead of another component. The output leads are obtained from the connected positive leads (to give us the positive output lead) and connected negative leads (to give us the negative output lead).

At the output of a parallel connection- the current (amps) of connected components are added up, while voltage remains the same as that of one component.

For parallel connections, the number of solar panels in each parallel string must be the same. For instance, you can have 2 strings in parallel with 2 panels in each string. But you should NOT parallel connect one string with 2 panels and another string with 3 panels. **The number of panels in each parallel string must be the same.**

Solar panels rated at 30 Volts and 6 Amps each are connected in parallel in the following wiring diagrams.



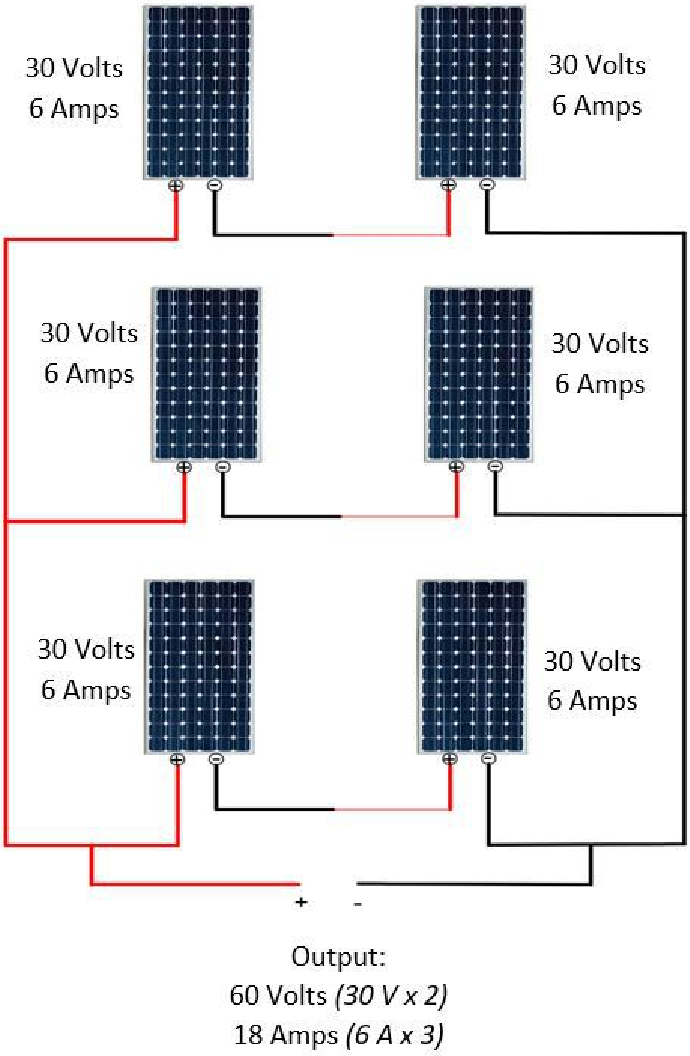


Series-Parallel Combination

It is also possible to have a combination of series and parallel connections. The output current and voltage follow the same rules as explained previously in this section according to the number of components in series and in parallel.

The following wiring diagram shows the 30 V/6 A solar panels connected in a series-parallel combination. Here, two panels are connected in series in each *string* and three *strings* are connected in parallel. A **string** is a line of components connected in series.

Since each string has two panels in series- the voltage is multiplied by two. Likewise, as there are three strings in parallel, the current is multiplied by three.



8.2 Battery Connections

Before we dive into the connection techniques for batteries, let us first understand a few important parameters for batteries- Amp-hours, voltage, and C-rate.

Amp-hours: This is a measure of the amount of current (Amps) the battery can produce over time (hours). Amp-hours (Ah) is one of the

ways to denote the capacity of the battery. Battery capacity is also sometimes denoted in terms of energy in kilowatt-hours (kWh).

The Amp-hours output of a battery bank can be increased by connecting them in parallel. For example, if we connect two 12 V-100 Ah batteries in parallel, the output will be *2 x 100 Ah = 200 Ah*. While the voltage remains the same at 12 V.

Voltage: The standard voltages of lead-acid battery banks are 12 V, 24 V, 48 V, and so on. Lithium-ion batteries are typically 48 V or higher. For smaller capacity requirements, we can use a single battery (such as a 12 V lead acid battery or a 48 V lithium ion battery) or several low-voltage batteries are connected together in series to obtain larger voltages (e.g. 24 units of 2 V lead acid batteries connected in series to produce 48 V). We will look at this next.

C-rate: The rate at which a battery is discharged has an effect on the overall capacity of the battery. C-rate is a measure of the rate at which a battery is discharged relative to its maximum capacity. The magnitude of the discharge current depicts the rate of discharge.

Let us understand C-rate with an example. We have a 200 Ah battery rated at C-20. Here, C-20 stands for a C-rate of 20 hours. What this means is that the battery can supply its rated capacity of 200 Ah if it is discharged over 20 hours. If we discharge the battery fully in 10 hours (i.e. C-10), the capacity will be reduced as the higher discharge current leads to higher losses in the cables. Therefore, we need to select a battery with an appropriate C-rate and capacity with our expected discharge time.

Below we see an excerpt from the datasheet of Ritar DG-12 200 battery.

Reference Capacity	C3	136.5AH
	C5	154.0AH
	C10	176.0AH
	C20	200.0AH

Source (modified): Ritar Power

Series and Parallel Connections for Batteries

The required battery capacity may be satisfied by a single battery. If we require a higher capacity, it is likely that we will need more than one battery.

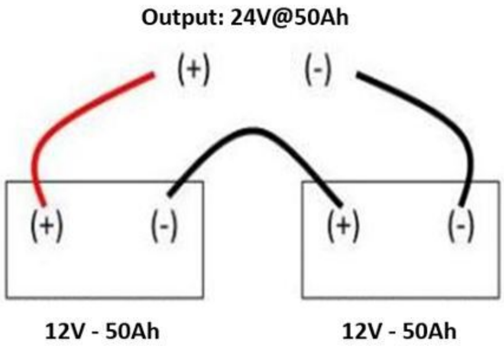
Remember for parallel connections, the number of batteries in each parallel string must be the same. For instance, you can have 2 strings in

parallel with 2 batteries in each string. You should NOT parallel connect one string with 2 batteries and another string with 3 batteries. **The number of batteries in each parallel string must be the same.**

Below we look at series and parallel connections of batteries and how the output amp-hours and voltage changes with different connections.

Only identical solar panels (i.e. Same brand, model, ratings, etc.) can be connected together in series and/or parallel.

Where possible go for more series connections than parallel (depending on charge controller or inverter limits). More parallel strings means more cabling which means more costs.



Left, each battery is 12 V-50 Ah.

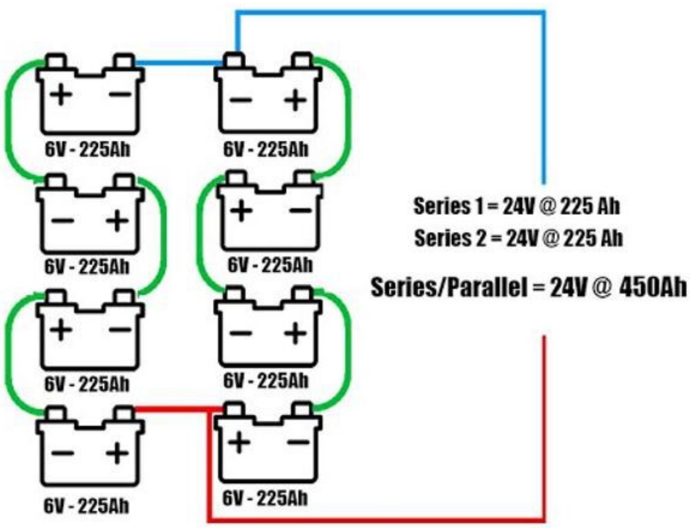
2 of these are connected in series.

The output voltage is 2 x 12 V = 24 V

The output Amp-hours remain the same at 50 Ah.

The total energy capacity of the battery bank is 24 V x 50 Ah = 1.2 kWh

Source (modified): Practical Fishing Tips



Here, each battery is 6 V-225 Ah.

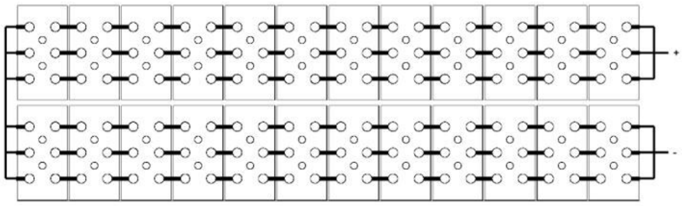
Source: Power Inverters

4 of these batteries are connected in series to give us a string of 6 V x 4 = 24 V output.

A similar second string of 4 batteries is then connected in parallel with the first string to give us 2 x 225 Ah = 450 Ah output

The total energy capacity of the battery bank is 24 V x 450 Ah = 10.8 kWh

Source: Power Inverters



Here, each battery is 2 V-2000 Ah.

24 of these batteries are connected in series to output 48 V.

Amp-hours remain the same at 2000 Ah

The total energy capacity of the battery bank is 48 V x 2000 Ah = 96 kWh

9 Solar System Planning & Design: Sizing and Selecting the Components

Now is when the real fun begins! You've already learned about the ins and outs of a solar system and its associated components. You know how to do a site survey and also how to calculate your energy needs. Now we shall move to the main topics of planning and designing your very own solar system.

We will first go through a couple of basics regarding series and parallel connections, and battery capacity. We will then learn how to size and select the components. We will look at practical design examples for different mobile and off-grid home systems including those for RVs, minivans, boats, cabins, and houses. We will also learn how to make diagrams and documents which will be used during installation.

We expect you to use this chapter along with other chapters in the book, especially chapters 5, 7, and 8.

9.1 The Planning & Design Procedure

The number of solar panels and components you'll need not only depends on the type and size of your vehicle or home, but also the quality of the equipment you choose, how much sunshine your location sees, and the amount of electricity you require.

Let us get down to business and go through the steps involved in the planning and design process. We will apply these steps in the design examples later in this chapter. The examples are provided for you to precisely understand how to put these steps into action. The planning and design procedure and examples were inspired by Roger A. Messenger & Amir Abtahi (2017).

The steps involved in the planning and design of an off-grid solar system are as follows-

1. Determining the Loads
2. Battery Selection & Sizing
3. Solar Array Sizing
4. Inverter Sizing
5. Charge Controller Selection
6. Cable Sizing
7. Protection Device Selection
8. Final System Schematic Diagram

We will now go through each step in more detail and understand what needs to be done at each stage.

1. *Determining the Load*

This is basically the stage where you calculate your energy needs as we saw in Chapter 7. We need to tabulate the AC and DC loads and determine their power and daily operating hours. We then use this data to work out the energy needed for each load per day. We then add this up to find the **total power** and **total energy** required in a day. The total power and total energy result will be required in sizing the rest of the system.

Along with the energy calculation, we also need to look at a few more important items. We have to write down the **voltage** and **current** for each of the loads. As discussed in Section 7.3, also make a note of the surge current for refrigerators (4 times), air conditioners (3 times), and water pumps (6 times).

This information will be found in the user manual, the technical information document, datasheet or you could look online. The reason we need this data is that the voltage of the loads has to be matched with the rest of the system as we will see later. The current information will be used later during inverter selection and charge controller selection.

Daily AC Load Consumption								
AC Load	Rated Power (W)	No. of Units	Subtotal Power (W)	Working Hours (h)	Energy (Wh)	Voltage (V)	Current (A) [inc Surge Current]	Power (W) [inc Surge Power]
LED Lights	15	4	60	6	360	120	0.5	60
Fans	30	2	60	10	600	120	0.5	60
Small TV	50	1	50	4	200	120	0.4	50
Small Fridge	70	1	70	12	840	120	2.3	280
Air Conditioner	1000	1	500	6.5	6500	120	12.5	1500
Home water pump	200	1	200	1	200	120	10.0	1200
Cabin water pump (deep well)	125	1	125	5.5	687.5	120	6.3	750
TOTAL			1065		9387.5		32.5	3900

2. *Battery Selection & Sizing*

The question of which type of battery you should choose was discussed in Chapter 5 (Section 5.3). Depending on the application, intensity of use, and your budget, you can choose between lithium batteries or lead acid batteries (FLA, SLA, AGM, Gel).

Next, the battery sizing stage can be divided further into smaller sub-steps. As we will see, this stage requires the daily energy calculation we found in step 1 along with system characteristics and planning concepts such as inverter efficiency, wiring losses, and additional days of storage as we will see here.

The basic method for battery sizing involves the following:

(i) Calculate the Battery Capacity: The required battery capacity is calculated using the following equation-

$$\text{Required Battery Capacity (kWh)} = \frac{\text{Daily Load (kWh) x Days of Autonomy}}{\text{Inverter Efficiency x Wiring Efficiency x Depth of Discharge x Temperature Factor}}$$

Let us now look at each of the parameters in the equation in detail, along with the values we need to choose for each of them.

a. **Daily Load:** This is the daily total energy requirement (also known as daily load) that we calculated in step 1 (*Determining the Load*). The daily load is converted to kWh units for ease (Remember 1000 Wh = 1 kWh).
b. **Inverter Efficiency:** The inverter efficiency needs to be accounted for as some energy is used up or lost in the inverter. This energy has to be provided by a battery as well. The value of the inverter efficiency ranges from 90% to 98% depending on the size and brand of the inverter. To be conservative at this stage, we can use a value of **90%** in our calculation. Note that for pure DC systems without an inverter, this factor is irrelevant.
c. **Wiring Efficiency:** Some energy is lost in the wiring as heat. We can allow for a 2% energy loss in wiring from the batteries to the loads (via other components). In other words, we can use a wiring efficiency of **98%.**
d. **Depth of Discharge (DoD):** Depth of discharge (DoD) of a battery is the amount of energy that is discharged from the battery. It is denoted as a percentage.

Typically, batteries are not allowed to discharge fully (i.e. 100%) to ensure good longevity of the battery. The depth of discharge is higher for lithium ion batteries than lead acid batteries, as follows-

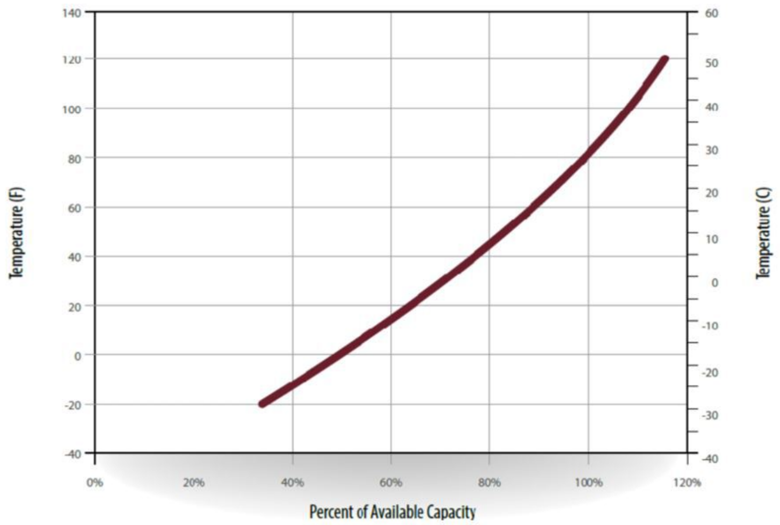
- For **lithium ion batteries** we can consider a DoD of **80%** .
- For **lead acid batteries** we can use a DoD of **50%** .

e. **Days of Autonomy:** This is basically the number of days the batteries can continue supplying energy during periods without sunshine. It may be the case that a location experiences a consecutive number of cloudy days wherein no solar power is produced. The solution is to oversize our batteries to store enough energy to supply during these days.

The number of days of autonomy depends on your preferences, budget, location, space for the battery bank, and availability of back-up sources (such as grid charging or diesel generator). Depending on these

parameters, it is normal to choose **1-3** days or more based on your requirements and budget.

f. **Temperature Factor:** Batteries lose some usable capacity in very cold conditions. We need to account for this if the batteries are planned to be located outside where they may be exposed to cold weather (especially in the winter). Graphs such as the one presented below are usually available in the battery datasheet or available on request from the supplier. Using the battery data, we can work out the available capacity for each month based on the temperature data for your location.



Temperature vs Usable Battery Capacity
Source: Prostar

(ii) Select Suitable Batteries: Finally, after the battery sizing calculation is complete, we proceed to choosing suitable batteries that meet this capacity. Note that it is not always possible to find the exact size that matches our requirements. In that case, we choose the next highest battery size. In case of budget or space issues, we could also choose a size slightly lower than required. However, this would mean we would have less energy available for our use and so we would need to proportionately reduce our energy use.

The battery bank voltage we need to choose depends on our power requirements. We can choose the battery bank voltage based on the inverter size as a rule of thumb-

Inverter Size (W)	Battery Bank Voltage
Up to 1000 W	12 V
1000 W – 2000 W	24 V

Over 2000 W	48 V

As we saw earlier in this chapter, the capacity of lead acid batteries is typically labeled in Amp-hours. So, we need to know our required battery capacity in Amp-hours to select a battery. We convert our required battery capacity from kilo-watt hours (kWh) to Amp-hours (Ah) by dividing it by our chosen battery bank voltage.

$$\boldsymbol{Battery\ Amp - hours\ (Ah) = \frac{Battery\ Capacity\ (Wh)}{Battery\ Bank\ Voltage\ (V)}}$$

As discussed in Chapter 8, we may need more than one battery depending on the required capacity. In that case, we have to determine the series and parallel connections of the batteries. Remember Voltage increases in series connections while the Amp-hours increase in parallel connections.

3. Solar Array Sizing

Now we move on to sizing the solar array (a group of solar panels is called a solar array). This is done in three steps. First, we calculate the Required Daily Solar Energy; and next, we simulate the solar energy generation for your location using an online tool. Finally, we use the results from the first two steps to calculate the Required Solar Array size.

(i) Calculating the Required Daily Solar Energy:

The required daily solar energy is calculated using the following equation-

$$\boldsymbol{Required\ Daily\ Solar\ Energy\ (kWh) = \frac{Daily\ Load\ (kWh)}{Charge\ Controller\ Efficiency\ x\ Wiring\ Efficiency\ x\ Battery\ Efficiency}}$$

The parameters used in this equation are explained as follows-

a. **Daily Load:** This is the same daily load that we calculated in step 1.
b. **Charge Controller Efficiency:** This is would depend on the type of charge controller choose-

- For an MPPT charge controller , we can assume an efficiency of **90%** ,
- while for a PWM charge controller, we can take **70%.**

c. **Wiring Efficiency:** Similarly, this was also discussed in step 2. The value we use is 98%.

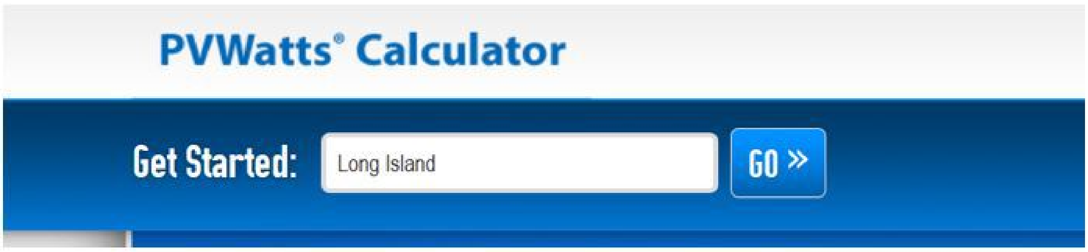
d. **Ba ttery Efficiency:** Here, the value depends on the type of battery as follows-

- Lithium ion battery: We can use a value of 90%.
- Lead acid battery: We can use a value of 80%.

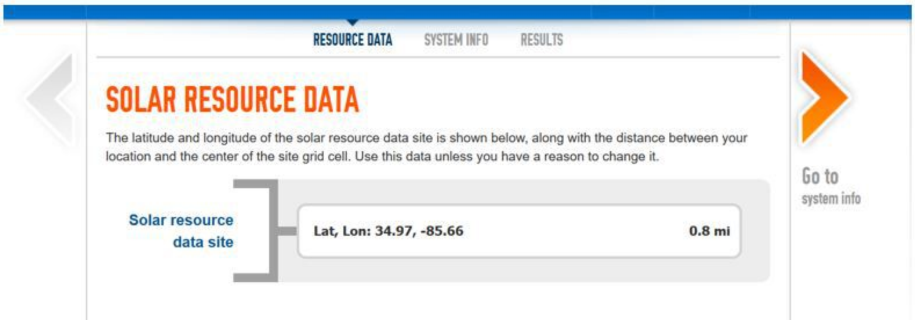
(ii) **Solar Energy Simulation:** There are various software and online tools available to simulate the solar energy simulation for a particular location and system. We will use the online tool NREL PVWATTS for its simplicity. You can access this tool for free at https://pvwatts.nrel.gov/ . Here we will simulate the generation of a 1kW system, which will then be used to work out our required array size.

The steps involved are as follows-

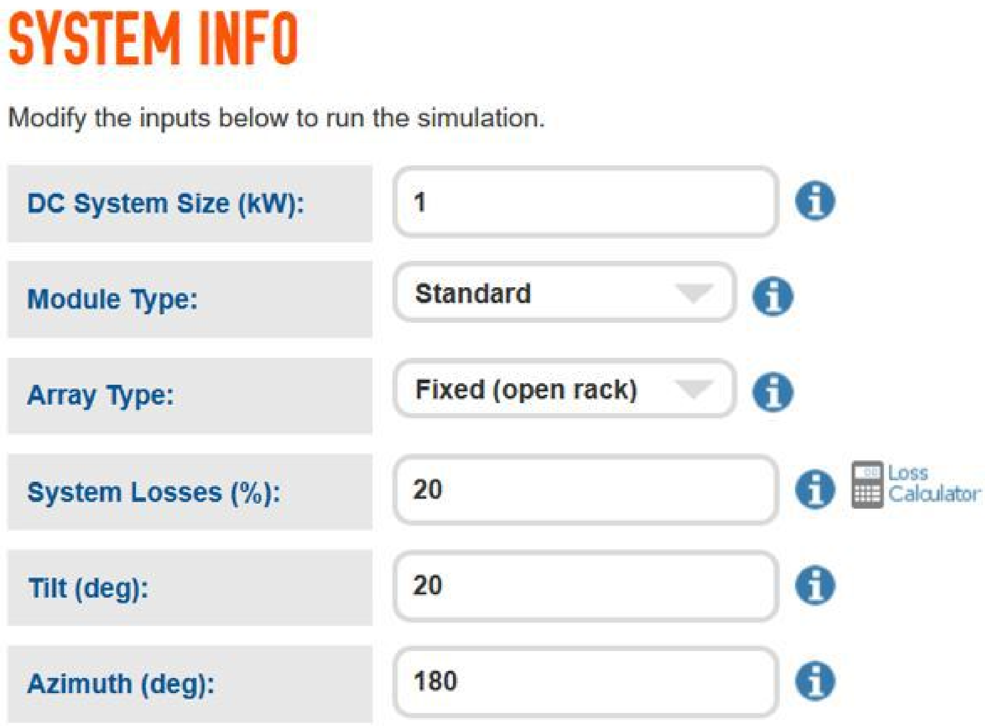
a. Type in your location at the *Get Started* page



b. PVWatts tool will automatically select the resource data for your location. Next, click on the arrow on the right labeled *Go to system info.*



c. Next, the *System Info* tab will pop up.



DC System Size (kW): In this field, type in 1.

Module Type: Here, either use *Standard* if you are using crystalline silicon solar panels o if you plan to use Thin Film panels (e.g. for heavily shaded sites)- select *Thin Film* .

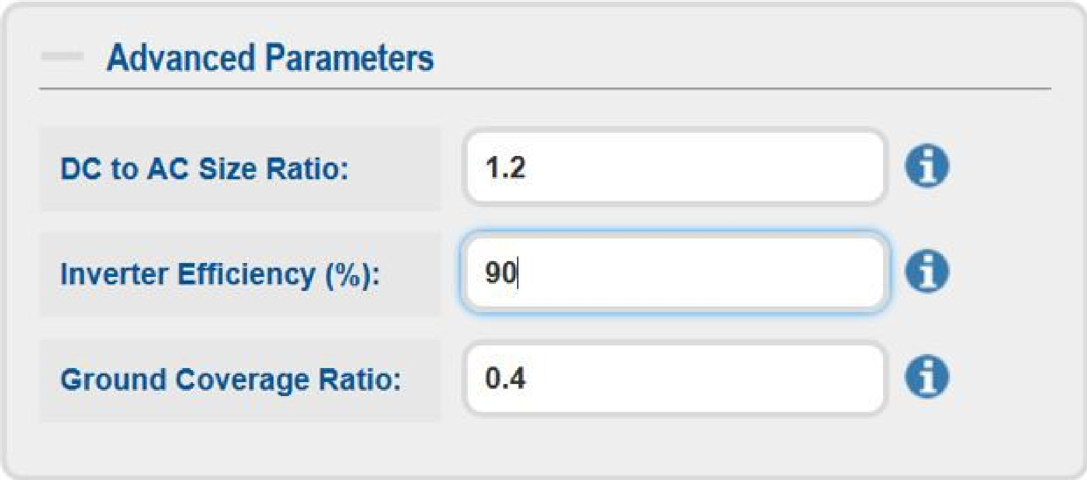
System Losses: By summing up the total losses in soiling, wiring, shading, charge controllers, and so on- we use a value of **20%** .

Array Type: Here, select *Fixed (roof mount)* for roof-mount systems, and *Fixed (open rack)* for ground mounted systems.

Tilt: This is the tilt angle for your solar panels as we learned in Chapter 6 Site Survey and Locating the Components chapter.

Azimuth: Similarly, this is the azimuth angle your panels will be facing that we also learned about in Chapter 6.

d. Next, scroll down to the *Advanced Parameters* section and click on it to expand the section. Here only change the *Inverter Efficiency* value to **90%**.



e. We are now done with this tab. Click on the arrow on the right labeled *Go to PVWatts Results.*

f. Now we arrive at the results tab which includes a table with monthly generation values of the solar system for the particular location we chose and the parameters we set. We will use these values in the next step.

Month	Solar Radiation (kWh / m^2 / day)	AC Energy (kWh)	Value ($)
January	3.36	72	8
February	4.01	76	8
March	4.83	99	11
April	5.78	111	12
May	6.36	123	14
June	6.43	119	13
July	6.24	117	13
August	6.12	115	13
September	5.62	104	12
October	5.06	99	11
November	3.97	80	9
December	3.17	68	8

(iii) **Calculate the Solar Array Size:** To calculate the solar array size, first we calculate the *Required Monthly Solar Energy* by multiplying the *Required Daily Solar Energy* value we calculated in step (i) with the number of days in the lowest energy month in question (i.e. 31/30/28 days depending on the month).

Next, for a system that is used throughout the year we take the lowest *AC Energy* value in the Results Table in step (ii) f. For instance, the lowest energy month in the table presented here is December with 68kWh. Note that the table presented is only an example for Long Island, and it can vary for your location. If the solar system is planned to be used only in a particular month or months, choose the lowest *AC Energy* month within these months.

This is a simple unitary method which can be summarized as "1 kW solar system can produce 'X' amount of energy. How many kW of the solar array do we need to produce our required amount of energy 'Y'?"

$$\textit{Solar Array Size}\ (kW) = \frac{\textit{Required Daily Solar Energy}\ (kWh)}{\textit{Lowest Energy Month AC Energy}\ (kWh) \div \textit{Number of Days in Lowest Energy Month}}$$

Note that we might get a solar array size value that is higher than we can physically fit on the roof (as we saw in Chapter 6). In that case, we may need to go back to step 1 and reduce our load usage or go for more efficient appliances. If load usage cannot be reduced, we can go for a second source of energy such as a diesel generator.

(iv) **Solar Panel Selection:** Finally, we make a selection of panels based on three things- your calculated *Solar Array Size* , what will physically fit on your roof, and what panel brands are available. For example, if we obtain 2kW as our *Solar Array Size* and we have 300W solar panels from a reputable brand available at discount in our near store. We need *2000 W/300 W = 6.25 panels* . We simply round this off to 7 panels.

The panels are then arranged into series and/or parallel connections as we learned in Chapter 8. The total output voltage and current of the arrangement are then calculated. Note that the output voltage and current rating of the solar array must be within the PV/DC maximum current and voltage ratings of the charge controller or inverter as we will see later.

4. Inverter Sizing

The size of the inverter will depend on the total power and total current of the loads (including surge ratings) as we recorded in step 1. Sometimes, the inverter datasheet will specify maximum output power/current as well as a maximum surge output.

The maximum surge power/current can sustain for a short time and can be matched with our total power/current values that include surge ratings.

While, the maximum output power/current is rated for continuous use, is to be matched with our total power/current values excluding surge ratings.

The next thing is that the voltage and frequency rating of the inverter needs to be matched with the loads. The inverter is also influenced by the number of phases- single or three phases. Most off-grid systems up to 5kW will be a single phase. The standard voltage and frequency (in Hz) vary from country to country, e.g. in the USA, it is 120 V 60 Hz for single-phase, while in Europe it is 230 V 50 Hz.

Finally, the inverter must be compatible with the battery in terms of voltage (12 V, 24 V, 48 V, etc.) and the type of battery (lithium ion or lead acid [AGM, FLA, etc.]).

Inverters with integrated charge controllers

Note that if we choose an inverter that has an integrated charge controller within it, the solar panels have to be connected to the inverter. We must make sure that the **Corrected Output Current and Voltage of the solar array is equal to or less than the DC Input Voltage and Current of The Inverter.** The DC input voltage and current of the inverter will be specified in the inverter datasheet. While the maximum solar array voltage and current is calculated as follows-

Corrected Array Voltage (V) = 1.15 x Solar Panel Open Circuit Voltage (V) x Number of Solar Panels in Series

Corrected Array Current (A) = 1.56 x Solar Panel Short Circuit Current (A) x Number of Strings in Parallel

Note that the solar panel open circuit voltage and short circuit current is available in the solar panel datasheet. While the numbers 1.15 and 1.25 are essential safety factors. You may need to change the number of series and parallel connections of the solar array or even need to select different solar panel models to fit in with the inverter. Else, we need to choose a different inverter to fit in with our solar array output.

The next thing we need to keep in mind is the **MPPT voltage range** . The inverter works best when the solar array voltage is within the inverter's MPPT voltage range. For the inverter in this example below, we see the MPPT voltage range is 125 to 550V. So, we need to make sure the maximum solar voltage is well above 125 V but below 550 V. The voltage needs to be well above 125 V as practically the maximum output voltage of the array will face losses in cables and due to temperature.

Let us take the example of the following solar panel and inverter datasheets, and find the corrected values.

ELECTRICAL DATA (STC)

Peak Power Watts-P_{MAX} (Wp)*	320	325	330	335	340
Power Output Tolerance-P_{MAX} (W)	0 ~ +5				
Maximum Power Voltage-V_{MPP} (V)	37.1	37.2	37.4	37.6	37.8
Maximum Power Current-I_{MPP} (A)	8.63	8.73	8.83	8.91	8.99
Open Circuit Voltage-V_{OC} (V)	45.5	45.6	45.8	46.0	46.2
Short Circuit Current-I_{SC} (A)	9.15	9.19	9.28	9.35	9.42
Module Efficiency η_m (%)	16.5	16.7	17.0	17.2	17.5

Excerpt from Solar Panel Datasheet- usually data for panels of different wattages are specified within a single datasheet. The required data for the 320 W panel is highlighted here

Source: Trina Solar

X1-HYBRID-3.0T

INPUT (DC)	C Version E Version I Version
Max.PV array power [Wp]	4500
Max.recommended DC power[W]	A:3000 B:3000
Max.DC voltage [V]	600
Nominal DC operating voltage [V]	360
Max. input current (input A/input B) [A]	12/12
Max. short circuit current (input A/input B) [A]	14/14
MPPT voltage range[V]	125-550
Start operating voltage[V]	150
No. of MPP trackers / Strings per MPP tracker	2(1/1)

Excerpt from Hybrid Inverter Datasheet - the hybrid inverter has an integrated charge controller

Source: SolaX Power

Taking the 320 W solar panel as an example, which has a maximum voltage of 37.1 V. We can find the minimum and maximum panels that can be used to stay within this inverter's MPPT voltage range.

$$\textbf{Minimum No. of Panels} = \frac{\textbf{Minimum Inverter MPPT Voltage (V)}}{\textbf{Solar Panel Maximum Power Voltage (V)}}$$

$$= \frac{125\,V}{37.1\,V} = 3.36\,panels \approx 4\,panels$$

$$\textbf{Maximum No. of Panels} = \frac{\textbf{Maximum Inverter MPPT Voltage (V)}}{\textbf{Solar Panel Maximum Power Voltage (V)}}$$

$$= \frac{550\,V}{37.1\,V} = 14.8\,panels \approx 14\,panels$$

Let us consider 2 strings with 4 panels in series. We then find the corrected voltage and current to see if it is within the inverter's range. We

see that voltage wise we are well within the range- corrected array voltage is 209.3 V while inverter maximum DC voltage is 600 V. For current, the inverter maximum short circuit current for two of the string inputs is 14 A + 14 A = 28 A. Our corrected array current is 28.48 A- this is acceptable as it is only 0.48 A higher with a good amount of safety factor considered.

Corrected Array Voltage (V) = 1.15 x Solar Panel Open Circuit Voltage (V) x Number of Solar Panels in Series

= 1.15 x 45.5 V x 4 = 209.3 V

Corrected Array Current (A) = 1.56 x Solar Panel Short Circuit Current (A) x Number of Strings in Parallel

= 1.56 x 9.15 A x 2 = 28.48 A

5. *Charge Controller Selection*

In Chapter 5 we saw how to select between the types of charge controller (MPPT vs PWM). We also noted that charge controllers are integrated within some inverters. While for other inverters they are not integrated and we need a separate charge controller.

Charge controller selection and sizing are quite simple, let us see how it is done.

Battery compatibility: First of all, we need to match the DC output voltage or recommended battery voltage rating of the charge controller with the battery bank voltage (12 V, 24 V, 48 V …). We will also need to match the type of battery (lithium ion or lead acid [AGM, FLA, etc.]).

Charge current: Charge controllers are usually rated according to their charge current, e.g. 20 A PWM charge controller or 60 A MPPT charge controller. We find the charge current using the total solar array power and the DC system voltage which is essentially the battery bank voltage. We also use a 1.25 safety factor multiplier.

$$\textbf{Charge Current } (A) = \frac{\textbf{1.25 x Solar Array Size } (W)}{\textbf{Battery Bank Voltage } (V)}$$

Solar array limits: Next, we need to ensure that the Corrected Solar Array Output Current/Voltage/Power is less than or equal to the Input Current/Voltage/Power of the Charge Controller. Similar to what we saw in step 5, the input voltage and current of the charge controller will be specified in its datasheet. The maximum solar array voltage and current is calculated as follows-

Corrected Array Voltage (V) = 1.15 x Solar Panel Open Circuit Voltage (V) x Number of Solar Panels in Series

Corrected Array Current (A) = 1.56 x Solar Panel Short Circuit Current (A) x Number of Strings in Parallel

BlueSolar Charge Controller	MPPT 75/10	MPPT 75/15
Battery voltage (auto select)		12/24V
Rated charge current	10A	15A
Nominal PV power, 12V 1a,b)	145W	220W
Nominal PV power, 24V 1a,b)	290W	440W
Nominal PV power, 48V 1a,b)	n. a.	n. a.
Max. PV short circuit current 2)	13A	15A
Automatic load disconnect		Yes
Max. PV open circuit voltage	75V	
Peak efficiency		98%
Self-consumption		12V: 25 mA 24V: 15 mA
Charge voltage 'absorption'		14,4V / 28,8V (adjustable)
Charge voltage 'float'		13,8V / 27,6V (adjustable)
Charge algorithm		multi-stage adaptive
Temperature compensation		-16 mV / °C resp. -32 mV / °C
Max. continuous load current		15A

Charge Controller Datasheet Excerpt
Source: Victron Energy

Again, the solar panel open circuit voltage and short circuit current are available in the solar panel datasheet. You may need to reconfigure your solar panel connections or even need to select different solar panels or charge controller.

6. Cable Sizing

We are now done with the selection and sizing of most of the major system components. All that remains is the cables and protection devices. This is a very important step because incorrectly sized cables and protection devices can be very risky. It might seem like a lot at first, but just look at them one at a time and you'll realize how simple it all is.

We will follow the procedures for cable sizing specified in the US National Electrical Code (NEC).

As noted earlier in Chapter 5, we have to size the following cables-

✓ Solar panels to DC Combiner Box (Solar cables)

✓ DC Combiner Box to Charge Controller (THW cables)

✓ Cables connecting the Battery, Charge Controller, and Inverter (THWN-2 or THHN or XHHW-2 cables)

✓ Cables from Inverter to AC Distribution Box (THW cables)

✓ *…And if not installed already-* AC Distribution Box to AC Loads and Charge Controller to DC Loads (i.e. lights, appliances, sockets, etc.)

(THW cables)

Let us now understand how to correctly size each of the above cables. There are two broad steps to finalizing the cable size- first finding the cable size based on ampacity and next verifying the cable size based on voltage drop .

Below is the **Copper Wire Ampacity Table** depicting the ampacity (current carrying capacity) for copper cables of different sizes and temperature rating. We will use this table for all of our cable sizing calculations in this section. So, make sure to refer to this table when sizing cables for your solar system.

Cable Size		**Ampacity According to Temperature Rating of Copper Wire***	
AWG	mm^2	75°C (167°F)	90°C (194°F)
18 AWG	1	—	14
16 AWG	1.5	—	18
14 AWG	2.5	20	25
12 AWG	4	25	30
10 AWG	6	35	40
8 AWG	10	50	55
6 AWG	16	65	75
4 AWG	25	85	95
3 AWG	35	100	115
2 AWG	35	115	130
1 AWG	50	130	145
1/0 AWG	70	150	170
2/0 AWG	70	175	195
3/0 AWG	95	200	225
4/0 AWG	120	230	260

*Cable temperature ratings and types:

75°C (167°F) : THHW, THW, THWN,

90°C (194°F) : Solar Cable, THHN, THHW, THW-2, THWN-2, USE-2, XHH, XHHW, XHHW-2

Copper Wire Ampacity Table

Source: National Electric Code 2017

Solar Panels to DC Combiner Box (Solar Cables)

Let us go through the calculation steps with an example solar panel. We will use the 260 W solar panel by Vikram Solar for our example as we see in the datasheet excerpt below. For the 260 W panel can see that the short circuit current is 8.93 A and the open circuit voltage is 37.9 V. While the maximum voltage is 30.8 V and the maximum current is 8.43 A. These values will be used in our solar cable calculation example.

Electrical Data[1] All data refers to STC (AM 1.5, 1000 W/m², 25 °C)

Peak Power P_{max} (Wp)	260.0	262.5	265.0	267.5	270.0	272.5	275.0	277.5	280.0	282.5	285.0
Maximum Voltage V_{mpp} (V)	30.8	30.9	30.9	31.0	31.0	31.1	31.2	31.2	31.3	31.4	31.5
Maximum Current I_{mpp} (A)	8.43	8.50	8.57	8.62	8.70	8.76	8.82	8.89	8.94	9.00	9.07
Open Circuit Voltage V_{oc} (V)	37.9	38.0	38.1	38.2	38.3	38.4	38.5	38.6	38.7	38.8	38.9
Short Circuit Current I_{sc} (A)	8.93	8.98	9.03	9.09	9.12	9.17	9.22	9.27	9.32	9.37	9.41
Module Efficiency η(%)	15.98	16.14	16.29	16.44	16.60	16.75	16.90	17.06	17.21	17.36	17.52

1) STC: 1000 W/m² irradiance, 25°C cell temperature, AM 1.5g spectrum according to EN 60904-3.
Average relative efficiency reduction of 5% at 200 W/m² according to EN 60904-1.

Source: Vikram Solar

I. Cable Size Based on Ampacity:

To work out the cable size based on ampacity, we need to work out the maximum possible current in the cables. We need the Short Circuit Current of the solar panel.

There are two formulas. We need to choose the higher result from the two formulas.

a.

$$Corrected\ Current\ (A) = 1.56\ x\ Solar\ Panel\ Short\ Circuit\ Current\ (A)$$

b.

$$Corrected\ Current\ (A) = \frac{1.25\ x\ Solar\ Panel\ Short\ Circuit\ Current\ (A)}{Temperature\ Correction\ Factor\ x\ Conduit\ Fill\ Factor}$$

For the second formula b., we need to work out the Temperature Correction Factor and Conduit Fill Factor.

- **Temperature Correction Factor** is used to compensate for the surrounding temperature of the cable. It is calculated using the following steps-

(i) Maximum Ambient Temperature: For this, we need to first find out the maximum ambient temperature expected in your location. You can find this data online on weather websites such as en.climate-data.org. For instance, the data for the city of Phoenix in the USA is shown below. As we can see, the maximum temperature is 40.8°C and that occurs in July.

	January	February	March	April	May	June	July	August	September	October	November	December
Avg. Temperature (°C)	11.4	13.6	16.1	20.1	24.8	29.7	32.7	31.7	28.6	22.5	15.7	11.6
Min. Temperature (°C)	3.6	5.3	7.5	10.7	15.1	19.9	24.7	23.8	20	13.5	7.3	3.8
Max. Temperature (°C)	19.3	22	24.7	29.5	34.5	39.6	40.8	39.7	37.2	31.5	24.2	19.5

Source: Climate-Data.org

(ii) Correction for Rooftop Systems: This factor is applicable for rooftop systems only. If you are looking at a ground-mount system, skip this step and go to step III.

This factor depends on the height of the cable or cable conduit above the roof. For our example, let us consider it is a solar system on an RV where the cable conduit is placed directly on the roof. In other words, the height is 0 inches above the roof. Referring to the table below, we need to add 33°C to the maximum ambient temperature we found in step I. So, in our case, we get-

Corrected Ambient Temperature = 40.8 °C + 33°C = 73.8°C.

Height of cables/conduit above roof (inches)	0-0.5	0.5-3.5	3.5-12	Above 12
Add to Ambient (°C)	33	22	17	14

Source: National Electric Code 2017

(iii) Temperature correction factor calculation: We then use the maximum ambient temperature (from step I, for ground mount system) or the Corrected Ambient Temperature (from step II, for roof mount system) to find the Temperature Correction factor from the below table.

Referring to the table below for our example with Corrected Ambient Temperature of 73.8°C, we get a Temperature Correction Factor of 0.5.

Ambient Temperature		**Temperature Correction Factor**
50°F or less	10°C or less	1.15
51-59°F	11 to 15°C	1.12
60-68°F	16 to 20°C	1.08
69-77°F	21 to 25°C	1.04
78-86°F	26 to 30°C	1.00

Ambient Temperature		Temperature Correction Factor
87-95°F	31 to 35°C	0.96
96-104°F	36 to 40°C	0.91
105-113°F	41 to 45°C	0.87
114-122°F	46-50°C	0.82
123-131°F	51-55°C	0.76
132-140°F	56-60°C	0.71
141-149°F	61-65°C	0.65
150-158°F	66-70°C	0.58
159-167°F	71-75°C	0.50
168-176°F	76-80°C	0.41
177-185°F	81-85°C	0.29
Source: National Electric Code 2017		

- **Conduit Fill Factor** is used when we have several cables inside a conduit.

For our example let us consider we have 3 parallel strings of solar panels. Each string will have a positive and a negative cable, so in total there will be *3 x 2 = 6 cables*. Referring to the table below, for 4 cables in a conduit, the cable fill factor is 0.8.

Number of Cables/Wires Inside Conduit	0-3	4-6	7-9	10-20	21-30
Conduit Fill Factor	1	0.8	0.7	0.5	0.45

Finally, after obtaining the Temperature Correction Factor and the Conduit Fill Factor- we can work out the Corrected Current for our example. We work out both the formulas here. Remember we need to choose the highest from the two formulas.

a.

$$\boldsymbol{Corrected\ Current\ (A) = 1.56\ x\ Solar\ Panel\ Short\ Circuit\ Current\ (A)}$$

$$= 1.56\ x\ 8.93\ A = 13.93\ A$$

b.

$$\boldsymbol{Corrected\ Current\ (A) = \frac{1.25\ x\ Solar\ Panel\ Short\ Circuit\ Current\ (A)}{Temperature\ Correction\ Factor\ x\ Conduit\ Fill\ Factor}}$$

$$= \frac{1.25\ x\ 8.93\ A}{0.5\ x\ 0.8} = 27.91\ A$$

- **Choosing Cable Size:** Finally, we choose the highest of the two, which is 27.91 A, and choose the appropriate size of the cable from the ***Copper Wire Ampacity Table*** . Normally, solar cables have a temperature rating of 90°C. So, by referring to the Copper Wire Ampacity Table for 90°C temperature rating and 27.9 A current rating, we can choose a minimum cable size of 4 mm ^{2} (12 AWG) for each PV string.

Cable Size		**Ampacity According to Temperature Rating of Copper Wire***	
AWG	**mm²**	**75°C (167°F)**	**90°C (194°F)**
18 AWG	1	—	14
16 AWG	1.5	—	18
14 AWG	2.5	20	25
12 AWG	4	25	30
10 AWG	6	35	40
8 AWG	10	50	55
6 AWG	16	65	75
4 AWG	25	85	95
3 AWG	35	100	115
2 AWG	35	115	130
1 AWG	50	130	145
1/0 AWG	70	150	170
2/0 AWG	70	175	195
3/0 AWG	95	200	225
4/0 AWG	120	230	260

*Cable temperature ratings and types:

75°C (167°F) : THHW, THW, THWN,

90°C (194°F) : Solar Cable, THHN, THHW, THW-2, THWN-2, USE-2, XHH, XHHW, XHHW-2

Source: National Electric Code 2017

II. Cable Size based on Voltage Drop:

To finalize the cable size, we need to check the voltage drop for the size we chose in the previous step 1. Voltage drop is basically the loss of voltage in the cable. The longer a cable is- the thicker the cable needs to be in order to limit the voltage drop to the acceptable 2%.

We verify our chosen cable size in step I with the minimum cable size to stay within our voltage drop limit, using the formula below-

$$\textit{Minimum Cable Size}\ (mm2) = \frac{\textit{Wire Resistivity}\ \left(\frac{\Omega \mathrm{mm2}}{\mathrm{m}}\right)\ x\ \textit{Total Cable Length}\ (m)\ x\ \textit{Maximum Current}\ (A)}{\textit{Voltage Drop}\ x\ \textit{Maximum Voltage}\ (V)}$$

Let us go through the values we need to use in the above equation-

- **Wire Resistivity:** As discussed previously, it is recommended to use copper cables for solar systems. The resistivity of copper is **0.0171 Ωmm2/m.**
- **Total Cable Length:** This will be the total cable length including the positive and the negative cable. Since there are two cables, we need to multiply the one-way distance of the cable by 2.

For our example let us take a one-way distance from the solar array to the DC combiner box to be 7 m (23 ft). So, the total cable length will be *2 x 7 = 14 m.*

- **Maximum Current:** Take note that unlike the previous step of finding the Corrected Current, we don't use the short circuit current. Instead, we use the maximum current of the solar panel.

For our example solar panel, as we can see in the datasheet excerpt below, the maximum current is 8.43 A.

- **Voltage Drop:** According to international standards, it is acceptable to use a voltage drop of **2%**.
- **Maximum Voltage:** Again, we don't use the open circuit voltage here. Instead, we use the maximum voltage of the solar panel. Remember we need to multiply the number of solar panels that are connected in series to find the total voltage of a string.

In our example, let us consider we have 2 panels in series in each string; thus, the total maximum voltage for each string is *2 x 30.8 V= 61.6 V* .

Peak Power P_{max} (Wp)	260.0
Maximum Voltage V_{mpp} (V)	30.8
Maximum Current I_{mpp} (A)	8.43
Open Circuit Voltage V_{oc} (V)	37.9
Short Circuit Current I_{sc} (A)	8.93
Module Efficiency η(%)	15.98

Source: Vikram Solar

Now using the above values for our example calculation, we get-

$$Minimum\ Cable\ Size\ (mm2) = \frac{Wire\ Resistivity\ \left(\frac{\Omega mm2}{m}\right) x\ Total\ Cable\ Length\ (m)\ x\ Maximum\ Current\ (A)}{Voltage\ Drop\ x\ Maximum\ Voltage\ (V)}$$

$$= \frac{0.0171 \frac{\Omega mm2}{m}\ x\ 7\ m\ x\ 2\ x\ 8.43\ A}{0.02\ x\ 61.6} = 1.64\ mm2$$

As we see the minimum cable size to stay within a 2% voltage drop is 1.64 mm^2 . The cable we chose, $4mm^2$ is greater than this minimum cable size. So, we can use the $4mm^2$ cable as the solar cable size. Great!

Well done for acing the cable sizing calculations! The process is more or less the same (even simpler rather) for the other cables. Since the next cables will be used indoors, we don't need to calculate the temperature correction factors like we had to do for the solar cables. What a relief, right?

Let us quickly go through the rest of the cables.

DC Combiner Box to Charge Controller (THW cables)

As we discussed earlier, the DC Combiner Box is used to combine the output of two or more parallel strings of solar panels. In that case the current increases according to the number of strings. Therefore, the cable has to be thick enough to handle the combined current.

The combined current is obtained by using the formula-

Combiner Box Output Current (A) = 1.56 x Solar Panel Short Circuit Current x Number of Strings

Continuing our example system, with 3 strings of solar panels, each having a short circuit current of 8.93A, we get-

Combiner Box Output Current (A) = 1.56 x 8.93 A x 3 strings

= 41.79 A

We need to use the **Copper Wire Ampacity Table** again for finding the cable size for this current. Refer to the table towards the beginning of this section on

Cable Sizing. This time we use THW cables as this cable will be located indoors. THW cables have a temperature rating of 75°C.

The cable size for a 75°C temperature rating and 41.79 A is 10mm2 (8 AWG).

Next, we still need to verify the voltage drop for this size. `

Remember for voltage drop we use the maximum current and not the short circuit current. As we have 3 PV strings, the maximum current of the panel is thus multiplied by 3- i.e. *8.43 A x 3.*

Let us consider the one-way length from the combiner box to the charge controller to be 3 m (10 ft).

Meanwhile, the maximum voltage is calculated by multiplying the solar panel maximum voltage with the number of panels in series. We consider 2 panels in series in each string in our example, which gives us a total maximum voltage of *30.8 V x 2 = 61.6 V* .

$$\boldsymbol{Minimum\ Cable\ Size\ (mm2) = \frac{Wire\ Resistivity\ \left(\frac{\Omega mm2}{m}\right) x\ Total\ Cable\ Length\ (m)\ x\ Maximum\ Current\ (A)}{Voltage\ Drop\ x\ Maximum\ Voltage\ (V)}}$$

$$= \frac{0.0171\ x\ 3\ x\ 2\ x\ 8.43\ A\ x\ 3}{0.02\ x\ 61.6\ V} = 2.11\ mm2$$

Perfect! Our chosen cable 10mm^2 is thicker than the required minimum cable size to stay within our voltage drop limit.

Let us now move on to the battery cables.

Charge Controller to Battery (THWN-2 or THHN or XHHW-2 cables)

The cable connecting the charge controller to the battery is sized based on the charge controller output current rating. In most cases, the recommended cable/terminal size will be specified in the charge controller datasheet or manual. If this information is not mentioned in the charge controller documents we need to manually calculate it.

Let us take an example charge controller, the Renogy RVR60.

PARAMETERS

Nominal System Voltage	12V/24V/36V/48V Auto Recognition
Rated Charge Current	60A
Rated Load Current	20A
Battery Voltage	9V-70V
Max. PV Input Voltage	150 VDC (25°C), 145VDC (-25°C)
Self-Consumption	0.7W-1.2W
Temperature Compensation	-3mV/°C/2V
Dimensions	285 x 205 x 102mm (11.2 x 8.1 x 4.0 in)
Max Terminal Size	25mm2 4 AWG
Net Weight	3.6 kg; 7.9 lbs.

Source: Renogy

As we can see in the datasheet excerpt above, the maximum terminal size is given as 25 mm^2 (4 AWG). That means we cannot install cables bigger than this size for this charge controller.

At any rate, we will do the calculation to find the appropriate cable size.

For the calculation, we take the Rated Load Current (also known as the Charge Controller Output Current) and apply a safety factor of 1.25.

Corrected Charge Controller Output Current (A) = 1.25 x Charge Controller Output Current (A)

= 1.25 x 60 A

= 75 A

Now we move on to the voltage drop verification. For example, let us consider the distance between the charge controller to the battery as 2 m and the battery voltage to be 24 V.

$$Minimum\ Cable\ Size\ (mm2) = \frac{Wire\ Resistivity\ \left(\frac{\Omega mm2}{m}\right) x\ Total\ Cable\ Length\ (m)\ x\ Maximum\ Current\ (A)}{Voltage\ Drop\ x\ Maximum\ Voltage\ (V)}$$

$$= \frac{0.0171\ x\ 2\ x\ 2\ x\ 75\ A}{0.02\ x\ 24\ V} = 10.69\ mm2$$

Referring back to the Copper Wire Ampacity table and looking at 90°C rated *THWN-2 or THHN or XHHW-2 cables* , we can use 16 mm^2 (6 AWG) cables. 16 mm2 cable can handle currents up to 75 A and is above the required minimum cable size based on voltage drop.

Battery to Inverter and Battery to Battery (THWN-2 or THHN or XHHW-2 cables)

Next, we look at the cables that connect the battery bank to the inverter. A couple of pointers for planning battery to inverter cables-

✓ It is advisable to keep the cable distance between the battery and the inverter to less than 3 m (10 ft).

✓ The higher the battery bank voltage, the smaller the size of the battery to the inverter cable.

The inverter datasheet and manual should have a recommended size and length for battery cable as we see below in the manual of GoodWe ES inverter.

Figure 2.4.2-1

Grade	Description	Value
A	Outside Diameter Insulation	10-14 mm
B	Isolation Section	NA
C	Conductor Core Section	20-35 mm²

Source: Goodwe

If the recommended size and length is not given in the inverter documents, we need to calculate it. We need the Maximum DC Input Current (also known as Maximum Battery Discharge Current) to work out the cable size. Let us take the example of a GoodWe 3.6 kW inverter.

Technical Data		GW3648D-ES	GW5048D-ES
Battery Input Data	Battery Type	Li-Ion	
	Nominal Battery Voltage (V)	48	
	Max. Charging Voltage (V)	≤60 (Configurable)	
	Max. Charging Current (A)*1	75	100
	Max. Discharging Current (A)*1	75	100
	Battery Capacity (Ah)*2	50~2000	
	Charging Strategy for Li-Ion Battery	Self-adaption to BMS	

Source: Goodwe

From the datasheet excerpt, we can see the Maximum Charging/Discharging current is 75 A. We consider double this maximum current to account for surge currents that may occur due to some loads such as refrigerators and water pumps. So, the current we use is *2 x 75 A = 150 A.*

Looking back at the Copper Wire Ampacity Table given at the beginning of the Cable Sizing section, 150 A can be handled by cable of size 70 mm^2 (1/0 AWG). Remember we use THWN-2 or THHN or XHHW-2 cables here with a 90°C temperature rating.

Next, let us verify the cable size based on voltage drop for a distance of 2.5 m for a 48 V battery bank.

$$Minimum\ Cable\ Size\ (mm2) = \frac{Wire\ Resistivity\ \left(\frac{\Omega mm2}{m}\right) x\ Total\ Cable\ Length\ (m)\ x\ Maximum\ Current\ (A)}{Voltage\ Drop\ x\ Maximum\ Voltage\ (V)}$$

$$= \frac{0.0171\ x\ 2.5\ m\ x\ 2\ x\ 150\ A}{0.02\ x\ 48\ V} = 13.36\ mm2$$

As we can see, our choice of 70 mm2 cable is well over our required minimum cable size based on voltage drop- so we can go for that!

Calculating from inverter power rating, efficiency and input voltage

There is also another way to calculate the battery to inverter cable size in case battery charging/discharging current or inverter input current is not given.

Let us take the example of a Victron Multiplus 1600 VA inverter/charger to be connected to a 24 V battery bank. An excerpt from the datasheet is shown below.

12 Volt 24 Volt 48 Volt	12/500/20 24/500/10 48/500/6	12/800/35 24/800/16 48/800/9	12/1200/50 24/1200/25 48/1200/13	12/1600/70 24/1600/40 48/1600/20
PowerControl / PowerAssist	Yes / No	Yes / Yes		
Three Phase and parallel operation	Yes			
Transfer switch	16A			
INVERTER				
Input voltage range	9,5 – 17V 19 – 33V 38– 66V			
Output	Output voltage: 230VAC ± 2% Frequency: 50Hz ± 0,1% (1)			
Cont. output power at 25°C (3)	500VA	800VA	1200VA	1600VA
Cont. output power at 25°C	430W	700W	1000W	1300W
Cont. output power at 40°C	400W	650W	900W	1100W
Cont. output power at 65°C	300W	400W	600W	800W
Peak power	900W	1600W	2400W	2800W
Maximum efficiency	90 / 91 / 92%	92 / 93 / 94%	93 / 94 / 95%	93 / 94 / 95%
Zero-load power	6 / 6 / 7W	7 / 7 / 8W	10 / 9 / 10W	10 / 9 / 10W
Zero-load power in search mode	2 / 2 / 3W	2 / 2 / 3W	3 / 3 /3W	3 / 3 /3W

Source: Victron Energy

To calculate the battery to inverter current, we need the values of Rated Inverter Output Power, Minimum Inverter DC Input Voltage, and Inverter Efficiency.

It is interesting to note that this inverter can be used with a 12 V, 24 V, or 48 V battery. The inverter input voltage range when using a 24 V battery is 19 – 33 V. Therefore, the Minimum Input DC Voltage is 19 V.

The rated power of this inverter is 1600 VA. VA (Apparent Power) is related to W (Real Power) through the power factor. We will consider a power factor of 1, which gives us 1600 VA=1600 W. So, 1600 W is the Rated Inverter Output Power. While, we take an efficiency of 90%, which is below the maximum efficiency of 94% for 24 V configuration.

$$Inverter\ Input\ Current\ (A) = \frac{Rated\ Power\ (W)}{Minimum\ Input\ Voltage\ (V)\ x\ Inverter\ Efficiency}$$

$$= \frac{1600\ W}{19\ V\ x\ 0.9} = 93.57\ A$$

Next, we apply the surge consideration- *2 x 93.57 A = 187.14 A.*

Once again, looking at our Copper Wire Ampacity Table for 90°C rated cables, we can use 70 mm2 (2/0 AWG) cables, which can handle up to 195A current.

Let us now verify the cable size based on voltage drop for an inverter to battery distance of 2.5 m. Remember we take the Battery to Inverter current without surge consideration for the voltage drop calculation.

$$Minimum\ Cable\ Size\ (mm2) = \frac{Wire\ Resistivity\ \left(\frac{\Omega mm2}{m}\right)\ x\ Total\ Cable\ Length\ (m)\ x\ Maximum\ Current\ (A)}{Voltage\ Drop\ x\ Maximum\ Voltage\ (V)}$$

$$= \frac{0.0171\ x\ 2.5\ m\ x\ 2\ x\ 93.57\ A}{0.02\ x\ 24\ V} = 16.67\ mm2$$

Great, the 70 mm2 is above the voltage drop minimum cable size requirement!

When we have more than one battery, the cables used to interconnect batteries are the same size as the Battery to Inverter cable size that we just calculated here.

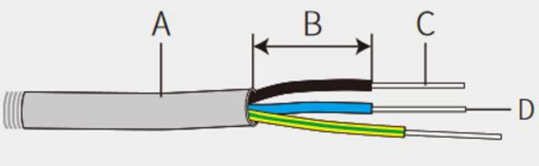
Battery interconnection cables connecting eight batteries
Source: Project AmpEater

Now that we're done with the battery cables, let us move on to the cables from the Inverter output to AC Distribution Box.

Inverter to AC Distribution Box (THW cables)

Like the other cables connected to the inverters, the recommended size of the Inverter AC Output cable that will connect to the AC Distribution Box. The recommended cable size and length are usually provided in the inverter datasheet or manual. An excerpt from the manual of the Goodwe ES inverter is shown below.

Prepare the terminals and AC cables according to the right table.



Grade	Description	Value
A	Outside diameter	13-18 mm
B	Separated wire length	20-25 mm
C	Conductor wire length	7-9 mm
D	Conductor core section	4-6 mm²

Source: Goodwe

If the cable size and length data are not provided we need to calculate it. We use the Maximum Inverter AC Output (available in the inverter datasheet) to size this cable. An excerpt from the datasheet of the Solax X1 Hybrid inverter is shown below.

OUTPUT AC	
Nominal AC power [VA]	3000
Max. apparent AC power [VA]	3300
Nominal grid voltage(AC voltage range) [V]	220/230/240(180-270)
Nominal grid frequency/range [Hz]	50/60
Nominal AC current [A]	13
Max. AC current [A]	14.4

Source: SolaX Power

We can see the Maximum AC Output Current of the inverter is 14.4A. Here, we have to apply a safety factor of 1.25.

Corrected Inverter AC Output Current (A) = 1.25 x Maximum AC Output Current (A)

= 1.25 x 14.4 A

= 18 A

Next, we refer to our Copper Wire Ampacity Table to find a matching size for 75°C rated THW cable. From the table, we can see that 2.5 mm2 (14 AWG) cable is adequate.

Finally, we verify the size based on the voltage drop. Let us say the distance from the inverter to the AC Distribution Box is 3 m and the standard AC voltage in the location is 230 V.

$$\text{Minimum Cable Size (mm2)} = \frac{\text{Wire Resistivity} \left(\frac{\Omega \text{mm2}}{\text{m}}\right) x \text{ Total Cable Length (m)} x \text{ Maximum Current (A)}}{\text{Voltage Drop } x \text{ Maximum Voltage (V)}}$$

$$= \frac{0.0171 \ x \ 3 \ m \ x \ 2 \ x \ 18 \ A}{0.02 \ x \ 230 \ V} = 0.401 \ mm2$$

That's great! Our selected 2.5mm2 cable is adequately above the minimum cable size based on voltage drop!

What if the Inverter output current is not specified in the datasheet?

In a case where this current is not provided, we can find the rated current of the inverter from its rated power and output voltage and then use these calculated currents to do the cable sizing calculations.

Taking again the example of the Victron Multiplus 1600 W inverter.

12 Volt 24 Volt 48 Volt	12/500/20 24/500/10 48/500/6	12/800/35 24/800/16 48/800/9	12/1200/50 24/1200/25 48/1200/13	12/1600/70 24/1600/40 48/1600/20
PowerControl / PowerAssist	Yes / No	Yes / Yes		
Three Phase and parallel operation	Yes			
Transfer switch	16A			
INVERTER				
Input voltage range	9,5 – 17V 19 – 33V 38– 66V			
Output	Output voltage: 230VAC ± 2%	Frequency: 50Hz ± 0,1% (1)		
Cont. output power at 25°C (3)	500VA	800VA	1200VA	1600VA
Cont. output power at 25°C	430W	700W	1000W	1300W
Cont. output power at 40°C	400W	650W	900W	1100W
Cont. output power at 65°C	300W	400W	600W	800W
Peak power	900W	1600W	2400W	2800W
Maximum efficiency	90 / 91 / 92%	92 / 93 / 94%	93 / 94 / 95%	93 / 94 / 95%
Zero-load power	6 / 6 / 7W	7 / 7 / 8W	10 / 9 / 10W	10 / 9 / 10W
Zero-load power in search mode	2 / 2 / 3W	2 / 2 / 3W	3 / 3 /3W	3 / 3 /3W

Source: Victron Energy

$$\text{Inverter Output Current (A)} = \frac{\text{Rated Power (W)}}{\text{Output Voltage (V)}}$$

$$= \frac{1600 \ W}{230 \ V} = 6.96 \ A$$

Corrected Inverter AC Output Current (A) = 1.25 x Maximum AC Output Current (A)

= 1.25 x 6.96 A

= 8.7A

As we saw earlier, we use the Corrected Inverter AC Output Current for cable sizing based on ampacity. We then verify the cable size based on voltage drop using the Rated Inverter Output Current.

AC Distribution Box to AC Loads and Charge Controller to DC Loads (THW cables)

Finally, we are at the last set of cables for your solar system! These are the cables that run from the AC Distribution Box to the loads such as the lighting circuits, sockets, and all other appliances. These cables may be already installed in an RV or a home. If they are not installed, we need to calculate the size and install them ourselves.

If there is a Consumer Unit with cables connected to the loads and sockets already in your home or RV we just need cables from the AC Distribution Box to be connected to the Consumer Unit. The size of this cable can be calculated using the usual cable sizing formulas based on the Inverter Output Maximum Current and the cable distance between the AC Distribution Box and the Consumer Unit.

The current rating of the appliance is usually specified in its manual or datasheet. We can also find the current rating from the Wattage of the appliance and its Rated Voltage. After finding the current, we simply do the sizing calculations as we saw earlier based on the copper wire ampacity ratings and voltage drop.

We need to apply a safety factor of 1.25 on the current rating to size the cables.

For AC appliances, the rated voltage depends on your country and type of connection (e.g. 120 V for the USA, 230 V for many Asian and European countries, etc.). While for DC appliances, it depends on the chosen battery bank voltage (e.g. 12 V, 24 V, 48 V, and so on).

Note that if a wire is planned to serve a circuit with more than one load, the current rating of all the loads must be added up.

Example calculation for a 75 W ceiling fan that operates with 120 V AC-

$$\boldsymbol{Rated\ Current}\ (\boldsymbol{A}) = \frac{\boldsymbol{Rated\ Power}\ (\boldsymbol{W})}{\boldsymbol{Rated\ Voltage}\ (\boldsymbol{V})}$$

$$= \frac{75\ W}{120\ V} = 0.625\ A$$

Example of a 15 W 12 V DC light-

$$\boldsymbol{Rated\ Current}\ (\boldsymbol{A}) = \frac{\boldsymbol{Rated\ Power}\ (\boldsymbol{W})}{\boldsymbol{Rated\ Voltage}\ (\boldsymbol{V})}$$

$$= \frac{15\ W}{12\ V} = 1.25\ A$$

For refrigerators, air conditioners, and water pumps - Remember we need to account for the surge currents when sizing the cable size! Refrigerators (4

times rated current), air conditioners (3 times rated current), and water pumps (6 times rated current) as we saw earlier.

For example, let us look at a 300W fridge that works with 120V AC.

$$\text{Rated Current } (A) = \frac{\text{Rated Power } (W)}{\text{Rated Voltage } (V)}$$

$$= \frac{300\ W}{120\ V} = 2.5\ A$$

Current Including Surge Consideration for Refrigerator (A) = 4 x Rated Current (A)

= 4 x 2.5 A = 10 A

So, when doing the cable sizing calculation for this example, we use 10 A to select the cable size based on ampacity ratings, while for the voltage drop sizing calculation, we use the rated 2.5 A.

Up next, we look at the sizing process for a couple of extra items that go with cables- busbars and cable conduits.

Busbar sizing

Busbars are necessary to combine outputs from different sources and distribute the electricity to various load circuits. As mentioned, we use busbars in the DC Combiner Box, AC Distribution Box, and so on.

Busbars have different thicknesses and sizes for different current ratings. The busbar must be rated to handle the maximum current it may be exposed to. We also apply a safety factor of 1.25.

Busbar Rating (A) = 1.25 x Total Current on Busbar

For instance, for a DC Combiner busbar that combines the output of 3 PV strings, each with a Short Circuit Current of 8.93 A we size the busbar as follows-

Busbar Rating (A) = 1.25 x 8.93 A x 3 strings = 33.49 A

We choose a busbar that is rated to handle above 33.49 A DC current. Remember to appropriately check the DC and AC current rating when selecting busbars.

Cable Conduit Sizing

As we saw in chapter 5, cables are usually placed inside cable conduits or ducts for safety and protection. There are a couple of norms when sizing the conduit.

- If one wire is placed in a conduit, the size or cross-sectional area of the wire (in mm2) shall not exceed 53% of the cross-sectional area of

the conduit (in mm2).

- If two wires are placed in a conduit, then the combined cross-sectional area of the cables shall not exceed 31% of the cross-sectional area of the conduit, and
- If three or more wires are placed in a conduit, then the total cable cross-sectional area shall not exceed 40% of the conduit cross-sectional area.

7. *Protection Device Selection*

Finally, the last components we need to select are the protection devices. This includes fuses, circuit breakers, residual current devices, surge protection devices, and grounding. We recommend you use this section together with the Protection Devices section in Chapter 5 to understand which types of devices you should choose.

Let us now go through the sizing formula for the protection devices. The calculations are similar to the cable sizing calculations, so we will just quickly go through them here. You may refer back to the cable sizing calculations to understand how to find current and voltage information from datasheets and manuals etc.

Important notes-

- When sizing protection devices, make sure the current rating of the protection device is lower than the current carrying capacity (ampacity) of the cable it is placed on.
- Make sure you choose the right rating and type of protection device (AC or DC) depending on where you plan to use it.

Fuses and Circuit Breakers

The standard ampere ratings for fuses and circuit breakers in USA/Canada are considered 15, 20, 25, 30, 35, 40, 45, 50, 60, 70, 80, 90, 100, 110, 125, 150, 175, 200, 225, 250, 300, 350, 400, 450, 500 and so on. Additional standard ampere ratings for fuses are 1, 3, 6, 10, and 601.

<u>DC Fuses</u> are typically installed in both the positive and negative wires between the solar array and the combiner box busbar. Solar inline fuses are the preferred type of fuses for their ease of use and installation. Fuses are favored over circuit breakers to be used with solar panels. This is because currents during peak sunshine time can sometimes cause circuit breakers to falsely trip.

However, if our solar system consists of only one string of solar panels, we can use a two-pole circuit breaker instead of fuses as the circuit breaker also acts as a switch between the solar array and charge controller. The circuit breaker will be sized with the same formulae for fuses given below.

DC Fuses used after solar panels are rated as follows-

Fuse Current Rating (A) = 1.56 x Solar Panel Short Circuit Current (A)

Fuse Voltage Rating (V) = 1.15 x Solar Panel Open Circuit Voltage (V)

Remember Solar Panel Short Circuit Current and Open Circuit Voltage is present in the solar panel datasheet.

Miniature Circuit Breakers (MCBs) are typically installed in the cables of the following locations-

- ✓ DC Combiner Box to Charge Controller (DC MCB)
- ✓ Charge Controller to Battery Bank (DC MCB)
- ✓ Battery Bank to Inverter (DC MCB)
- ✓ Inverter to AC Distribution Box (AC MCB)
- ✓ *...And if not installed already*- AC Distribution Box to Load Circuits (AC MCBs)

Let us now go through the selection process for each of these.

DC Combiner Box to Charge Controller (DC MCB)

As discussed, the DC combiner box combines the current from two or more solar panel strings. We use a 2 Pole DC Circuit breaker here.

We use the following formulas to calculate the ratings of this circuit breaker-

Circuit Breaker Current Rating (A) = 1.56 x Solar Panel Short Circuit Current (A) x Number of Strings

Circuit Breaker Voltage Rating (V) = 1.15 x Solar Panel Open Circuit Voltage (V) x Number of Solar Panels in Series

Charge Controller to Battery (DC MCB)

This MCB is sized based on the Maximum Charge Controller Output Current (also known as Charge Controller Load Current). The voltage rating is based on the battery bank voltage.

Circuit Breaker Current Rating (A) = 1.25 x Charge Controller Output Current (A)

Circuit Breaker Voltage Rating (V) = 1.15 x Charge Controller Output Voltage (V)

Battery Bank to Inverter (DC MCB)

The recommended circuit breaker rating between battery and inverter will usually be specified in the inverter manual. A 2 Pole DC Circuit breaker is needed here as well.

If it is not given, we can calculate the current and voltage rating of the battery breaker as follows-

Circuit Breaker Voltage Rating (V) = 1.15 x Maximum Inverter Input Voltage (V)

Circuit Breaker Current Rating (A) = 1.25 x Maximum Inverter Input Current (A)

OR

$$\textbf{Circuit Breaker Current Rating } (A) = \frac{\textbf{1.25 x Inverter Rated Power } (W)}{\textbf{Inverter Efficiency x Minimum Inverter Input Voltage } (V)}$$

Note that Maximum Inverter Input Current is also known as Maximum Inverter Charging/Discharging Current. This data as well as all the other inverter data will be present on the inverter datasheet.

Inverter to AC Distribution Box (AC MCB)

The recommended circuit breaker rating for the Inverter AC output should also be present in the inverter manual. Here, we use AC Circuit breakers, the number of poles will depend on the phases: 2-pole for single-phase and 4-pole for the three-phase system. (most small scale mobile and off-grid systems will be single-phase).

If the recommended circuit breaker is not given in the documents, it can be calculated as follows-

Circuit Breaker Voltage Rating (V) = Standard Inverter Output Voltage (V) (e.g. 120 V, 230 V)

Circuit Breaker Current Rating (A) = 1.25 x Maximum Inverter AC Output Current (A)

OR

$$\textbf{Circuit Breaker Current Rating } (A) = \frac{\textbf{1.25 x Inverter Rated Power } (W)}{\textbf{Inverter Output Voltage } (V)}$$

AC Distribution Box to AC Loads (AC MCB) and Charge Controller to DC Loads (DC MCB)

The breakers serving load circuits are sized by first finding the load current in the circuit as we saw in the AC Distribution Box to Loads cable sizing.

✓ For AC loads, we use AC circuit breakers- 2-pole for single-phase loads (most common) and 4-pole for 3-phase loads.

✓ For DC loads, we use 2-pole DC breakers.

Then apply a 1.25 safety factor. As we saw, the load current is either obtained from the appliance datasheet/manual or worked out by dividing its wattage by voltage as we saw in the load cable sizing section. Remember if multiple loads are to be served by the cable, the load currents of all the loads need to be added up.

Circuit Breaker Voltage Rating (A) = Rated Voltage of Loads (V) (e.g. DC- 12 V or AC- 120 V, 230 V)

Circuit Breaker Current Rating (A) = 1.25 x Total Load Current (A)

Residual Current Devices (RCD) are placed after the inverter output. Recommended ratings of RCD will typically be available in the inverter manual.

RCDs have a current rating, voltage rating, and an additional parameter called sensitivity. The current rating and voltage rating are calculated using the exact same procedure as that for the circuit breaker, as we have previously seen.

Sensitivity on the other hand is standardized as 30 mA, 100 mA, 300 mA, and so on. The sensitivity rating you should select, should be confirmed with the inverter manufacturer or supplier.

Surge Protection Devices (SPD) are usually placed in the DC combiner box (between the solar array and charge controller) and after the inverter. Make sure to use a DC SPD in the DC combiner box and an AC SPD after the inverter. As we discussed in Chapter 5 SPDs are connected in parallel with the circuit. SPDs also have a grounding terminal which has to be grounded.

40kA rated Type 2 SPDs are adequate for off-grid solar applications. The voltage rating is calculated as follows-

DC SPD Voltage Rating (V) = *1.15 x Solar Panel Open Circuit Voltage x Number of Solar Panels in Series*

AC SPD Voltage Rating (V) = *Inverter AC Output Voltage (e.g. 120V, 230V etc.)*

Grounding is necessary for the solar panel frames, mounting systems, inverters, charge controllers, surge protection devices, junction box enclosures, and other metallic parts.

The grounding cable chosen for solar panels and mounting systems should be **6mm2** (10AWG). Make sure to go through the manuals of the inverter, charge controllers, and also batteries (especially lithium-ion batteries) to understand their grounding requirements and recommended cable size.

Grounding cable is otherwise sized by taking the maximum current rating of the device in question. Then we follow the same cable sizing procedure based on the ampacity as we saw in the Cable Sizing section. Note we don’t need to consider voltage drop calculations for grounding cables.

8. Final System Schematic Diagram

That’s it! We are done with all the design calculations! Now all that is left is to put it all together in the form of a schematic diagram. This schematic diagram will be an essential guide during the installation process.

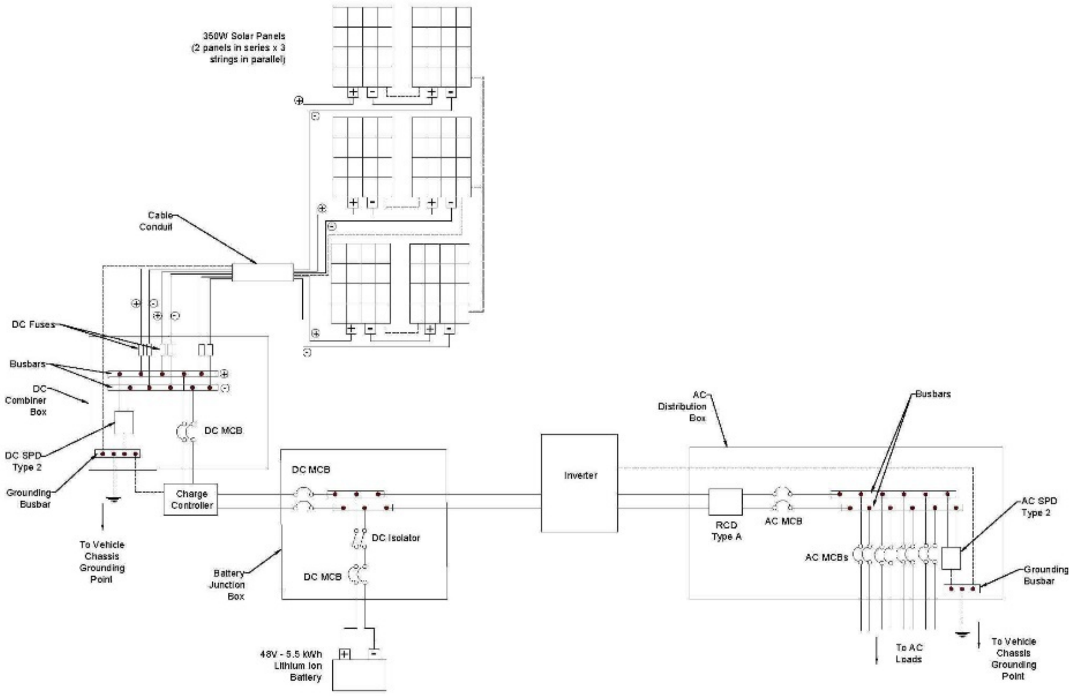
Here, we show an example schematic diagram based on the example calculations in this chapter.

The solar system has the following components-

- 260 W solar panels- 3 parallel strings with 2 panels in series in each string. The total solar array power is 1.56 kW.
- 60 A MPPT charge controller
- 1.2kW off-grid inverter

- 2 units of 12 V-300 Ah lead-acid batteries in series, giving us a 24 V battery bank with 4.8 kWh capacity
- Appropriately sized cables, busbars, protection devices, and switches. Note that the dotted lines represent grounding cables.

Notice the + and – signs in the diagram- they indicate the polarity, i.e. the positive (+) and negative (-) poles.



Now that we're done going over the planning and design procedure in detail, we will look at some example cases of mobile and off-grid home solar systems. In the examples, we will focus mainly on the load determination and sizing and selection of the main components. Various other practical concepts will also be covered.

However, we will not go into the depths of cable sizing and protection device selection as we have done so already in the previous section. The procedure is the same and we leave it to you to solve these as an exercise.

Whether you plan to install a solar system on your RV, boat, or home, we suggest you go through ALL the examples as a lot of practical information is spread out across the examples.

9.2 Simple Design for a Tiny House: Solar system, DC lights and fan

The first example is a very simple design for a tiny house in Phoenix, Arizona that consists of a small solar system, DC lights, and a fan. The tiny house is meant to be used as a weekend getaway.

Let us get started by first determining the loads.

9.2.1 Determining the loads

Let us consider 3 DC lights (5 W-12 V) that will be run 6 hours a day and a DC fan (15 W- 12 V) that will be run 12 hours a day. We see the daily energy requirement or daily load is **270 Wh or 0.27 kWh.**

Daily DC Load Consumption							
DC Load	Rated Power (W)	No. of Units	Subtotal Power (W)	Working Hours (h)	Energy (Wh)	Voltage (V)	Current (A)
DC lights	5	3	15	6	90	12	1.25
DC fan	15	1	15	12	180	12	1.25
TOTAL			30		270		2.50

9.2.2 Battery Selection and Sizing

We use the Required Battery Capacity formula as we saw earlier in this chapter. Since the tiny house will be occupied only at the weekend, let us consider 1 day of autonomy, meaning the battery can supply electricity for 1 day even if there is no sunshine. We consider a lead acid gel battery as the solar system will be used lightly and only at the weekend. As mentioned, we use 50% depth of discharge for lead acid batteries. Note that we have only DC loads, which means we can skip the inverter.

Also, looking at the temperature data for Phoenix, Arizona we see the temperature can go down to an annual minimum of 3.6°C (38.5°F) in January. Let us assume that our chosen battery datasheet shows 80% capacity at 3.6°C. This is what we consider as the temperature factor.

$$Required\ Battery\ Capacity\ (kWh) = \frac{Daily\ \ Load\ (kWh)\ x\ Days\ of\ Autonomy}{Wiring\ Efficiency\ x\ Depth\ of\ Discharge\ x\ Temperature\ Factor}$$

$$= \frac{0.27\ kWh\ x\ 1}{0.98\ x\ 0.5\ x\ 0.8} = 0.69\ kWh$$

Since this is a small system, using a 12V battery bank should be fine. We can find the battery capacity in Ah as follows. (*Remember 0.69 kWh is 690 Wh)* -

$$\boldsymbol{Battery\ Amp - hours\ (Ah) = \frac{Battery\ Capacity\ (Wh)}{Battery\ Bank\ Voltage\ (V)}}$$

$$= \frac{690\ Wh}{12\ V} = 57.5\ Ah$$

After searching online, we select a **12V – 60Ah** lead acid gel battery that fits the bill. Next, we move to size the solar array.

9.2.3 Solar Array Sizing

We first find our required daily solar energy requirements using the discussed formula. Since this is a small system, we can go with a PWM charge controller, assuming 70% efficiency. Battery efficiency is 80% for lead acid batteries.

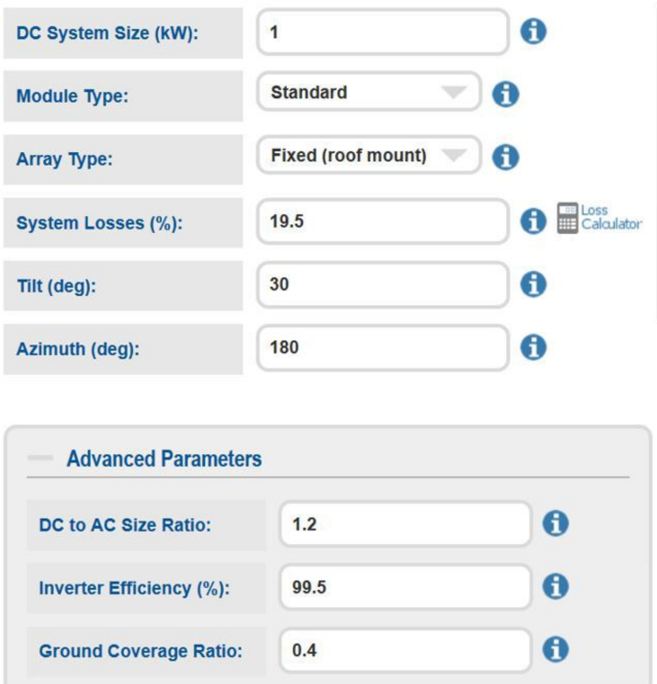
$$Required\ Daily\ Solar\ Energy\ (kWh) = \frac{Daily\ Load\ (kWh)}{Charge\ Controller\ Efficiency\ x\ Wiring\ Efficiency\ x\ Battery\ Efficiency}$$

$$= \frac{0.69\ kWh}{0.7\ x\ 0.98\ x\ 0.8} = 1.26\ kWh$$

Now we move on to sizing the solar array. As discussed earlier, we use the NREL PVWatts online tool (https://pvwatts.nrel.gov/) to do this. We set the location to Phoenix, Arizona.

Then we type in the necessary details of the system and panels. We input 1kW in the system size and consider the panels to be mounted on a south-facing roof (180° azimuth) with a 30° tilt.

Remember this is a pure DC system, so we set the inverter efficiency to the maximum possible 99.5% since inverter efficiency should technically be 100% as there is no inverter and thus no losses in the inverter. We can compensate for this 0.5% loss by using a reduced System Loss value of 19.5% (instead of 20%).



Moving next to the PVWatts results, we see the following table.

Month	Solar Radiation (kWh / m^2 / day)	AC Energy (kWh)
January	5.44	121
February	5.98	119
March	6.91	149
April	7.56	157
May	7.62	160
June	7.64	149
July	7.09	144
August	6.96	141
September	7.26	143
October	6.75	142
November	5.60	120
December	5.10	116
Annual	6.66	1,661

Assuming the house will be used all year round, all the months need to be considered. Looking at the results table, we see the least energy is produced in December at 116 kWh/month.

Since the house will be used at the weekend, we can assume the solar panels will charge the batteries over 3 days (with a couple of spare days in hand to account for cloudy periods). We thus divide the required daily solar energy by 3.

We then find the required solar array size using the formula-

$$\textit{Solar Array Size}\ (kW) = \frac{\textit{Required Daily Solar Energy}\ (kWh)}{\textit{Lowest Energy Month AC Energy}\ (kWh)\ \div \textit{Number of Days in Lowest Month}}$$

$$= \frac{1.26\ kWh\ \div 3}{116\ kWh\ \div 31\ days} = 0.112\ kW$$

Thus, we can compromise and use a **120 W solar panel** since the system will only be used at the weekend and the battery can charge throughout the week.

9.2.4 Charge Controller Selection

We first calculate the charge current as follows-

$$\textbf{\textit{Charge Current}}\ (A) = \frac{\mathbf{1.25}\ \boldsymbol{x}\ \textbf{\textit{Solar Array Size}}\ (W)}{\textbf{\textit{Battery Bank Voltage}}\ (V)}$$

$$= \frac{1.25\ x\ 120\ W}{12\ V} = 12.5\ A$$

Thus, we can choose a **15A PWM charge controller** that is compatible with a 12 V battery, and that can handle the corrected solar array voltage, current, and

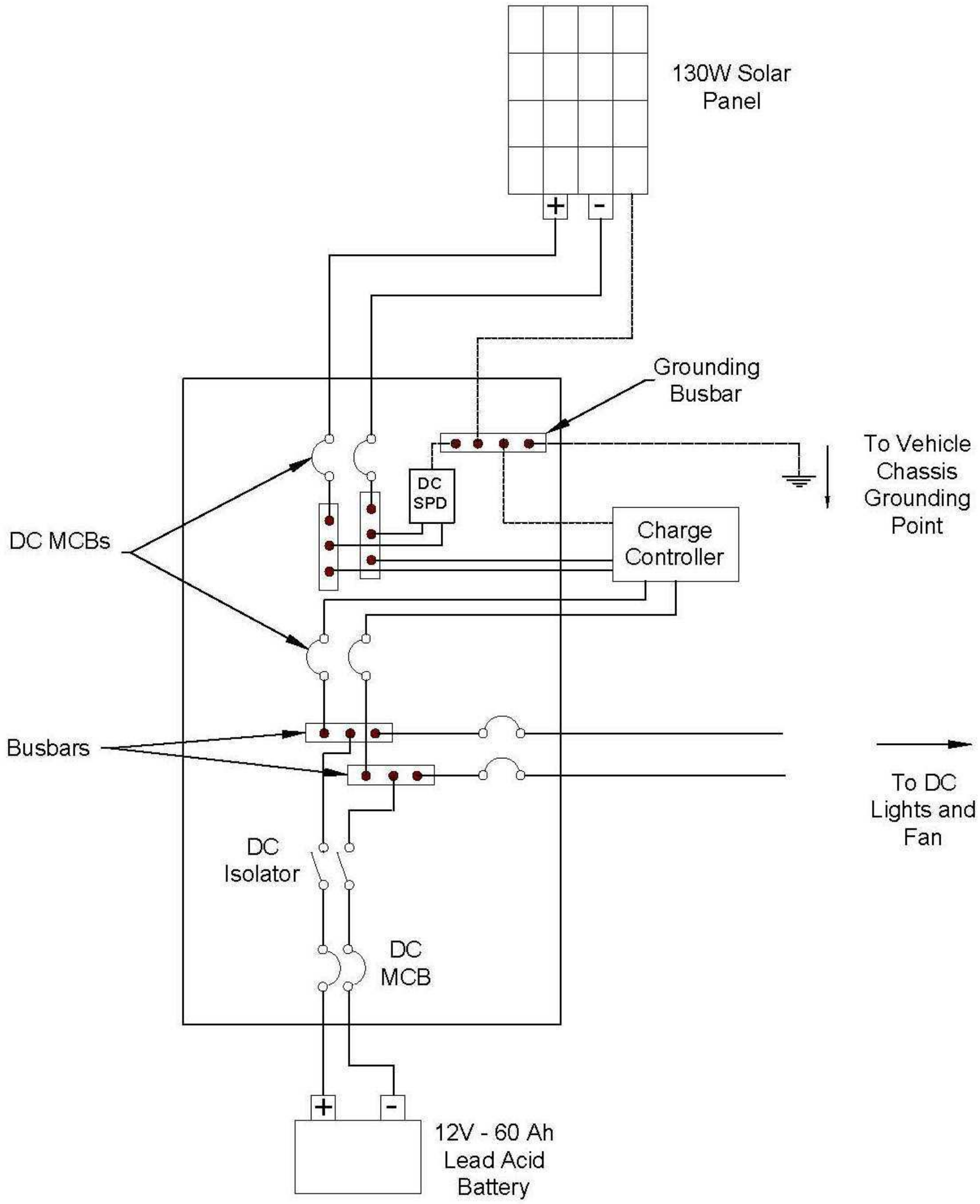
power of the solar panels. We can match the calculations with the limits mentioned in the charge controller datasheet.

As we saw earlier, we use the following two formulas to calculate the maximum array voltage and current. These values must be within the limits of the charge controller input voltage and input current respectively. Remember the values for solar panel open circuit voltage and short circuit current can be found on the solar panel datasheet.

9.2.5 Cable Sizing & Protection Device Selection

This is done in the same way we demonstrated in section 9.1. It is left as an exercise for the reader to work out the cable sizes and protection devices.

9.2.6 Final System Schematic Diagram



9.3 Design for a Car/Minivan

Let us now look at another simple set up to cater to a car or a minivan in Miami, Florida. The overall system needs to be small as a car or a minivan does not offer much roof space.

9.3.1 Load determination

The solar system is planned to power a couple of lights and fans, a laptop, a smartphone charger, and other small appliances. For this example, we consider all loads to be AC loads. The daily energy requirement comes to **0.48 kWh** , while the maximum power comes to **270 W** .

Daily AC Load Consumption								
AC Load	Rated Power (W)	No. of Units	Subtotal Power (W)	Working Hours (h)	Energy (Wh)	Voltage (V)	Current (A) [inc Surge Current]	Power (W) [inc Surge Power]
LED Lights	10	2	20	1	20	120	0.2	20
Fan	30	2	60	3	180	120	0.5	60
Smartphone Charger	10	2	20	3	60	120	0.2	20
Laptop	50	1	50	2	100	120	0.4	50
Consideration for Small Appliances	60	2	120	1	120	120	1.0	120
TOTAL			270		480		2.25	270

9.3.2 Battery Selection & Sizing

Let us assume that the car will have easy access to battery maintenance spots. Thus, we can go with flooded lead acid batteries instead of the more expensive sealed lead acid batteries. We go with 1 day of autonomy to keep the battery size small (remember we need this system to be small and lightweight).

Along with this, the weather data for Miami, Florida shows that the minimum temperature goes down to 16°C. Since it doesn't get very cold, we can ignore the temperature factor for the battery.

We can go with a 12 V battery to keep it simple and lightweight.

$$Required\ Battery\ Capacity\ (kWh) = \frac{Daily\ Load\ (kWh)\ x\ Days\ of\ Autonomy}{Inverter\ Efficiency\ x\ Wiring\ Efficiency\ x\ Depth\ of\ Discharge\ x\ Temperature\ Factor}$$

$$= \frac{0.48\ kWh\ x\ 1}{0.9\ x\ 0.98\ x\ 0.5} = 1.088\ kWh$$

Next, finding the required Battery Amp-hours-

$$\boldsymbol{Battery\ Amp - hours\ (Ah) = \frac{Battery\ Capacity\ (Wh)}{Battery\ Bank\ Voltage\ (V)}}$$

$$= \frac{1088\ Wh}{12\ V} = 90.67\ Ah$$

We can thus go with a **12 V – 100 Ah** flooded lead acid battery.

9.3.3 Solar Array Sizing

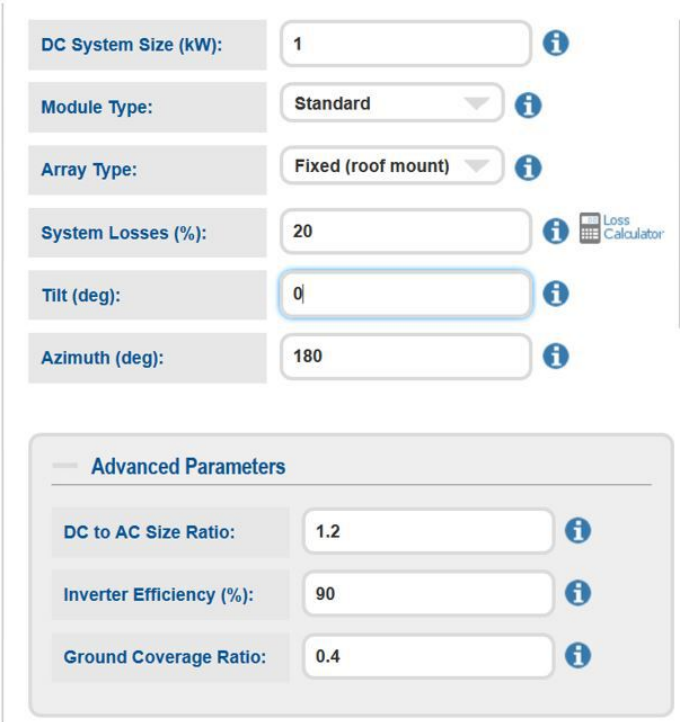
Moving on to the solar array sizing, as usual, we first find the required daily solar energy. Here, we consider an MPPT charge controller which has an efficiency of 90% compared to 70% for PWM controllers. This efficiency

increase will lead to a smaller solar array size requirement which is great for a car.

$$Required\ Daily\ Solar\ Energy\ (kWh) = \frac{Daily\ Load\ (kWh)}{Charge\ Controller\ Efficiency\ x\ Wiring\ Efficiency\ x\ Battery\ Efficiency}$$

$$= \frac{0.48\ kWh}{0.9\ x\ 0.98\ x\ 0.8} = 0.68\ kWh$$

Next, we use the NREL PVWatts online tool to simulate the energy generation for 1 kW as we saw earlier. Here we take the tilt angle as 0 since the solar panels will be placed flat on the roof of the car or minivan. We will use an inverter for this system, thus we set the system losses to 20% and Inverter efficiency to 90%.



The results are shown below.

Month	Solar Radiation (kWh / m^2 / day)	AC Energy (kWh)
January	3.81	78
February	4.57	84
March	5.72	117
April	6.56	128
May	6.90	135
June	6.31	119
July	6.51	126
August	6.32	122
September	5.11	97
October	4.76	96
November	3.98	78
December	3.50	71
Annual	5.34	1,251

The system is planned to be used all year round. Once again, we see that the lowest energy yield is in December. Then again, we want this system to be small. The difference between the highest energy month (May) and the lowest month (December) is significant at 64 kWh! It is therefore up to you to decide if you really need the full supply of energy in December or are you willing to compromise slightly on energy use in the winter months?

In our example, we choose to compromise and reduce our energy use in winter to keep the system small. Let us go ahead and choose the month of **October** for our calculation. This can cover the full energy supply required from March to October. In the winter months of November, December, January, and February we may need to reduce our energy use a little bit. But not to worry, this reduction is very little. All we have to do is not use the fans in the winter. Who needs fans in the winter anyway?!

$$Solar\ Array\ Size\ (kW) = \frac{Required\ Daily\ Solar\ Energy\ (kWh)}{Lowest\ Energy\ Month\ AC\ Energy\ (kWh) \div Number\ of\ Days\ in\ Lowest\ Energy\ Month}$$

$$= \frac{0.68\ kWh}{96\ kWh\ \div 31\ days} = 0.220\ kW$$

So, a single **220 W solar panel** will be sufficient! If the 220 W panel is not available, select the closest panel above 220 W (such as 250 W).

9.3.4 Inverter Sizing

As we saw in the load determination step, the total maximum power of the loads is 270W. So, choosing an **off-grid inverter** rated at **300 W** or above with a 12 V flooded lead acid battery compatibility should be fine. Remember, the

voltage for the loads was 120 V for the USA, so we need our inverter AC output voltage to be 120V as well.

9.3.5 Charge Controller Selection

Here, we opt for an MPPT charge controller which is more efficient than the PWM type. We size the charge controller as follows-

$$\textit{Charge Current}\ (A) = \frac{1.25\ x\ \textit{Solar Array Size}\ (W)}{\textit{Battery Bank Voltage}\ (V)}$$

$$= \frac{1.25\ x\ 220\ W}{12\ V} = 22.92\ A$$

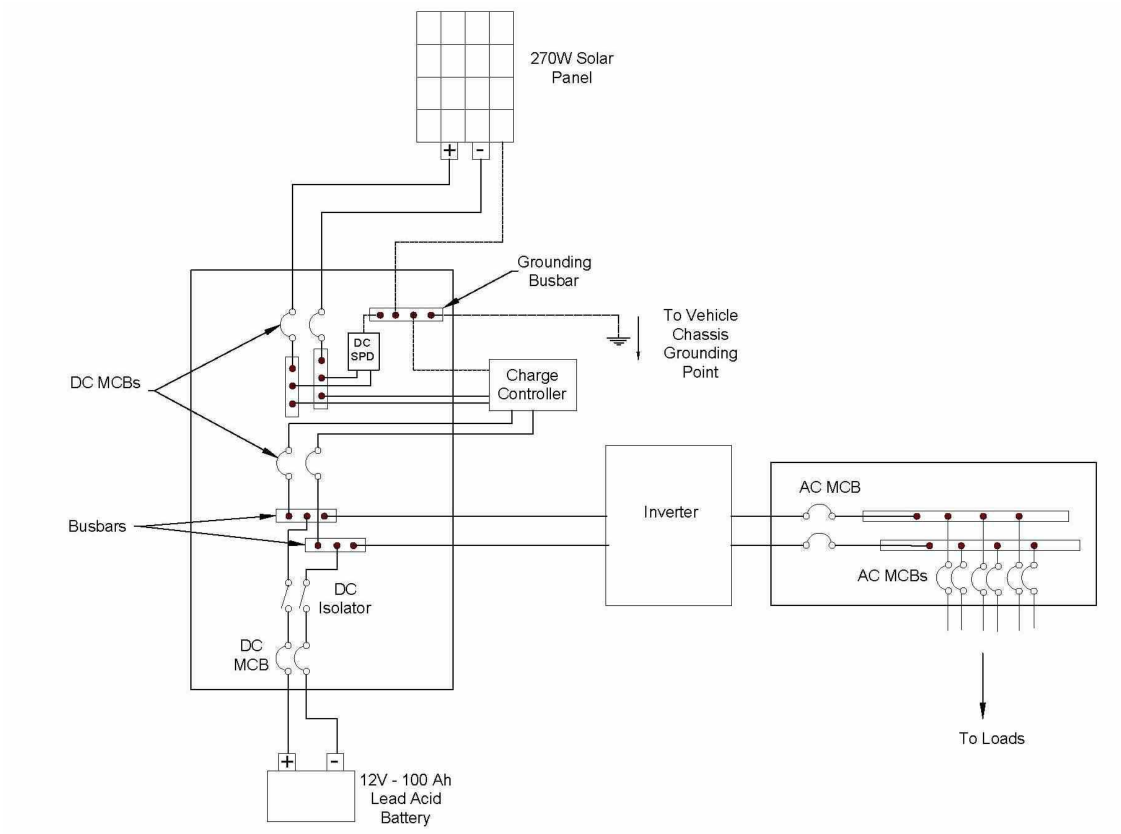
We can go with a **25-A charge controller** that can handle the total solar size at 12 V battery configuration. If the 25-A controller is unavailable, we can go for a more common 30-A charge controller.

As we saw in the planning and design procedure and in previous examples, we need to make sure the corrected solar array voltage and current, as well as the total solar array power, are within the limits of the charge controller.

9.3.6 Cable Sizing & Protection Device Selection

Once again, we leave this as an exercise for the reader. Refer to section 9.1 for more details.

9.3.7 Final System Schematic Diagram



9.4 Design for a Boat

At last, we leave the land and get onto the water! Having solar panels on your boat can be very beneficial in terms of monetary savings and not having to use a loud and polluting generator. In fact, the main issue is that we can't have very much solar on a boat due to the limited space.

9.4.1 Determining the Loads

We start by listing the loads as usual. Let us consider some common appliances we use in boats[2] . Note that we account for the starting surge current and power for the fridge (4 times the operating power) and the bilge pump (6 times). We see the daily load is **6000 Wh** , while total power including starting surge comes to **2950 W** .

Daily AC Load Consumption								
AC Load	Rated Power (W)	No. of Units	Subtotal Power (W)	Working Hours (h)	Energy (Wh)	Voltage (V)	Current (A) [inc Surge Current]	Power (W) [inc Surge Power]
LED Lights	30	2	60	6	360	120	0.5	60
LED TV	50	1	50	4	200	120	0.4	50
Microwave	800	1	800	0.5	400	120	6.7	800
Mini-fridge	300	1	300	12	3600	120	10.0	1200
Fans	300	2	600	2	1200	120	5.0	600
Bilge pump	40	1	40	1	40	120	2.0	240
GPS display	50	1	50	4	200	120	1.3	50
TOTAL			1900		6000		25.83	3000

9.4.2 Battery Selection and Sizing

Whether we wish to use the boat at night or not, we will still need a battery to supply power and maintain stability during cloudy periods during the day. For our boat, we will consider lithium ion batteries. These batteries are three times lighter compared to lead acid batteries. They have a higher usable capacity which means we can get the job done with a small and lightweight battery bank. They are also more efficient which equates to less lost energy and therefore a smaller solar array requirement. This is just what we want with the limited space we have on a boat.

We use one day of autonomy as we want the battery bank to be compact. Note that the depth of discharge for lithium batteries is taken at 80%.

$$\textit{Required Battery Capacity}\ (kWh) = \frac{\textit{Daily Load}\ (kWh)\ x\ \textit{Days of Autonomy}}{\textit{Inverter Efficiency}\ x\ \textit{Wiring Efficiency}\ x\ \textit{Depth of Discharge}\ x\ \textit{Temperature Factor}}$$

$$= \frac{6\ kWh}{0.9\ x\ 0.98\ x\ 0.8} = 8.5\ kWh$$

After an online search, we select a **48 V - 8.5 kWh** lithium battery.

9.4.3 Solar Array Sizing

Right, moving on to sizing the solar array. Let us find the required solar energy. Note that lithium batteries have improved efficiency of over 90%.

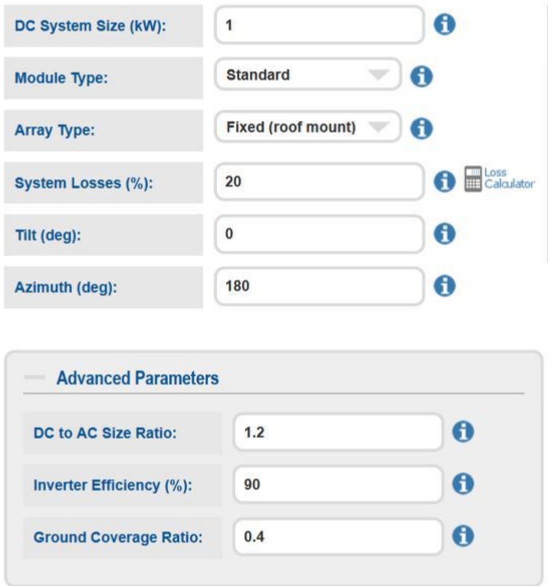
$$\textit{Required Daily Solar Energy}\ (kWh) = \frac{\textit{Daily Load}\ (kWh)}{\textit{Charge Controller Efficiency}\ x\ \textit{Wiring Efficiency}\ x\ \textit{Battery Efficiency}}$$

$$= \frac{6\ kWh}{0.9\ x\ 0.98\ x\ 0.9} = 7.56\ kWh$$

For this example, we consider the location to be set in the beautiful boating destination of Newport, Rhode Island. We create the solar energy simulation for the NREL PVWatts online tool.

We can see in the results again that the solar generation is quite different in the winter months compared to the rest of the year ranging from 127 kWh in July to just 34 kWh in December. At the same time, it is less common to go sailing in the biting winds of winter.

So, let us size the system to fully supply the energy in the warmer period of March to October. The lowest energy month within this period is October with 64 kWh.



Month	Solar Radiation (kWh / m^2 / day)	AC Energy (kWh)
January	1.99	44
February	2.96	59
March	4.05	87
April	5.28	107
May	5.72	117
June	6.11	118
July	6.54	127
August	5.55	108
September	4.60	89
October	3.09	64
November	2.17	44
December	1.63	34
Annual	**4.14**	**998**

The next thing we consider is that the boat will not be used every day. We plan to use this boat once a week. This will further help to reduce the size of the solar array. On the other hand, if you are planning to use the boat on a daily basis, you need to use the usual formula as we have seen earlier in this chapter.

Since the boat will be used once a week, our solar system can take its time and charge the batteries over the other six days. However, we maintain a safety factor and keep two days in hand in case we face cloudy days in the week. We don’t want our weekend boat trip ruined just because it rained for a day or two in the week, now do we? So, we design our solar system to charge the batteries fully within 4 days. Thus, in the formula, we divide the required daily solar energy by 4 days.

$$Solar\ Array\ Size\ (kW) = \frac{Required\ Daily\ Solar\ Energy\ (kWh)}{Lowest\ Energy\ Month\ AC\ Energy\ (kWh) \div Number\ of\ Days\ in\ Lowest\ Energy\ Month}$$

$$= \frac{7.56\ kWh\ \div 4\ days}{64\ \div 31\ days} = 0.915\ kW$$

We will need around **1000 Watts of solar panels** . Let us consider that our site survey revealed we have 10 m^2 of available space for panels on the boat. This means we can fit up to 5 to 6 panels depending on the wattage of the solar panel. Remember we must use panels with IEC 61701 certification to withstand the salt mist conditions of the sea.

9.4.4 Inverter Sizing

As indicated, we will go with an Inverter/Charger which is able to use both solar energy as well as grid energy to charge the batteries. We can thus charge the batteries from the grid during low sunshine periods and still enjoy our boat trip.

We saw in step 1, the maximum power of the loads including starting surge comes out to be 2950 W. With the continuous maximum power (i.e. without surge), the total power is 1900 W. We could go with a 3 kW Inverter/Charger or the alternative would be to find a 2- or 2.5-kW Inverter/Charger which has a surge capability of 3 kW. Look for the information on surge in the inverter datasheet/manual.

So, we go with a **2 kW Inverter/Charger with a surge capability of 3 kW or above that** is compatible with a 48 V lithium ion battery bank. We also choose an Inverter/charger which has a charge controller integrated into it. So, we don't need to buy a separate charge controller. However, we need to make sure that the maximum voltage and maximum current of the array are within the corrected voltage and current range of the inverter/charger. Also, we need to make sure the maximum voltage of the solar array is within the MPPT voltage range of the inverter.

We use the following formula together with the values we get from the solar panel and inverter datasheet.

Let us calculate using the datasheet excerpts shown below.

ELECTRICAL DATA (STC)

Peak Power Watts-P_{MAX} (Wp)*	320	325	330	335	340
Power Output Tolerance-P_{MAX} (W)	0 ~ +5				
Maximum Power Voltage-V_{MPP} (V)	37.1	37.2	37.4	37.6	37.8
Maximum Power Current-I_{MPP} (A)	8.63	8.73	8.83	8.91	8.99
Open Circuit Voltage-V_{OC} (V)	45.5	45.6	45.8	46.0	46.2
Short Circuit Current-I_{SC} (A)	9.15	9.19	9.28	9.35	9.42
Module Efficiency η_m (%)	16.5	16.7	17.0	17.2	17.5

Excerpt from Solar Panel Datasheet
Source: Trina Solar

INPUT (DC)	X1-HYBRID-3.0T C Version E Version I Version
Max.PV array power [Wp]	4500
Max.recommended DC power[W]	A:3000 B:3000
Max.DC voltage [V]	600
Nominal DC operating voltage [V]	360
Max. input current (input A/input B) [A]	12/12
Max. short circuit current (input A/input B) [A]	14/14
MPPT voltage range[V]	125-550
Start operating voltage[V]	150
No. of MPP trackers / Strings per MPP tracker	2(1/1)

Excerpt from Hybrid Inverter Datasheet
Source: SolaX Power

$$\boldsymbol{Minimum\ No. of\ Panels} = \frac{\boldsymbol{Minimum\ Inverter\ MPPT\ Voltage\ (V)}}{\boldsymbol{Solar\ Panel\ Maximum\ Power\ Voltage\ (V)}}$$

$$= \frac{125\ V}{37.1\ V} = 3.36\ panels\ \approxeq 4\ panels$$

$$\boldsymbol{Maximum\ No. of\ Panels} = \frac{\boldsymbol{Maximum\ Inverter\ MPPT\ Voltage\ (V)}}{\boldsymbol{Solar\ Panel\ Maximum\ Power\ Voltage\ (V)}}$$

$$= \frac{550\ V}{37.1\ V} = 14.82\ panels\ \approxeq 14\ panels$$

Thus, to stay within the MPPT voltage range of the inverter, we need to select from 4 to 14 of the considered 320 W panels. Let us take just one string with 4 pieces of 320 W solar panels to be connected in series.

Corrected Array Voltage (V) = 1.15 x Solar Panel Open Circuit Voltage (V) x Number of Solar Panels in Series

= 1.15 x 45.5 V x 4 panels = 209.3 V

Corrected Array Current (A) = 1.56 x Solar Panel Short Circuit Current (A) x Number of Strings in Parallel

= 1.56 x 9.15 x 1 = 14.274 A

We see from our calculations and the datasheets above that the corrected array voltage 209.3 V is below the maximum voltage of the inverter (i.e. 600 V). Also, the corrected array current 14.274 A is just around the inverter's short circuit current of 14 A. So, it is acceptable to use this inverter with our 320 W solar panels.

You may be curious as to why we chose 4 panels of 320 W each. This gives us 1.28 kW, which is above our required solar array size of 0.915 kW. But as we need to stay above the inverter's minimum MPPT voltage of 125 V, we choose high power and high voltage solar panels which are usually above 300W.

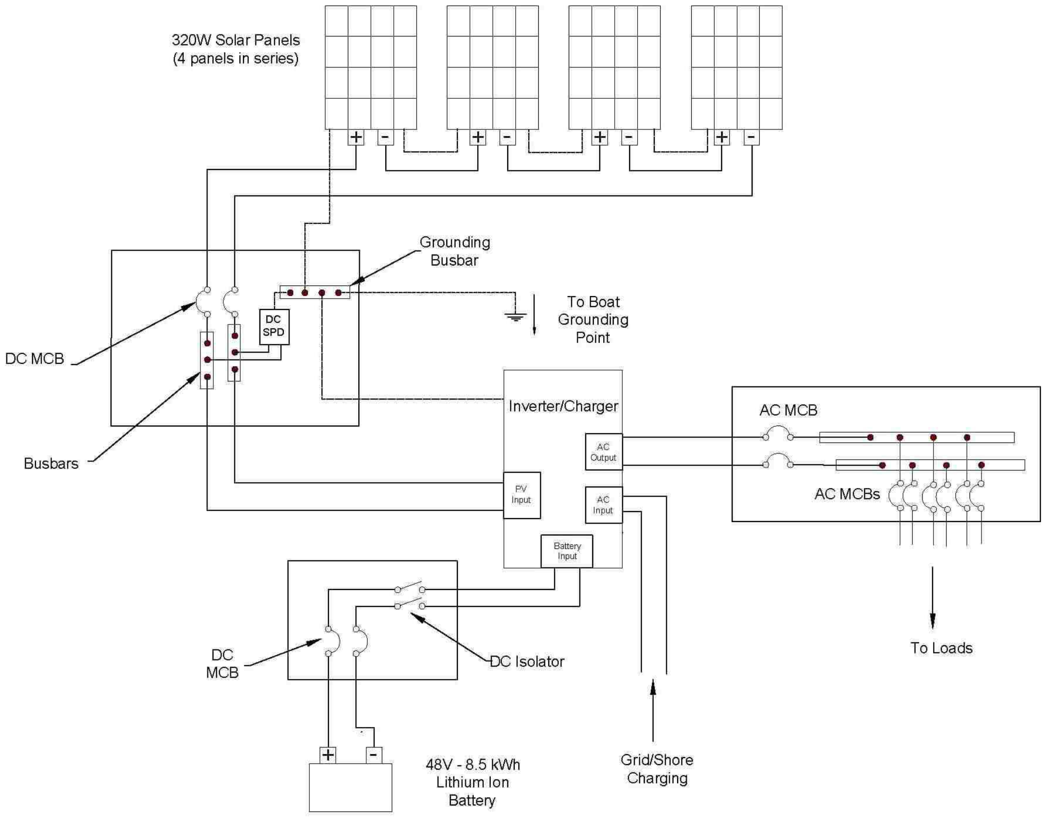
250 W solar panels are usually rated at around 30 V maximum voltage. So, 4 of these in series would give us *4 x 30 V = 120 V,* which is below our inverter MPPT voltage range of 125 – 550 V.

Note, we don't need a separate charge controller as it is included with this particular inverter.

9.4.5 Cable Sizing and Protection Device Selection

We keep emphasizing this step as this is a very important step. But this is also not a very difficult step and we have covered it in detail in Section 9.1. So, we leave it to you to work it out.

9.4.6 Final System Schematic Diagram



By now you are well equipped to handle planning and design tasks. So, we will quickly go through the next few examples.

9.5 Design for a Simple RV/Camper Van

This example will concern a solar system that is good for a normal sized RV, camper, or a large van that will be used on a daily basis during holiday periods. In our site survey, let us consider that we have measured an available area for panels on the roof as $12m^2$. So, we can fit 6 to 8 solar panels depending on the panel size.

For this example, we will consider the location of Melbourne, Australia to mainly show the difference in the standard AC voltage which is 230 V, and the change in the solar azimuth angle. Since Australia is in the southern hemisphere, we choose for the solar panels to face north for the best power production.

9.5.1 Determining the Loads

The following are the loads considered for this RV. We see the total load is **3675 Wh** and the total power is **1930 W** .

Daily AC Load Consumption								
AC Load	Rated Power (W)	No. of Units	Subtotal Power (W)	Working Hours (h)	Energy (Wh)	Voltage (V)	Current (A) [inc Surge Current]	Power (W) [inc Surge Power]
LED Lights	15	6	90	6	540	220	0.4	90
Fans	50	3	150	4	600	220	0.7	150
Laptops	50	2	100	4	400	220	0.5	100
Mini-fridge	200	1	200	8	1600	220	3.6	800
LED TV	50	1	50	4	200	220	0.2	50
Coffee Maker	700	1	700	0.25	175	220	3.2	700
Smartphones	10	4	40	4	160	220	0.2	40
TOTAL			1330		3675		8.77	1930

9.5.2 Battery Selection and Sizing

Since the battery will be used regularly during holiday periods each lasting about a month, we can either choose lithium ion battery or flooded lead acid batteries depending on our initial budget.

Let us go with lithium ion batteries for this one as they are more compact and lightweight. We consider 1 day of autonomy as we want to keep the battery small and we always have the option of driving to a grid charging point whenever we face rainy days.

$$Required\ Battery\ Capacity\ (kWh) = \frac{Daily\ Load\ (kWh)\ x\ Days\ of\ Autonomy}{Inverter\ Efficiency\ x\ Wiring\ Efficiency\ x\ Depth\ of\ Discharge\ x\ Temperature\ Factor}$$

$$= \frac{3.675\ kWh\ x\ 1}{0.9\ x\ 0.98\ x\ 0.8} = 5.21\ kWh$$

After searching online for lithium batteries, we can go with a **48 V – 5.5 kWh** battery.

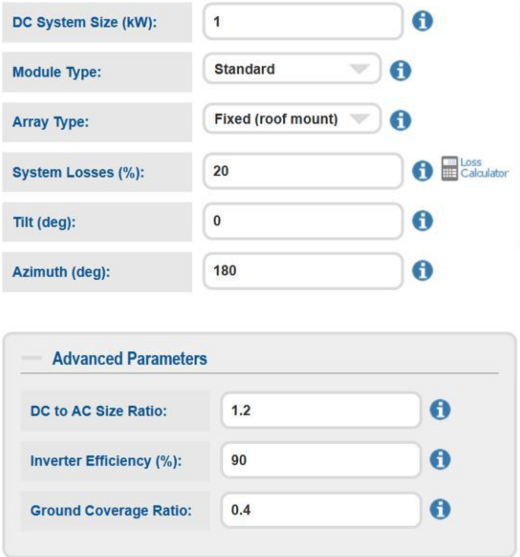
9.5.3 Solar Array Sizing

We first find our required daily solar energy. Remember the battery efficiency considered for lithium batteries is 90%-

$$Required\ Daily\ Solar\ Energy\ (kWh) = \frac{Daily\ Load\ (kWh)}{Charge\ Controller\ Efficiency\ x\ Wiring\ Efficiency\ x\ Battery\ Efficiency}$$

$$= \frac{6\ kWh}{0.9\ x\ 0.98\ x\ 0.9} = 7.56\ kWh$$

Next, we go back to the PVWatts website and simulate a 1 kW solar system in Melbourne, Australia. Remember we set the solar panel Azimuth Angle to 0° (north facing) since Australia is in the southern hemisphere.



Month	Solar Radiation (kWh / m^2 / day)	AC Energy (kWh)
January	1.99	44
February	2.96	59
March	4.05	87
April	5.28	107
May	5.72	117
June	6.11	118
July	6.54	127
August	5.55	108
September	4.60	89
October	3.09	64
November	2.17	44
December	1.63	34
Annual	4.14	998

Let us consider the RV will be used in the holiday periods in April, September, and December. Out of these months, we see that April has the lowest energy with 70 kWh. Calculating the solar array size-

$$Solar\ Array\ Size\ (kW) = \frac{Required\ Daily\ Solar\ Energy\ (kWh)}{Lowest\ Energy\ Month\ AC\ Energy\ (kWh) \div Number\ of\ Days\ in\ Lowest\ Energy\ Month}$$

$$= \frac{7.56\ kWh\ \div 4\ days}{64\ \div 31\ days} = 0.915\ kW$$

As mentioned, the available space on the roof of the RV is 12 m^2 . High power solar panels (above 300 W) cover around 2 m^2 per panel. So, we can go for **6 panels rated at 350 W** , which gives us **2100 W** of solar in total.

9.5.4 Inverter Sizing

We saw in step 1 that the total power including surge comes to 1930 W, while the total power excluding surge is 1330 W. While the solar array size is 2100 W we can go for a **2000 W Inverter/Charger** capable of handling the 2100 W solar array and compatible with 48 V lithium batteries. If not, we can go for a 2500 W Inverter/Charger. Having an inverter/charger also means we have the option of grid charging as back up.

Note that since this example is located in Australia, we make sure the inverter output voltage and frequency are that of the Australian standard AC voltage and frequency of 230 V and 50 Hz respectively.

9.5.5 Charge Controller Selection

We could very well go for an inverter integrated with a charge controller. In a case where such an inverter is not available, we need a charge controller.

Let us size our charge controller as follows-

$$\boldsymbol{Charge\ Current\ (A) = \frac{1.25\ x\ Solar\ Array\ Size\ (W)}{Battery\ Bank\ Voltage\ (V)}}$$

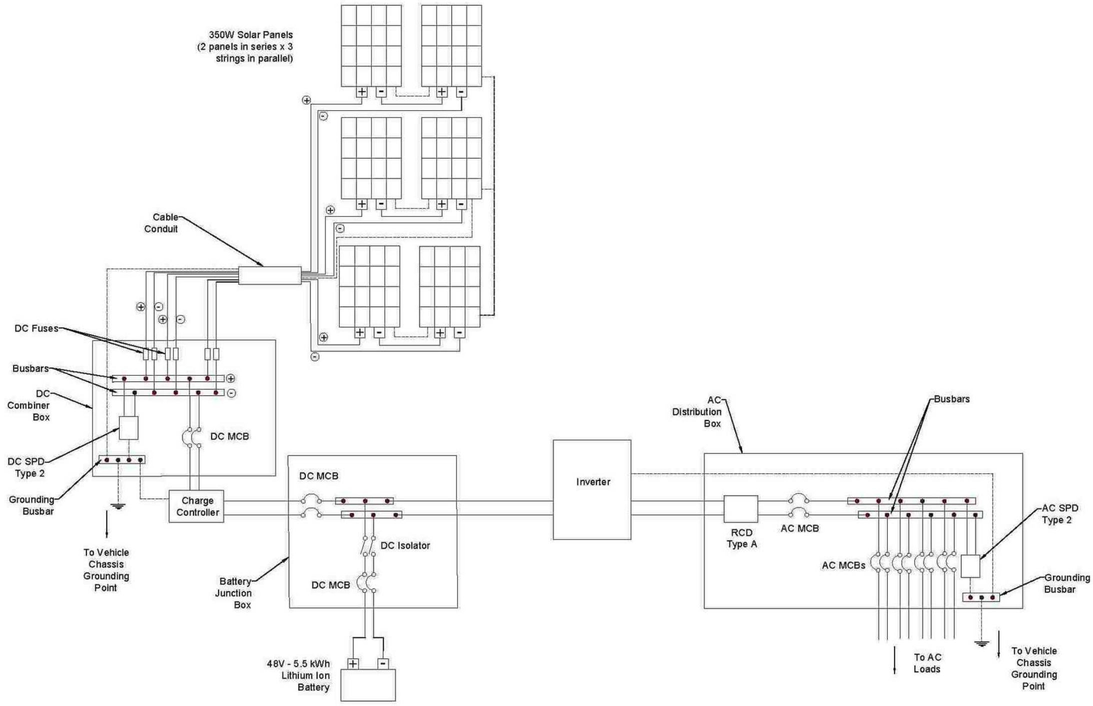
$$= \frac{1.25\ x\ 2100\ W}{48\ V} = 54.69\ A$$

So, we can go with a **60 A MPPT Charge Controller** that is compatible with a 48 V Lithium Ion battery. Again, we need to make sure the solar array voltage and current are within the range of the charge controller as we have seen in the previous examples.

Let us then consider that our chosen charge controller can handle 2 of our chosen solar panels in series to stay within the voltage limits. From our solar array sizing calculation, we decided on 6 panels of 350 W each. So, we can arrange the solar array at **2 panels in series in each string and 3 strings in parallel** .

By now you have a fair idea of how to size the cables and protection devices. Once again, we leave it as an exercise for the reader to work these out.

9.5.6 Final System Schematic Diagram



9.6 Design for a Luxurious RV/Large Van

We will now move on to a king-sized luxurious RV. We consider large appliances such as air conditioners, induction cooker, microwave, television, satellite receiver, and water pump. For water heating needs, we consider a propane water heater instead of an electric water heater. Electric water heaters are notorious electricity guzzlers which could very well result in a solar array size bigger than the RV roof can accommodate.

Both DC and AC appliances are included to demonstrate how both types of loads can be hooked up to a single solar system. Moreover, modern DC appliances are efficient and draw less power compared to traditional AC loads.

9.6.1 Determining the Loads

We present below the AC and DC loads for our RV that is fit for a king. As we want our solar system size to stay low and less costly, we will go for the most efficient appliances.

As we can see, the daily load for **AC loads is 4630 Wh** and for **DC loads it is 1488 Wh** . While the power (including starting surge) is **4920 W for AC loads** and **668 W for DC loads** .

Daily DC Load Consumption								
DC Load	Rated Power (W)	No. of Units	Subtotal Power (W)	Working Hours (h)	Energy (Wh)	Voltage (V)	Current (A) [inc Surge Current]	Power (W) [inc Surge Power]
Puck Lights	5	10	50	6	300	12	4.2	50
Fans	24	3	72	6	432	12	6.0	72
RV Water Pump	36	1	36	1	36	12	18.0	216
Fridge	75	1	75	8	600	12	25.0	300
Exhaust Fans	15	2	30	4	120	12	2.5	30
TOTAL			263		1488		55.67	668

Daily AC Load Consumption								
AC Load	Rated Power (W)	No. of Units	Subtotal Power (W)	Working Hours (h)	Energy (Wh)	Voltage (V)	Current (A) [inc Surge Current]	Power (W) [inc Surge Power]
Laptops	50	2	100	4	400	120	0.8	100
Rooftop Air Conditioner	700	1	700	4	2800	120	17.5	2100
LED TV	50	1	50	4	200	120	0.4	50
Satellite Reciever	30	1	30	4	120	120	0.3	30
Coffee Maker	600	1	600	0.25	150	120	5.0	600
Induction Cooker	1200	1	1200	0.5	600	120	10.0	1200
Microwave	800	1	800	0.25	200	120	6.7	800
Smartphones	10	4	40	4	160	120	0.3	40
TOTAL			3520		4630		41.00	4920

9.6.2 Battery Selection and Sizing

We plan to use this RV on a daily basis, so we can go with flooded lead acid or lithium batteries depending on the budget. We go with lithium ion batteries to keep it compact and light. We also consider that the battery will be stored inside a decently insulated compartment within the RV so we can ignore the temperature factor.

Notice the AC loads and DC loads are separated in the formula. The only difference is we don’t need to consider the inverter efficiency for DC loads.

$$Required\ Battery\ Capacity\ (kWh) = \frac{Daily\ AC\ Load\ (kWh)}{Inverter\ Efficiency\ x\ Wiring\ Efficiency\ x\ Depth\ of\ Discharge} + \frac{Daily\ DC\ Load\ (kWh)}{Wiring\ Efficiency\ x\ Depth\ of\ Discharge}$$

$$= \frac{4.63\ kWh}{0.9\ x\ 0.98\ x\ 0.8} + \frac{1.488\ kWh}{0.9\ x\ 0.98\ x\ 0.8} = 8.67\ kWh$$

An online search revealed a **48 V – 9 kWh** lithium battery that fits the bill.

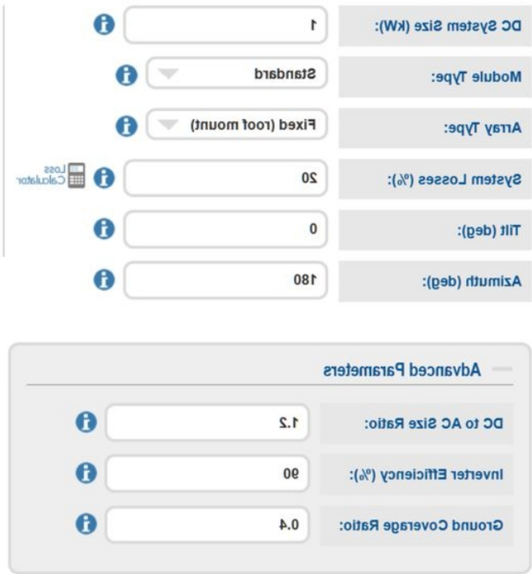
9.6.3 Solar Array Sizing

As usual, we first find our required daily solar energy-

$$Required\ Daily\ Solar\ Energy\ (kWh) = \frac{Daily\ Load\ (kWh)}{Charge\ Controller\ Efficiency\ x\ Wiring\ Efficiency\ x\ Battery\ Efficiency}$$

$$= \frac{4.63\ kWh + 1.488\ kWh}{0.9\ x\ 0.98\ x\ 0.9} = 7.71\ kWh$$

Once again, we log in to PVWatts online tool. Let us consider the location to be San Jose, California. We enter our usual inputs in PVWatts and carry on with our simulation.



Month	Solar Radiation (kWh / m² / day)	AC Energy (kWh)
January	2.41	50
February	3.14	60
March	4.91	101
April	6.11	123
May	7.20	145
June	7.94	154
July	8.12	161
August	7.22	141
September	5.85	110
October	4.18	83
November	2.83	56
December	2.21	45
Annual	5.18	1,229

We noted that this RV will be used on a daily basis throughout the year. As we see in the results table, the solar energy generation varies from 45 kWh in December to 161 kWh in July.

However, the point to consider here is that during the cold winter, it is certain that the air conditioner and even the fans will not be used. This would bring down our energy consumption by over 50%!

So, it makes little sense to size our solar system for the total energy consumption based on December solar generation. A wiser approach would be

to take the period of March to October to do our sizing. Within this period, October has the lowest energy generation at 83 kWh.

$$Solar\ Array\ Size\ (kW) = \frac{Required\ Daily\ Solar\ Energy\ (kWh)}{Lowest\ Energy\ Month\ AC\ Energy\ (kWh) \div Number\ of\ Days\ in\ Lowest\ Energy\ Month}$$

$$= \frac{7.71\ kWh}{83\ kWh\ \div 31\ days} = 2.88\ kW$$

Let us consider that our site survey revealed that there is around 20 m^2 (215 square feet) of available area on the roof. This gives us enough room for around 10 panels. So, going for **10 x 300 W panels** will be enough to get our RV rolling.

9.6.4 Inverter Sizing

The load tables show that our total AC power including surge is 4920 W, while the continuous power (without surge) is 3520 W. So, the best option would be to go for a 4 kW Inverter/Charger with a surge capability of 5 kW or above. If such an inverter is not available nearby, we can go for an Inverter/Charger rated at 5 kW. The inverter/charger must be compatible with our 48 V lithium ion battery of course. We also must verify that it will handle the corrected solar array output voltage and current as we saw earlier.

9.6.5 Charge Controller Selection

Remember, the DC appliances have to be connected between the charge controller and the battery. So, we must include a charge controller when we have DC appliances, as it protects both the batteries and DC appliances from high solar currents.

$$\boldsymbol{Charge\ Current\ (A) = \frac{1.25\ x\ Solar\ Array\ Size\ (W)}{Battery\ Bank\ Voltage\ (V)}}$$

$$= \frac{1.25\ x\ 3000\ W}{48\ V} = 78.125\ A$$

We can thus go for an 80-A MPPT charge controller.

As a side note, if an 80-A charge controller is unavailable in our location, we can go with two 40-A MPPT controllers, where the solar array is divided evenly between the two controllers. Again, we need to verify if the corrected solar array voltage and current are within the limits of the charge controller as we saw in previous examples.

Let us consider that the charge controller datasheet specifies a maximum input voltage of up to 150 V. While our chosen 300 W solar panel datasheet

specifies an open circuit voltage of 40.45 V and a short circuit current of 9.91 A.

Corrected Array Voltage (V) = 1.15 x Solar Panel Open Circuit Voltage (V) x Number of Solar Panels in Series

$$= 1.15 \times 40.45 \text{ V} \times 2 = 93.035 \text{ V}$$

Corrected Array Current (A) = 1.56 x Solar Panel Short Circuit Current (A) x Number of Strings in Parallel

$$= 1.56 \times 9.91 \text{ A} \times 5 = 77.298 \text{ A}$$

From the corrected array voltage, we can figure that having 2 panels in series will easily keep us within the 150 V limit of the controller. Since we have 10 panels, we can arrange these into 5 strings with 2 panels in series in each string. The corrected array current 77.298 A is below the 80 A charge current limit of the controller. So that's perfectly fine.

9.6.6 Converter for DC Appliances

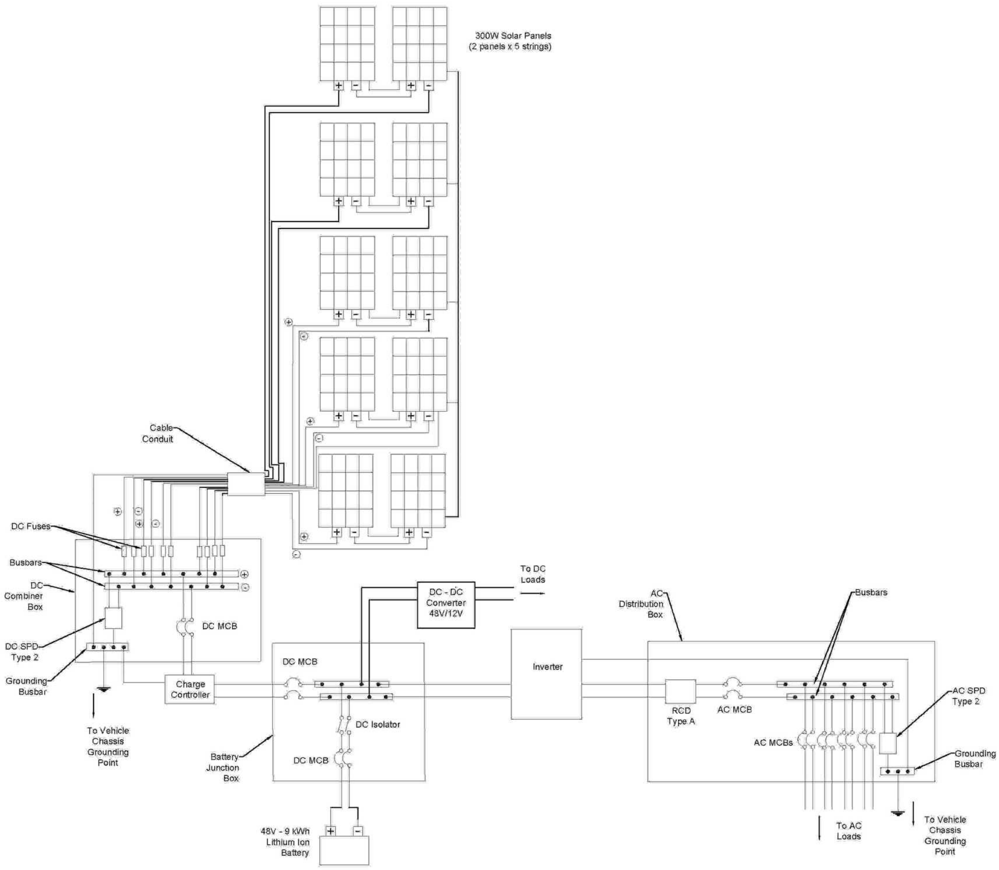
One important point that we have not touched upon so far is that the battery bank and DC voltage is 48 V while our DC appliances are 12 V. We can't directly hook 12 V appliances to a 48 V source. To make this work, we'll need extra equipment called a DC-DC converter to bring down the voltage. The converter must also be able to handle the total power (including surge) of the DC loads, which we saw as 668W. So, we choose a 48 V to 12 V step-down DC-DC converter rated at 720 W as shown below.

Input Voltage	19-72 VDC
Mounting Type	Panel Mount
Number of Outputs	1
Operation	Switching
Output	12VDC@60A
Output Current	60.00 A
Output Power	720 W
Output Voltage	12 VDC
Primary Type	DC-DC

DC-DC Converter by Mean Well

Source: Allied Electronics

9.6.7 Final System Schematic Diagram



9.7 Design for a Cabin

Let us now look at a cabin in the mountains that promises a much-needed refuge from our busy lives. The cabin will be situated in beautiful Gunnison, Colorado. It has two bedrooms, a kitchen, a living room, a dining area, and a bathroom. It is designed to be used for long weekends of up to 3-days, every month.

9.7.1 Determining the Loads

The loads include a deep well water pump and the usual lighting, fans, TV, and other appliances. Note that all the loads (except the refrigerator) are planned to be used only during the 3-day weekend. The refrigerator will be running all the time as the cabin owners would like a cold beer as soon as they arrive. The load study in this example will be done over a weekly basis.

Weekly AC Load Consumption								
AC Load	Rated Power (W)	No. of Units	Subtotal Power (W)	Working Hours per Week (h)	Energy per Week (Wh)	Voltage (V)	Current (A) [inc Surge Current]	Power (W) [inc Surge Power]
LED Lights (Bedrooms, Living Room, Outdoor, Bathroom)	10	5	50	10	500	120	0.4	50
LED Lights- Kitchen	20	1	20	10	200	120	0.2	20
LED Lights- Dining	15	1	15	10	150	120	0.1	15
Fans	30	2	60	10	600	120	0.5	60
Laptops	50	2	100	7	700	120	0.8	100
LED TV	80	1	80	9	720	120	0.7	80
Satellite Reciever	30	1	30	9	270	120	0.3	30
Refrigerator (runs 7 days a week)	150	1	150	48	7200	120	5.0	600
Microwave	800	1	800	0.75	600	120	6.7	800
Smartphones	10	4	40	10	400	120	0.3	40
Hair Dryer	800	1	800	0.25	200	120	6.7	800
Water Pump	120	1	120	6	720	120	6.0	720
TOTAL			2215		11760		27.21	3265

9.7.2 Battery Selection

The battery will be designed to charge through the week and used mainly during the weekends, except for the refrigerator which runs all week.

Since the cabin will be located away in the mountains and it will not be used regularly, we can go for AGM sealed lead acid batteries. Upon consulting with the battery supplier it is discovered that in cold winter temperatures in Gunnison, the battery may go down to 80% of its capacity, so this factor is accounted for in the formula.

$$Required\ Battery\ Capacity\ (kWh) = \frac{Daily\ Load\ (kWh)\ x\ Days\ of\ Autonomy}{Inverter\ Efficiency\ x\ Wiring\ Efficiency\ x\ Depth\ of\ Discharge\ x\ Temperature\ Factor}$$

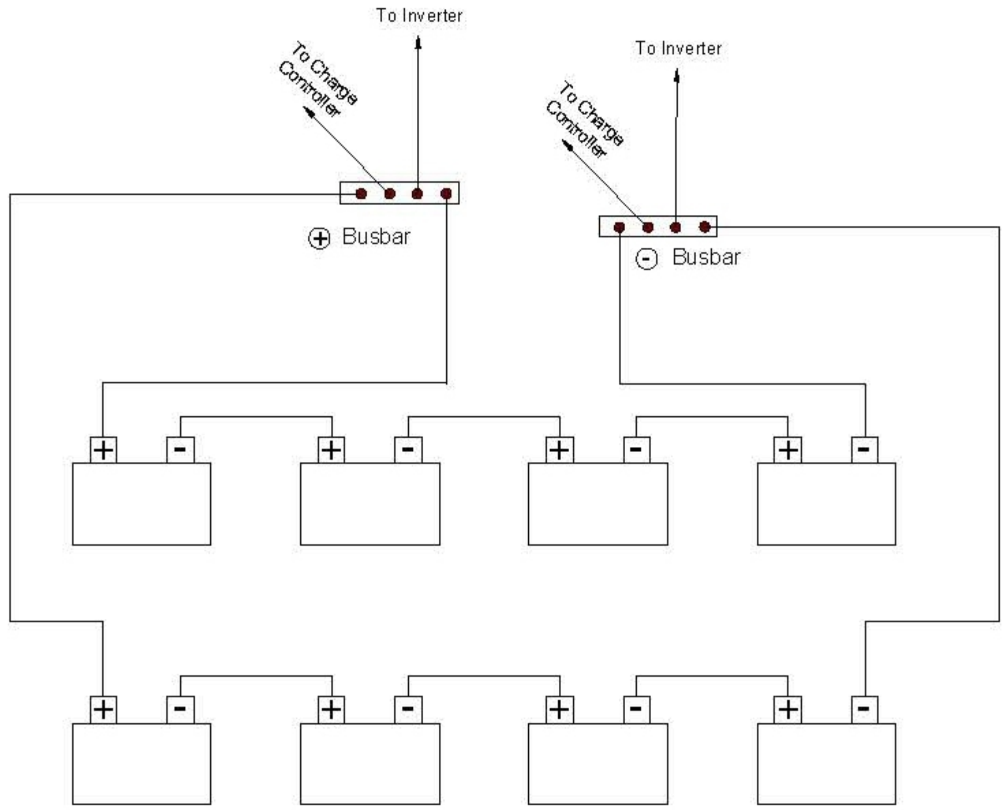
$$= \frac{11.76\ kWh}{0.9\ x\ 0.98\ x\ 0.5\ x\ 0.8} = 33.333\ kWh$$

Next finding the battery amp-hours considering a 48 V battery bank -

$$Battery\ Amp - hours\ (Ah) = \frac{Battery\ Capacity\ (Wh)}{Battery\ Bank\ Voltage\ (V)}$$

$$= \frac{33333\ Wh}{48\ V} = 694.438\ Ah$$

After searching online stores, we found the best option to be using a combination of **12 V – 350 Ah SLA AGM batteries** . To achieve our required voltage of 48 V and 700 Ah- we need to have **4 of these batteries in series** and have **two strings in parallel** . The calculations and the battery arrangement are shown below.



Battery arrangement showing 4 batteries in series and 2 strings in parallel . (Note: Junction box, circuit breakers and DC isolator not shown)

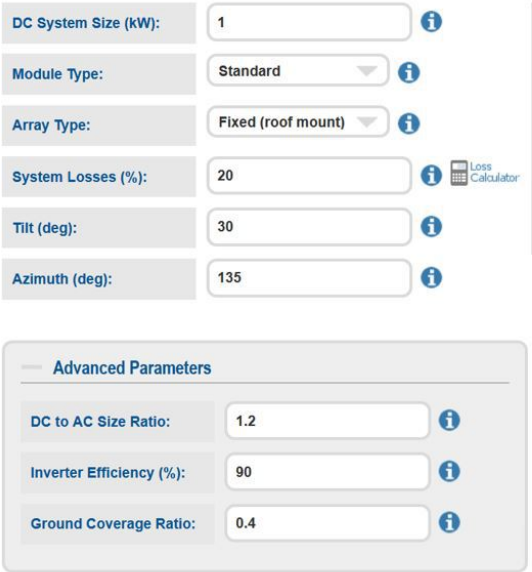
9.7.3 Solar Array Sizing

As usual, we first find the required solar energy and then simulate the solar energy generation for our location using PVWatts online tool.

$$\textit{Required Daily Solar Energy (kWh)} = \frac{\textit{Daily Load (kWh)}}{\textit{Charge Controller Efficiency x Wiring Efficiency x Battery Efficiency}}$$

$$= \frac{11.76\ kWh}{0.9\ x\ 0.98\ x\ 0.8} = 16.67\ kWh$$

Next, we simulate the solar energy in Gunnison using PVWatts. We decide on the southwest-facing roof of the cabin for the placement of our panels (i.e. azimuth angle is 135°). The roof is tilted at 30° to shed the snow easily. We input these details and other usual details on PVWatts and continue.



Month	Solar Radiation (kWh / m^2 / day)	AC Energy (kWh)
January	3.44	79
February	4.30	88
March	5.89	131
April	6.82	143
May	7.26	155
June	7.76	153
July	7.30	144
August	6.49	130
September	6.37	125
October	5.51	117
November	4.49	97
December	3.29	74
Annual	5.74	1,436

Next, we find the required solar array size. We consider that the battery is charged over the week and used mainly at the weekend. So, we size the solar array to charge the battery for over 7 days. Since the system will be used throughout the year, we consider the lower energy month of December.

$$Solar\ Array\ Size\ (kW) = \frac{Required\ Weekly\ Solar\ Energy\ (kWh)}{Lowest\ Energy\ Month\ AC\ Energy\ (kWh) \div Number\ of\ Weeks\ in\ Lowest\ Energy\ Month}$$

$$= \frac{16.67\ kWh}{74\ kWh\ \div 4\ weeks} = 0.901\ kW$$

We can thus opt for **3 x 300 W solar panels** in series.

9.7.4 Inverter Sizing

Looking at the total loads, we can go with a **3000 W rated off-grid inverter with a surge capability of at least 3300 W** . If not, a 3500 W rated inverter will do. The inverter must be compatible with a 48 V lead acid battery. It must also be compatible with the corrected solar array output current and voltage as we have seen throughout this chapter.

9.7.5 9.7.5 Charge Controller Selection

We calculate the maximum charge current as usual.

$$\boldsymbol{Charge\ Current\ (A)} = \frac{\boldsymbol{1.25\ x\ Solar\ Array\ Size\ (W)}}{\boldsymbol{Battery\ Bank\ Voltage\ (V)}}$$

$$= \frac{1.25\ x\ 900\ W}{48\ V} = 23.44\ A$$

We can thus choose a **25-A or 30-A charge controller** compatible with a 48 V battery bank and capable of handling the solar array output current and voltage as we have seen in the procedure and earlier examples.

Finally, the cable sizing, protection device selection, and final schematic diagram are created as usual. Make sure to go through the next example as it includes a similar design and diagram for an off-grid home.

9.8 Design for an Off-grid Home

Our final design example will be that of a fully-fledged off-grid home powered by the sun. We'll consider a ground mount solar system to be located in the open area adjacent to the house. The house will be situated in Pikeville, Tennessee. It will have three bedrooms, two bathrooms, a living room, a study, a kitchen, a dining area, and a laundry room.

9.8.1 Determining the Loads

For this example, we take a slightly different approach. We separate the load consumption for the summer and the winter. The main difference is that the fans will be running only in the summer while the gas heater will run in the winter. Although the gas heater uses propane as heating fuel, the heater fan runs on electricity.

The summer and winter loads will be equated with the solar energy simulation for the respective summer and winter months later.

Summer Daily AC Load Consumption								
AC Load	Rated Power (W)	No. of Units	Subtotal Power (W)	Working Hours (h)	Energy (Wh)	Voltage (V)	Current (A) [inc Surge Current]	Power (W) [inc Surge Power]
LED Lights- 3 Bedrooms	10	3	30	2	60	120	0.3	30
LED Lights- 2 Bathrooms	10	2	20	0.5	10	120	0.2	20
LED Lights- Kitchen	20	1	20	3	60	120	0.2	20
LED Lights- Dining	15	2	30	2	60	120	0.3	30
LED Lights- Living & Study	15	3	45	4	180	120	0.4	45
Ceiling Fans	50	5	250	6	1500	120	2.1	250
Laptops	50	2	100	4	400	120	0.8	100
LED TV	120	1	120	4	480	120	1.0	120
Stereo System	120	1	120	2	240	120	1.0	120
Refrigerator	150	1	150	8	1200	120	5.0	600
Microwave	800	1	800	0.5	400	120	6.7	800
Smartphones	10	4	40	10	400	120	0.3	40
Washing Machine	500	1	500	0.5	250	120	4.2	500
Water Pump	300	1	300	1	300	120	15.0	1800
Other Appliances	1000	1	1000	2	2000	120	8.3	1000
Gas Furnace	400	1	0	0	0			
TOTAL			3475		7470		45.21	5425

Winter Daily AC Load Consumption								
AC Load	Rated Power (W)	No. of Units	Subtotal Power (W)	Working Hours (h)	Energy (Wh)	Voltage (V)	Current (A) [inc Surge Current]	Power (W) [inc Surge Power]
LED Lights- 3 Bedrooms	10	3	30	2	60	120	0.3	30
LED Lights- 2 Bathrooms	10	2	20	0.5	10	120	0.2	20
LED Lights- Kitchen	20	1	20	3	60	120	0.2	20
LED Lights- Dining	15	2	30	2	60	120	0.3	30
LED Lights- Living & Study	15	3	45	4	180	120	0.4	45
Ceiling Fans	50	5	0	0	0	120	0.0	0
Laptops	50	2	100	4	400	120	0.8	100
LED TV	120	1	120	4	480	120	1.0	120
Stereo System	120	1	120	2	240	120	1.0	120
Refrigerator	150	1	150	7	1050	120	5.0	600
Microwave	800	1	800	0.5	400	120	6.7	800
Smartphones	10	4	40	10	400	120	0.3	40
Washing Machine	500	1	500	0.5	250	120	4.2	500
Water Pump	300	1	300	1	300	120	15.0	1800
Other Appliances	1000	1	1000	2	2000	120	8.3	1000
Gas Furnace	400	1	400	8	3200	120	3.3	400
TOTAL			3625		9020		46.46	5575

9.8.2 Battery Selection & Sizing

The battery use in the off-grid home will be regular and rather heavy. So, lithium ion batteries would be the best option. Remember the higher costs will easily be compensated for with the almost double lifetime compared to lead acid batteries.

We calculate the battery capacity requirement for summer and winter. As winter temperatures can drop to -3°C, we find a 90% temperature factor for the battery. Moreover, we need the battery to supply for 2 days of autonomy in case we lack sunny days. In case there is no grid available in the location, it is also recommended to have a backup generator to cover us during prolonged no-sun periods.

As the daily load is higher in winter compared to summer, we size the battery according to the winter daily load.

$$Required\ Battery\ Capacity\ (kWh) = \frac{Daily\ Load\ (kWh)\ x\ Days\ of\ Autonomy}{Inverter\ Efficiency\ x\ Wiring\ Efficiency\ x\ Depth\ of\ Discharge\ x\ Temperature\ Factor}$$

$$= \frac{9.02\ kWh\ x\ 2}{0.9\ x\ 0.98\ x\ 0.8\ x\ 0.9} = 28.4\ kWh$$

An online search showed us the availability of **48 V – 200 Ah lithium ion batteries** . We can **connect three of these in parallel** to take us to our required amp-hours of 600 Ah. So, the capacity of this battery bank will be *48 V x (200 Ah x 3) = 28.8 kWh.*

9.8.3 Solar Array Sizing

Let us calculate the required daily solar energy for summer and winter.

$$Required\ Summer\ Daily\ Solar\ Energy\ (kWh) = \frac{Summer\ Daily\ Load\ (kWh)}{Charge\ Controller\ Efficiency\ x\ Wiring\ Efficiency\ x\ Battery\ Efficiency}$$

$$= \frac{7.47\ kWh}{0.9\ x\ 0.98\ x\ 0.9} = 9.41\ kWh$$

$$Required\ Winter\ Daily\ Solar\ Energy\ (kWh) = \frac{Winter\ Daily\ Load\ (kWh)}{Charge\ Controller\ Efficiency\ x\ Wiring\ Efficiency\ x\ Battery\ Efficiency}$$

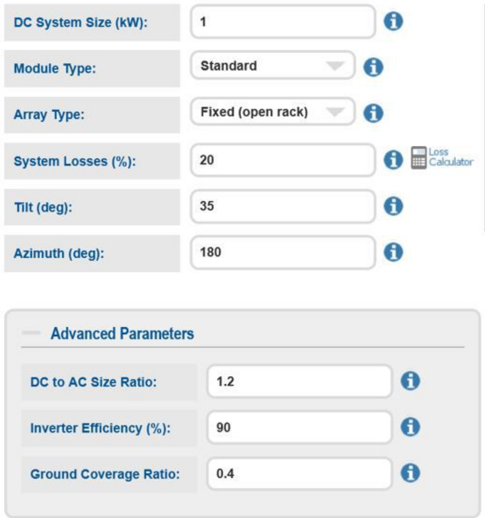
$$= \frac{9.02\ kWh}{0.9\ x\ 0.98\ x\ 0.9} = 11.36\ kWh$$

Next, we proceed to simulate the solar energy in PVWatts. As mentioned, we will go with a ground mount solar system. This means we have the freedom to choose our tilt and azimuth angles after accounting for the site and shading considerations.

The latitude of Pikeville is 37.4793°N, so our optimum tilt angle will be around this. Let us check the energy production using tilt angles of 30°, 35°, and 40° to find the best tilt angle. We use the other usual inputs in PVWatts as we have seen earlier. We use *Fixed (open rack)* as the *Array Type* and the usual azimuth angle of 180° (south-facing) for our location in the northern hemisphere.

The results are listed below. We see that using a 35° tilt angle produces the best results. So, we go for a 35° tilt angle.

Tilt Angle °	Annual Generation kWh
30	1176
35	1177
40	1172



Month	Solar Radiation (kWh / m^2 / day)	AC Energy (kWh)
January	3.88	82
February	4.29	81
March	5.01	102
April	5.56	107
May	5.69	111
June	5.89	109
July	5.65	106
August	5.87	110
September	5.43	101
October	5.31	104
November	4.42	87
December	3.55	77
Annual	5.05	1,177

It is abundantly clear that we need to size our system based on winter use. Our winter loads are higher while solar energy generation is the lowest in the winter month of December.

$$Solar\ Array\ Size\ (kW) = \frac{Required\ Daily\ Solar\ Energy\ (kWh)}{Lowest\ Energy\ Month\ AC\ Energy\ (kWh) \div Number\ of\ Days\ in\ Lowest\ Energy\ Month}$$

$$= \frac{11.36\ kWh}{77\ kWh \div 31\ days} = 4.57\ kW$$

After searching available online stores, we settle on using **16 pieces of 290 W solar panels** which gives us a total power of **4.64 kW** . Of course, sizing for winter means we will have some excess energy in summer and other seasons. This gives the user some freedom for running more loads from March to October.

9.8.4 Inverter Sizing

Looking at the load tables, the maximum power including surge is 5575 W, while the maximum continuous power is 3625 W. Note we will also include a

backup generator to charge batteries during prolonged cloudy/dark periods. Therefore, we can go for a **4 kW or 4.5 kW inverter/charger with a surge capacity of at least 5.6 KW.** If unavailable, go for a higher rated inverter/charger. The inverter/charger will also be connected to the back-diesel generator.

9.8.5 Charge Controller Sizing

We calculate the maximum charge current as normal.

$$\textit{Charge Current}\ (A) = \frac{1.25\ x\ \textit{Solar Array Size}\ (W)}{\textit{Battery Bank Voltage}\ (V)}$$

$$= \frac{1.25\ x\ 4640\ W}{48\ V} = 120.83\ A$$

We could go for a single 120A-charge controller or two 60A- charge controllers. It is rather rare to find charge controllers from reputable brands rated above 100 A charge current. So, let us go for two 60A-charge controllers provided that each controller can handle the total power of the panels that will be connected.

Remember we have 16 solar panels to connect. We can divide the panels equally among two controllers with 8 panels connected to each controller.

We take the example of Waaree 290 W solar panels and Victron Energy 60 A-charge controllers for our calculation. As we can see in the charge controller datasheet, it can handle 3440 W of solar power at 48 V battery configuration. This is perfect as 8 panels connected to each controller amounts to a total power of *8 x 290 W = 2320 W.*

Now let us check how many solar panels we can have in series and parallel to fit within the controller input limits. The charge controller can handle up to 245 V maximum voltage- which means 8 panels can be divided into two strings of 4 and connected to each controller.

It is interesting to note that the Solar Panel Open Circuit Voltage can be denoted as $\mathbf{V_{OC}}$ and the Short Circuit Current can be denoted as $\mathbf{I_{SC}}$. We always use the STC values in our formula.

Models	Pmax (W)		Vmp (V)		Imp (A)		Isc (A)		Voc (V)		Module Eff. (%)
	STC	NOCT	STC	NOCT	STC	NOCT	STC	NOCT	STC	NOCT	
WS-250	250	185.3	31.15	27.72	8.05	6.68	8.90	7.21	37.10	34.11	15.40
WS-255	255	188.6	31.30	27.91	8.15	6.76	9.00	7.28	37.50	34.48	15.71
WS-260	260	192.1	31.35	28.08	8.30	6.84	9.10	7.36	37.80	34.77	16.01
WS-265	265	195.6	31.45	28.33	8.45	6.90	9.15	7.40	37.90	34.85	16.32
WS-270	270	198.6	31.60	28.53	8.55	6.96	9.20	7.45	38.00	34.93	16.63
WS-275	275	201.8	31.80	28.77	8.65	7.01	9.25	7.48	38.15	35.05	16.94
WS-280	280	205.3	32.00	28.94	8.75	7.09	9.35	7.57	38.30	35.17	17.25
WS-285	285	209.2	32.25	29.18	8.85	7.17	9.45	7.64	38.60	35.45	17.55
WS-290	290	212.9	32.45	29.39	8.95	7.24	9.55	7.73	38.90	35.73	17.86
WS-295	295	216.2	32.60	29.57	9.05	7.31	9.65	7.80	39.20	36.00	18.17

Solar Panel Datasheet Excerpt

Source: Waaree

SmartSolar Charge Controller	250/60	250/70	250/85	250/100
Battery voltage	12 / 24 / 48V Auto Select (software tool needed to select 36V)			
Rated charge current	60A	70A	85A	100A
Nominal PV power, 12V 1a,b)	860W	1000W	1200W	1450W
Nominal PV power, 24V 1a,b)	1720W	2000W	2400W	2900W
Nominal PV power, 36V 1a,b)	2580W	3000W	3600W	4350W
Nominal PV power, 48V 1a,b)	3440W	4000W	4900W	5800W
Max. PV short circuit current 2)	35A (max 30A per MC4 conn.)		70A (max 30A per MC4 conn.)	
Maximum PV open circuit voltage	250V absolute maximum coldest conditions 245V start-up and operating maximum			

Charge Controller Datasheet Excerpt

Source: Victron Energy

Corrected Array Voltage (V) = 1.15 x Solar Panel Open Circuit Voltage (V) x Number of Solar Panels in Series

= 1.15 x 38.9 V x 4 panels = 178.94 V

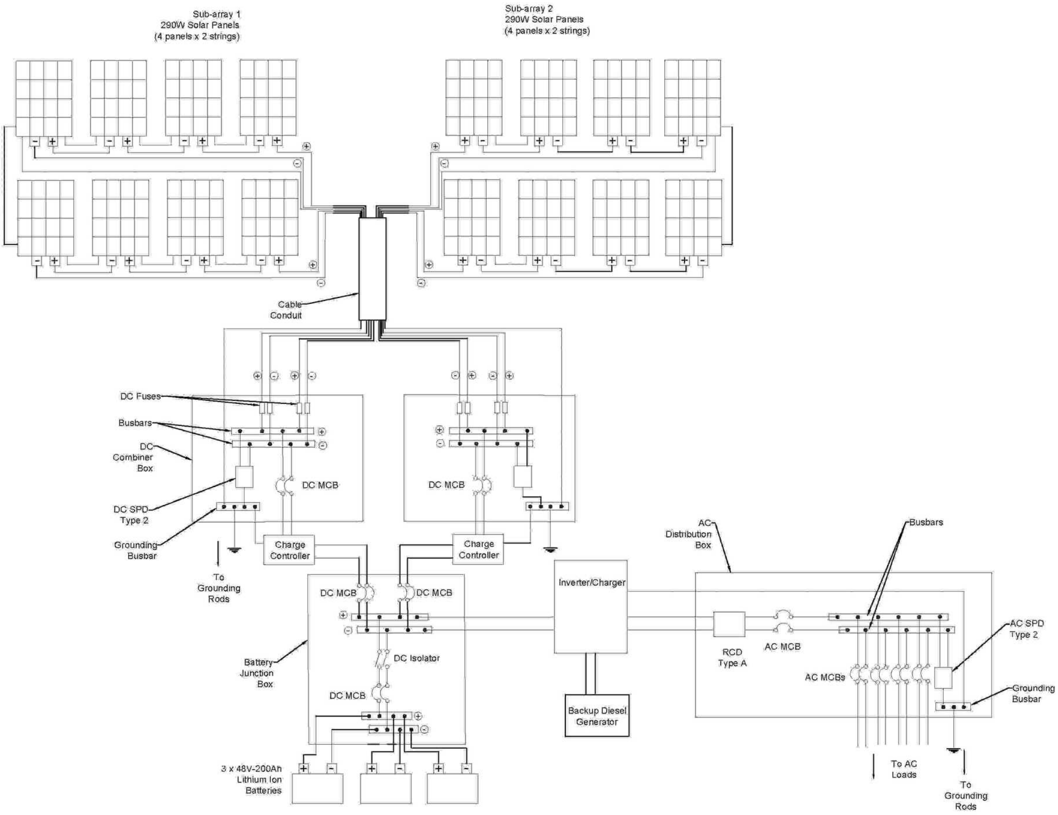
Corrected Array Current (A) = 1.56 x Solar Panel Short Circuit Current (A) x Number of Strings in Parallel

= 1.56 x 9.55 A x 2 strings = 29.796 A

Thus, the corrected array voltage (178.94 V) and current (29.796 A) are within the charge controller limits- Max PV Input Voltage (245 V) and Max PV Short Circuit Current (35 A) as seen in the datasheet. We can conclude that the chosen configuration of 2 stings with 4 panels in series in each string will work perfectly with each charge controller. This is the same for both the charge controllers and their connected sub-arrays.

Finally, the cable sizing and protection device selection is done, as we saw earlier in this chapter.

9.8.6 Final System Schematic Diagram



9.9 Finalizing the Plan and Design

Once you are done selecting and sizing the components of your choice during the planning and design stage, make sure to double-check if everything is in order. Planning and designing is an active process that goes beyond books, notebooks, or computers. You must verify your design with your site, location, component availability, and so on.

✓ Look at your site survey notes and see if your chosen solar components (solar array, batteries, inverter, charge controller, etc.) fit in the designated locations. If required, do a second site survey and take necessary measurements of the previous or new areas for placing your components. The component datasheets and manuals will have information about their dimensions, weight, etc.

✓ It is important to double-check your calculations and methods employed. Remember we are dealing with electricity and wrong sizing may lead to risks.

✓ Check if your chosen components are available from your nearest store or online shop.

✓ We have explained everything you need to know in this book but still some sites may have unique issues. So, if you are unsure about anything, get in touch with an appropriate consultant. You may also get in touch

with the author of this book for consultation (see About the Authors section). I will be happy to help.

- ✓ Once everything is finalized, you can proceed to make a budget and then buy the components. Make sure you go for high-quality components with good warranty terms.
- ✓ Make sure you buy some extra length of cable as spare for each set of cables. You never know when you might need it. In some cases, you may need to route the cable through greater distances than planned due to obstacles or for safety reasons. You may also need to cut out lengths of cable due to damage to wires e.g. from imperfect crimping. It also makes sense to get some spare cable connectors, fasteners, and other materials.

10 Which Tools Do We Need?

Just like performing any other electrical installation or construction work, we need our tools for solar installations. It is essential you use high-quality tools to ensure a safe and smooth installation process. Go for insulated tools wherever possible.

Let us quickly walk through the tools and instruments.

10.1 Digital Multimeter

Etekcity Digital Multimeter
Source: Etekcity

Digital multimeters are used to measure voltage, current, resistance, and other useful parameters.

We can use a multimeter in four simple steps:

1. Hook up the test leads to the multimeter inputs. The black lead always goes to the COM input. For the red lead, choose the input based on what you want to measure (Hint: look at the input labels).
2. Turn the rotary switch to select what you want to measure (voltage, current, resistance….)
3. Place the test lead probes on the two ends of the electric circuit you want to measure. The positive red lead goes on the positive pole of the circuit, while the black lead goes to the negative pole or ground.
4. The measured value will be displayed.

Note: Make sure to read the manual of your digital multimeter before using it.

10.2 Clamp Meter

Etekcity Clamp Meter
Source: Etekcity

A clamp meter can measure everything a digital multimeter can measure (except DC current). The additional feature is that you can use the clamp to measure AC current in a cable (as shown in the illustration above right).

With clamp meters, we can measure higher AC currents compared to digital multimeters. They are particularly useful for solar systems with inverters (more on that later).

Make sure to read the manual of your clamp meter before using it.

10.3 Screwdriver Set

Screwdrivers are among the most common tools. They are used to install and remove screws. It is recommended to use insulated screwdrivers as solar installations involve electricity.

Screwdrivers also come in various sizes which are used with different sized screws. As solar installations typically involve screws of different sizes it is useful to get an insulated screwdriver set which conveniently contains the different sized screwdrivers.

Source: Wiha Tools

10.4 Wrench Set

Wrenches are used to install, remove, or tighten fasteners such as nuts and bolts. It is again useful to get a wrench set housing different sizes to deal with the different sized fasteners present in solar installations. Once again, it is best to go for insulated wrenches.

Source: Cementex

10.5 Ratchet Set

Ratchets are another common tool used in solar installations. They are used to fasten or loosen nuts and bolts. They are also used to tighten battery terminals.

Source: Best Parts

10.6 Needle Nose Pliers

Pliers are required to bend wires and other metallic parts such as metal conduits. Needle nose pliers are the best type of pliers for the job. Thanks to their long and narrow jaws, they can reach spots where other pliers cannot reach. We should use needle nose pliers with insulated handles for solar installations.

Source: Wiha

10.7 Wire Strippers

Wire srippers are used to strip the electrical insulation from electric wires in order to create electrical connections. The following types of wire strippers are useful for solar installations (according to the cable sizes they can be used with).

Make sure to check the cable size stripping ability of the strippers and the cable sizes you are working with before buying.

Automatic Wire Stripper
for 24 – 10 AWG cables

Wire Stripper

for 6 – 12 AWG cables

Cable knife for 4AWG -4/0 cables
Source: Uvital; Klein Tools; Jokari

10.8 Wire Cutters and Cable Cutters

Wire cutters are essential tools used to cut wires to the required length. Some wire cutters have insulated handles for added safety.

Wire cutters are usually suitable for cables sized 9 AWG – 24 AWG.

Flush-cut wire cutters are a variant of wire cutters that have angled and long jaws that are useful for cutting at an angle.

Cable cutters are used for larger cables up to 4/0 and above.

Make sure to check the cable size cutting ability of the cutter and the cable sizes you are working with before buying.

Wire Cutter

Flush-cut Wire Cutter

Cable Cutter
Source: IGAN; Temco

10.9 Crimping Tools

Crimping tools or crimpers are tools used to make cold weld joints between two wires or a wire and a connector, such as a lug. Similar to the other cable tools, crimping tools are sized according to the cable sizes they can accept.

Crimping Tools are used to connect cables between 10 AWG to 22 AWG.

Cable Lug Crimping Tools are used for connecting larger cables (such as the battery cables) with cable lugs for sizes between 8 AWG to 1/0 AWG.

Hammer Lug Crimping Tools are another option for connecting battery cables of a larger size of up to 2/0 AWG.

Cable Crimping Tool

Cable Lug Crimping Tool

Hammer Lug Crimping Tool
Source: Qibaok; IWISS; Simple Electric Solutions

10.10 MC4 Assembly Tool

The MC4 assembly tool is needed to install MC4 connectors on the solar extension cables. It is essential to tighten the MC4 connector onto the wire.

Source: Vktech

10.11 Torpedo Level

Components need to be installed in a straight manner for balancing within the equipment. When installing solar components on a wall or a structure, we need to make precise measurements and ensure they are kept straight. A spirit level is useful for this. A torpedo level is a type of spirit level that is useful for working in tight spaces.

Source: Dewalt

10.12 Cordless Drill and Drill Bits

A power drill is used to make holes in walls, wood, plastic, and metal in order to install screws or bolts. The screws and bolts are in turn used to mount solar components such as the inverter or charge controller.

Drill bits of appropriate sizes are attached to the drill to make holes of our required size. Alternately, a screwdriver tip can be attached to the drill to fasten screws.

A cordless drill is best suited for solar installations as it does not have an attached power cable. It can be operated on rooftops and ground sites without having to worry about a power connection and cable.

Cordless Drill with Drill Bits
Source: Dreamstime

10.13 Hole Saw

Hole saws (also known as hole cutters or hole drill bits) are drill attachments designed for cutting perfectly round holes in a variety of materials including wood, plastic, soft plaster, and metal.

Source: Panovos

10.14 Hacksaw

A hacksaw is a hand tool used for cutting through materials such as metals and plastic. It is especially useful for cutting mounting systems to our required size. Hacksaws usually include an adjustable blade which allows us to perform cuts at our desired angle.

Source: Capri Tools

10.15 Conduit Cutting Tools

Conduit cutting tools are required to cut cable conduits to our required length. Conduit cutting tools are also known as pipe cutters or tube cutters.

Conduit cutters can be used to cut PVC and plastic cable conduits.

Metal conduit cutters are used to cut metal conduits made of steel, copper, aluminum, etc.

Conduit Cutter
Source: Zantle

Metal Conduit Cutter
Source: Toolto

11 Safety Measures and the Art of Wiring

Just like any electrical installation work, safety is of paramount importance for solar PV installation. There are risks of electric shock, physical injury, and fire that may occur due to carelessness. However, by following certain safety rules and wearing appropriate PPE we can ensure 100% safety during installation and beyond.

11.1 Golden Rules for Safety

Let us go through the safety rules that we must follow at all times.

1. Make sure to wear appropriate PPE- helmets, gloves, protective clothing, and footwear, etc. Inspect the condition of your PPE before use. We will look at these in detail in section 11.2.
2. Always make sure the circuit or device is not energized before performing any work on it. You may do this using an electrical tester (make sure the light does not glow) or by measuring the voltage using a digital multimeter (the voltage will be zero for a de-energized circuit).
3. Keep the first aid kit well-stocked and ready.
4. Do not work during wind, rain, snow, or other adverse weather conditions.
5. Remember there is no way of switching off solar panels. They produce electricity when there is light. Make sure to secure the output cables within the panel before transporting them. Be sure to wear insulating gloves when making solar cable connections. If needed, cover the face of the solar panel with a thick sheet or covering to block out the light before working.
6. Similarly, batteries cannot be switched off. Current will flow from the batteries when there is a connection between the positive and negative terminals or between the terminals and the ground. Always wear insulating gloves and footwear when working with batteries.
7. Make sure the entire system is ground fault-proof! This means you must take all measures to ensure there is no connection between the wiring, busbars, or any other live electrical parts and the ground or other equipment such as enclosures or metal conduits. Any accidental connection between live electric parts and the enclosure or other parts will lead to ground faults that

present risks of electrocution upon contact and damage to equipment.

8. Make sure the entire system is short circuit proof! You must take all measures to make sure that there is no accidental connection between the positive and negative poles of a circuit. Any undue short circuits can lead to a dangerous flow of current leading to risks of electrical blasts, injury, or damage to equipment.
9. Make sure that batteries are located in a ventilated space. Do not smoke or carry a flame near batteries.
10. Be extra careful when transporting charged batteries. Cover the terminals and make sure nothing is placed on top of them.
11. Use stable ladders, and position them correctly. Have somebody hold the bottom part of the ladder.
12. Wear safety harnesses or personal fall arrest systems when working at heights especially on tilted roofs.
13. Always keep your hands, feet, and body dry when working with electrical circuits. Keep a hand towel nearby.
14. Make sure the floor is dry.
15. Use tools with insulated handles when working on electrical circuits.
16. Do not use metallic objects near electrical parts, e.g. metallic pencils or rulers. Do not wear rings or metallic watches when working with electricity.
17. If water or other liquids are spilled on or near an electrical device be sure to shut down the power by turning off the main switch, circuit breaker, or unplugging the device.
18. Always disconnect the power source before performing maintenance on electrical equipment.
19. Keep the electrical equipment away from flames and flammable liquids.
20. Be aware of multiple electrical sources such as solar panels, batteries, diesel generators, etc. Make sure everything is switched off before working.

11.2 Personal Protective Equipment (PPE)

Personal protective equipment is essential for solar installation work. They protect the worker from injury due to impacts, electrical shock as well as other risks. However, don't look at PPE as the "ultimate savior from all dangers", and make sure to follow all the other safety rules as well.

Protective Helmet *(also known as a hard hat)* must be worn where there is potential for injury from falling objects or exposure to electrical hazards. Make sure the helmet is of Type II Class E to provide adequate physical and electrical protection.

Source: Omega II

Safety Glasses are needed to protect against hazards such as dust and other flying particles, corrosive gases, liquids, and operations such as drilling and welding. A comfortable fit is important when choosing safety goggles.

Source: Namsan II

Electrical insulating gloves must be worn to provide protection from live voltages such as when working with solar panel cables and batteries. Normally Class 00 rated gloves will be adequate for our small scale off-grid solar applications, offering protection at up to 500 Volts.

It is extremely important to air test electrical insulating gloves before wearing them as even minuscule pinholes in the gloves can be dangerous. To air test the gloves simply hold the gauntlet (sleeve) end of it closed trapping air inside. Then tightly roll the closed end of the glove downward toward the fingers. If no air leaks out, the glove is free from holes.

Source: Magid

Protective footwear must be used when any of the following conditions are present: heavy objects such as equipment or tools that might roll onto or fall on one's feet; sharp objects such as nails or spikes that might pierce ordinary shoes; or working on hot, wet, or slippery surfaces.

Electrical hazard (EH) rated footwear has non-conductive soles and provides secondary protection from live electrical equipment.

Personal Fall Arrest System is required if you are working at a height especially on a tilted roof of a house. It must be considered when falling from the working height is high enough to injure or kill someone.

Source: The Cure Safety

Hearing protection is needed when things get loud, e.g. while operating a drill. Hearing protection options include earmuffs that fit over the ear and seal against the side of the head, hearing bands, or disposable and reusable earplugs inserted directly into the ear canal.

11.3 Art Of Wiring for A Fault-Proof System

There are a few things to keep in mind when laying down cables and wires during a solar installation. Proper wiring will ensure efficient, safe, and risk-free operation of your solar system.

✓ Cables should be installed in a way that they are beyond the reach of children, rodents, and pets.

✓ As discussed, ground faults can occur if a live wire accidentally comes in contact with the ground or equipment enclosure, while short circuits occur when the positive and negative wires inadvertently come in contact.

Our aim should be to lay the cables in an earth/ground fault-proof and short-circuit proof manner.

✓ Check the cable's allowable bending radius before bending cables to route them.

✓ Cables should be laid in such a way that rainwater run-off will not be impeded.

✓ Before installing a cable or set of cables, make sure the insulation is intact and undamaged throughout the whole length of the cable. The cable insulation is more easily damaged in cold winter temperatures; therefore, cables should be handled carefully.

✓ Do not lay cables on the roof covering. Instead, fix them to the support frame using cable ties and place the extensions in a protective conduit. Ensure the cable ties and conduits are weather and UV resistant.

✓ As much as possible, lay cables in shaded areas.

✓ Make sure the cable is laid straight and neatly to avoid loops and tangles.

✓ Ensure the cables are laid away from sharp edges and places where mechanical damage may occur.

✓ Before making connections, make sure the polarity of the cables and connectors are correct- positive to positive, negative to negative.

✓ When making connections make sure the wire is solidly attached to the terminal. Loose connections can lead to electrical arc flashes and even fire!

✓ Cables should be laid away from flames and flammable materials.

✓ Label the DC cables when bunching cables with different electricity types (DC and AC).

12 Putting it all Together: Installing Your System

Finally, it is time for installation! All the hard work you put into learning, planning, and designing your solar system will finally bear fruit.

In this chapter, we will go through the steps involved in installing your solar system. We will elaborate on each step so that you are fully geared up to install the solar system without any hassles.

12.1 Getting Ready

- ✓ It is always good practice to spend some time getting yourself and everything else ready before installation. Make sure all the components and their manuals, required tools, safety equipment are all available and ready. It helps to have a checklist of your components to make sure everything has been delivered or bought.
- ✓ Ensure that your design plans, schematic diagrams, and locations for the components are measured, double-checked, and finalized. Note down any necessary changes.
- ✓ Make sure you thoroughly go through the user manuals and instructions of the components. They always contain information on the do's and don'ts of installation, positioning the component, the clearance or space we must keep around the component, and so on.
- ✓ We must inspect the safety equipment as well as the tools to make sure nothing is damaged and all is operating correctly.
- ✓ Learn how to connect MC4 connectors to cables and how to crimp lugs and other connectors onto cables. There are several online videos and resources on this.

Let us now look at the installation of the different solar components. Install the components in the following order-

1. Batteries
2. Charge Controller
3. Inverter
4. Junction Boxes
5. Solar panels
6. Cables
7. Battery monitor

12.2 Installing Batteries

First things first, batteries are quite heavy. If they are too heavy for you, make sure you get assistance. Be sure to read through the manuals and documents (such as installation guidelines) of your chosen battery.

Remember batteries need to be located in a cool, well-ventilated space. Batteries sometimes emit harmful gases which should be allowed to escape. The battery bank has to be located near the charge controller, inverter, and battery junction box and as close as possible to the solar array.

Mounting batteries directly on the ground or on metal racking can cause them to drain. In mobile solar systems batteries are thus mounted in a compartment, while for home systems, the battery will be mounted on a rack. Battery racks are available for purchase, make sure they are of the right size. Some lithium ion batteries need to be mounted on the wall.

Test the voltage of each battery with a digital multimeter before you mount them. If you have more than one battery they should more or less be of the same voltage.

Next, mount the battery/batteries appropriately on the rack or compartment. For vehicle-based systems, the battery will need to be secured with a strap and fasteners to make sure it does not fall over when the vehicle moves.

Batteries in Vehicles

Source: Parked in Paradise; AM Solar; My Generator

Batteries in Homes & Cabins
Source: NRG Solar; Countryside

12.3 Installing Charge Controllers

Firstly, make sure to go through the manuals and other documents of your charge controller. They will contain valuable information on installation steps and what tools to use.

You must place the charge controllers as close to the batteries as possible. Remember the charge controller will have cables coming in from the batteries via the battery junction box. There will also be cables coming into the controller from the solar panels via the DC combiner box. So, you must plan the locations of the boxes close to the charge controller as well.

A dry, well-ventilated space is ideal. Also, ensure it is located away from sources of vibration, humidity, and heat. It also must be protected from precipitation and direct sunlight.

The charge controller is typically mounted on a wall using appropriate fasteners (such as screws or bolts). Small and lightweight charge controllers may be mounted using mounting tape. For larger charge

controllers you may need to reinforce the wall that you plan to mount it on, or you could mount it first on a piece of wooden board and then mount the wooden board on to the wall.

Remember clearances and spaces around the charge controller must be maintained according to the manual or instructions from the manufacturer. The space around the controller is required to allow better cooling. It is also necessary to ensure the charge controller is grounded according to the manual and datasheet.

Source: RVWeb

12.4 Installing the Inverter

Similar to charge controllers, inverters are also installed on a wall surface in a safe, ventilated space. Similarly, they must be protected from precipitation and direct sunlight. Another consideration is that inverters emit noise and electromagnetic waves, so are best placed away from people.

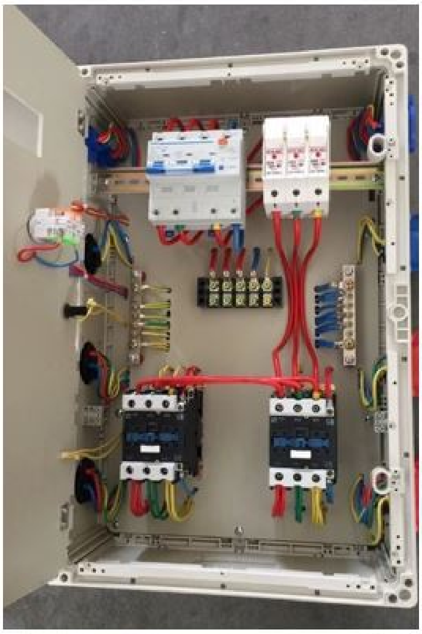
As usual, be sure to go through the inverter manual and guidelines and make sure to maintain the clearance spaces around the inverter to allow for cooling. The manuals will also provide instructions on installation and required tools. Make sure the inverter is adequately grounding according to manufacturer instructions.

Source: Northern Arizona Wind & Sun

12.5 Installing Junction Boxes

All connections and devices should be enclosed in junction boxes. Junction boxes should be in reasonably accessible locations so that they can be accessed if there is a problem.

Before we mount the junction boxes, we need to put in all the devices that will go into the boxes. Circuit breakers, surge arrestors, fuses, and other protection devices need to be mounted on a DIN rail. The DIN rail is then attached to the junction box with suitable fasteners. Look at your schematic diagram and attach any other devices such as busbars that need to be mounted in the box.



Source: Kae ; Ezitown

The junction boxes are then mounted on wall surfaces near the indoor solar components. We should mount them in positions such that cabling is easy and of minimum length as much as possible. Junction boxes need to be mounted using appropriate fasteners (such as screws or bolts) after drilling into the wall surface.

As mentioned, junction boxes may have pre-drilled entry holes for cables or holes may need to be drilled according to the cable size. One hole is drilled for each cable. A cable gland is attached at each entry hole to ensure sealing and protection from the outside. Cables are passed through the cable glands at the entry hole and into the box.

If the junction box is made of metal, make sure the enclosure is grounded.

Remember the cable connections for each of the boxes. They can guide you on choosing the best position for each of the boxes-

- **DC Combiner Box** will be connected to solar cables coming in from the solar array on the roof or outside. It will also have cables connected to the Charge Controller.
- **Battery Junction Box** will be connected to the battery bank, the charge controller as well as the inverter. The battery junction box, battery bank, and inverter should be positioned as close to

each other as possible to keep the thick and expensive battery cable costs low as well as improving the system efficiency.

- **AC Distribution Box** will have cable connections from the inverter output. So, it is best placed close to the inverter. The AC Distribution Box may also have cables going to loads. Or if there is a separate Consumer Unit (that is connected to the loads) already installed in your home or RV, then the AC Distribution Box will have cables connected to the Consumer Unit.

12.6 Installing Solar Panels

There are a few things to keep in mind when it comes to installing solar panels. Firstly, make sure you read the instructions that come with the solar panels and mounting kit. Solar panels can be heavy depending on their size/wattage. Smaller panels can usually be handled by one person but larger panels will require at least two people to move them. Wear a protective helmet when handling large modules and mounting structures.

Before carrying out installation work, carefully go through the installation instructions for the solar panels and the mounting system. The panels must be properly fixed and secured in order to withstand harsh climatic conditions and movement of your vehicle. Without secure attachment, heavy winds or movements can blow away the panels which may fatally injure humans and destroy property.

For roof mounted systems, you need to make sure the installation is waterproof. Use proper sealants (such as joint sealants and lap sealants) around the mounting holes to prevent any water leakage. One also has to be comfortable with working at heights to be working on the roof.

A key consideration for choosing the location for solar panels is accessibility. They need to be accessible for cleaning and maintenance purposes. Cleaning of panels is essential as dirt and dust can cause shading and reduce power output.

Leave a little gap between the solar panel and the roof surface. This ensures ventilation and cooling under the solar panel which can considerably improve the power generating efficiency of the solar panel.

The panels should be positioned in a way that minimizes the overall length of the solar cabling to the DC combiner box. It can help to first

draw the position of the panels on the roof using chalk.

Installation should be carried out only during dry weather conditions using dry tools. Solar panels should be lifted, carried, and placed carefully, ensuring they do not face any impact. They should not be stepped on, and no heavy or sharp-edged objects should be placed on them.

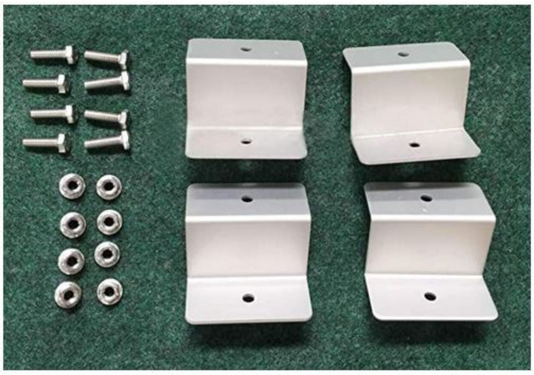
Make sure you use high-quality hardware, materials, and tools. Go for stainless-steel fasteners (screws and bolts) if you don't want them to get rusty and be damaged easily.

Let us now go through the mounting options for mobile and off-grid home solar systems.

I. Mobile Solar Systems

1. **Mounting Brackets:** If your vehicle roof is suitable for drilling and installing mounting brackets this would be the ideal option for quick installation and secure fixing.

Z-brackets are a good option that does not require drilling the solar panel frame. They are attached using suitable fasteners on to the mounting holes that are already present on the solar panel frame. Next, clean the roof surface and apply sealants such as lap sealant or Sikaflex, after which you can clamp down the bracket onto the roof by drilling through and fastening the screw or bolt.



Source: ElectroPrime; Traipsing About; Panther RV Products

L-brackets require drilling the frame of the panel to attach the bracket using suitable bolts. Do this carefully and make sure you drill well below the level of the solar cells. The brackets are then clamped down on to the roof and have a sealant applied as we saw with Z-brackets.

Source: Build A Green RV

Roof rack: Alternatively, if your vehicle has a roof rack or if you can install a roof rack, you could bolt the brackets directly onto the rack.

Source: Vivid Racing; Pajero Sport

2. **Drill-free mounting:** If you are not very keen on drilling through the roof, you can go for corner brackets. This option works well with flat metal or fiberglass roofs. You will need VHB tape or weather-proof construction adhesive.

Corner brackets are first attached to the solar panel either on to the mounting hole of the panel or by drilling additional holes depending on the type of bracket.

Next, clean the roof thoroughly with soap and water. After it dries, apply rubbing alcohol on the surfaces where you plan to place the mounting brackets. Let it dry,

then apply 3M VHB tape or weather-proof construction adhesive on the entire bottom surface of the corner brackets. Place the panel with corner brackets on to the roof and apply some force to make sure they bond. Ensure all the brackets have bonded flat on to the roof surface. After this, apply sealant such as sika-flex or lap sealant around the mounts to protect the tape from water.

Source: U Motor; Renogy; Sunway Solar

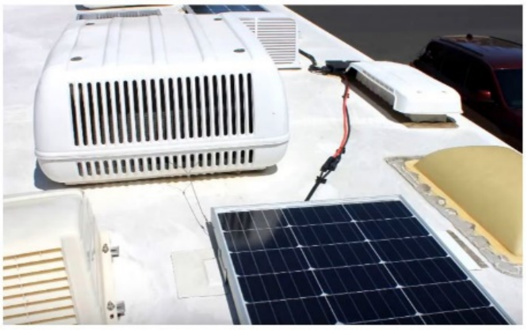
Solar Array Safety Line

A safety line is essential for mobile solar systems no matter how you decide to install your solar panel system. A solar panel safety line is a strong and sturdy rope that connects and attaches all the solar panels. It is the second line of defense to stop the solar panels from flying off and fatally injuring someone.

The safety line must be sturdy, UV-resistant, and weatherproof. It is best to go for a steel cable or marine-grade shock cord.

The aim of the safety line is if one solar panel flies off it will be held back on to other panels and other objects on the roof. The safety line is put through the mounting holes or newly drilled holes of the solar panels and attached to each other or individually. Next attach the safety line to a sturdy object on your vehicle's roof such as a roof rack, roof ladder, or air conditioner.

Once the safety line is safely connected, you must be careful not to trip on it. You may want to secure the safety line to the roof surface with roof sealing tape.



Source: Don Davis

II. Solar Systems for Homes and Cabins

1. **Roof mounted systems:** Safety first! If you are working on a tilted roof at a height that has a risk of injury or death upon falling you must wear a personal fall arrest system! We recommend people with some experience and confidence to work on the solar panel installation for roof mount systems. If you aren’t experienced or aren’t confident, just get some expert installers to do the roof installation work.

If your roof is not planked (truss structure), do not walk in the middle of the rafters/purlins or on the under-roof screen as there is a risk of falling.

Never make roof mounts the highest point on the roof, as they can attract lightning.

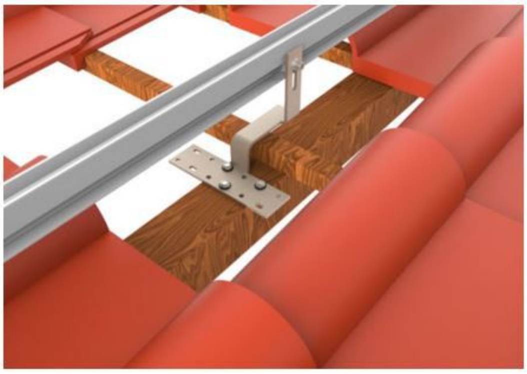
Make sure you make precise measurements and positioning before performing any drilling, as wrongly drilled holes may compromise the roof’s waterproofing or structural integrity.

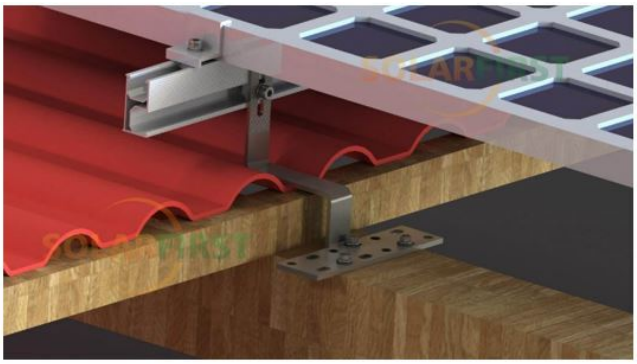
We need to keep the roof waterproof and prevent any water leakage into the house. Use sealants and rubber grommets with the mounting bolt or screw.

The type of mounting you use for roof mounted systems will depend on the type of roof, as discussed next.

Tiled roof: If your roof has tiles or shingles, we usually go for a roof hook and rail mounting kit. You will need to remove the tiles at positions where you will attach the roof hooks. Once the tile is removed, attach the roof hook to the rafter of your roof by drilling and using designated fasteners in the kit. The tile is then placed back into position.

Next, the other end of the roof hook is attached onto the rails. The number of hooks and rails will depend on the size of the solar array. Finally, the solar panels are attached to the rail with the designated clamp in the mounting kit. Do this for all the solar panels.



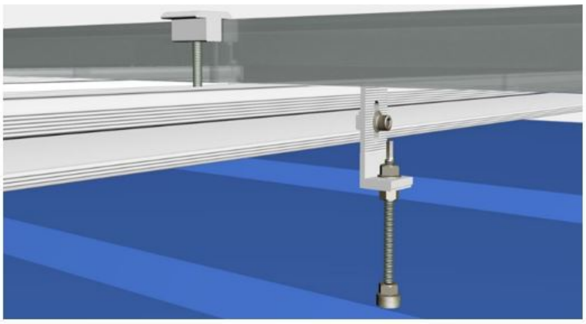


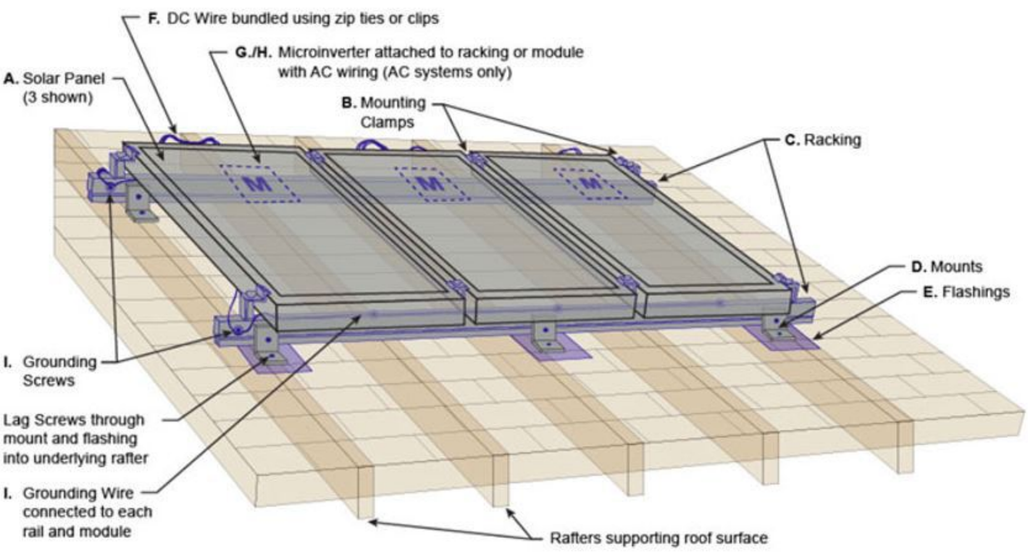
Source: Sunforson; Solar First

Source: Sunforson; Solar First

Sheet roof: Sheet roofs made of metal or plastic sheets are much simpler to work with. Usually, L-feet and Rail kits or mini-rail mounting kits are easy installation options for such roofs.

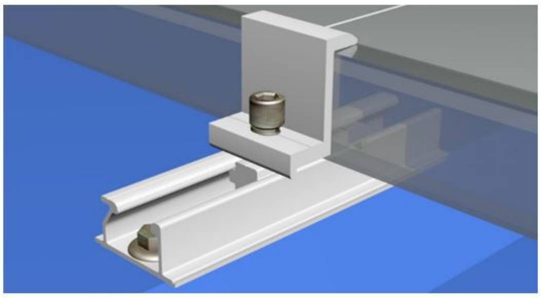
The installation process is simple, we need to drill the bolt through the roof into the rafter or purlin to attach the L-feet or mini-rail. Then the panel is placed and the designated clamps in the kit are attached onto the rail, securing the panel in the process.





L-feet and Rail Mounting System

Source: Mibet Energy; Sunforson; Solar Power World



Mini-rail Mounting System
Source: Mibet Energy; Hyper Green Renewable Energy

Flat roof: For flat roofs, ballasted mounting systems are the preferred option for their ease of installation and economics. This solution does not require drilling through the roof and consists of brackets and rails which are held down by the weight of pre-cast concrete ballasts.

The manufacturer guidelines for installation need to be followed as there may be variations in the type of system. Typically, first, the brackets along with the ballasts are placed on the roof with precise measurements. The panels are then attached using the designated clamps or brackets.

Source: Understand Solar

2. **Ground mounted system:** Ground mounted systems are applicable for cabins or homes. It’s our go-to option when there isn’t enough space on the roof or if the roof is not strong enough to hold solar panels.

The easiest DIY quick fix is making a mounting structure out of wood. We must make sure the structure is secure and the foundation is strong enough to withstand windy conditions. We don’t want our solar panels to fall apart or get blown away by the wind, do we?

Connect as many pieces of wood in a logical manner to make a stable frame as you can see in the illustrations below. Use high-quality L-brackets and screws to connect the wood together. Make sure they are made of stainless steel.

To connect the solar panels onto the frame use Z brackets. The Z bracket is attached onto the mounting holes of the solar panels with suitable screws and then secured onto the mounting frame.

Make some measurements of your panels to estimate the lengths and amount of wood you will need. You should be able to get this from the hardware store. We can plan the tilt of the mounting frame to the optimum tilt of the location as we saw in the Site Survey and Planning and Design chapters. You can set it as the latitude angle of your location. For more refined results, refer to section 9.8 Design for an Off-grid home, where we used PVWatts simulation to find the best angle.

There are several options to secure the mounting frame to the ground, such as ground stake screws, concrete, or sandbags. For larger systems and/or windy locations concrete is recommended.

The output cable from the solar array has to be drawn to the rest of the components. Usually, the cables are placed in a conduit and routed underground. Trenches need to be dug along the ground to accommodate the cable conduit.

Mounting rails, pipes, or poles made of aluminum/steel can also be used for ground mounting. These may require specialized equipment and professional installers to carry out the installation.


Trenching for
Underground Cables

Source: Build it Solar; Promsun; Ottawa Valley PV; Instructables

Source: Ottawa Valley PV; Instructables; Sto Energy

12.7 Installing Cables

Finally, we proceed to connect up our system with cables. Before you begin make sure you have all the required cables and cable connectors (crimp connectors, lugs, MC4 connectors). It is always a good idea to have spare cables and connectors. Make sure the cables and connectors are all of the right sizes by double-checking with the schematic diagram. Clip cables neatly to the wall, spacing the clips at regular intervals, or

run
cables in a conduit that is properly fixed to the wall.

For all cable work make sure you maintain all safety rules and wear appropriate safety gear- insulating gloves, helmet, protective footwear, and safety glasses.

The required steps for cable installation are in the following order-

1. Learn how to crimp if you haven't already
2. Connect the Batteries and Battery Junction Box
3. Connect Battery Bank to Charge Controller
4. Interconnect the Solar Panels
5. Connect the DC Combiner Box, Charge Controller, and Solar Array
6. Connect the Inverter to the Batteries
7. Install the Battery Monitor and any other Control or Monitoring units
8. Connect up your grounding system
9. Connect up wiring to your appliances and sockets

1. *Learn how to crimp if you haven't already*

Cables need to be fitted with crimp connectors in order to connect with solar system components. Crimping is the process of connecting the crimp connectors onto the cables using a crimping tool.

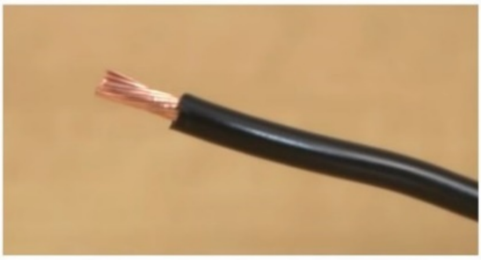
The quickest way to learn this is by watching an online video tutorial on YouTube. Then, do a few practice runs with some spare small cables to master the art of crimping.

The basic steps to crimping are as follows-

I. Get your cable and the right sized crimp connector for the cable.

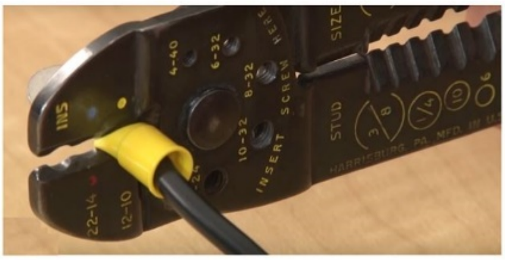
II. Use the correct size of wire stripper to strip the cable insulation so that the wire can fit inside the crimp connector. Make sure not to damage the wires.

III. Twist the strands with your fingers so that there are no loose strands and it is compact.



IV. Insert the desired crimp connector on to the wire.

V. Check the markings on your crimping tool and use the jaw with correct cable size. Firmly press the tool to make a solid connection.



VI. Pull the lug to see if it is properly connected.

Source: Galco TV

2. *Connect the batteries and battery junction box*

Next, we proceed to connect the batteries. Make sure to read the battery manual and guidelines before performing this step.

Safety first! Battery terminals are live with electricity, so make sure not to touch the battery terminals and wear the appropriate PPE including insulating gloves, safety glasses, helmet, and protective footwear.

If you have more than one battery, check your schematic diagram for the series/parallel connections.

Next, we need to attach the cable lugs on to the battery cables using the cable lug crimping tool or the hammer lug crimping tool. Once the lugs are fitted, interconnect the batteries by connecting the cables to the appropriate battery terminals- tighten the screws and secure them.

Source: The Drive; Boat U.S.

Next, the output battery cables are connected to the battery circuit breaker and DC battery isolator switch and then to the busbar in the

battery junction box. **Make sure the battery isolator switch is in the OFF position.**

3. *Connect Battery Bank to Charge Controller*

Be sure to read the charge controller manual before performing this connection.

Pay attention to the polarity- positive to positive and negative to negative.

Now that the battery bank is connected to the battery junction box busbar, we need to create a connection between the battery junction box bus to the charge controller.

Once again make sure the battery isolator and circuit breaker in the battery junction box are in the OFF position. The connection is then made according to the manual.

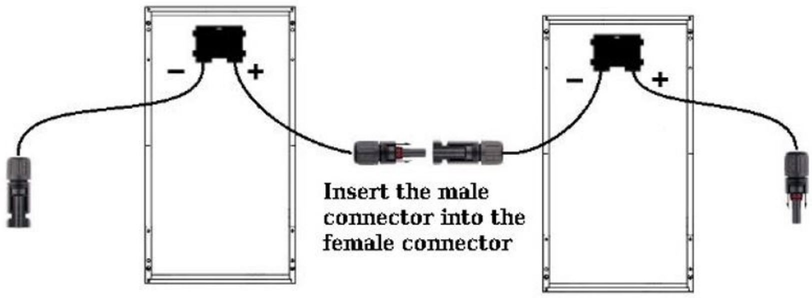
Also, make the grounding cable connections to the charge controller according to the charge controller manual.

4. *Interconnect the solar panels*

Solar panels will have output cables already connected to them (positive and negative). These cables will also have MC4 connectors already attached to them. So, the job here is to connect the solar panels in series or parallel according to your schematic diagram. It may help to refer back to the Solar Panel connections section in Chapter 8.

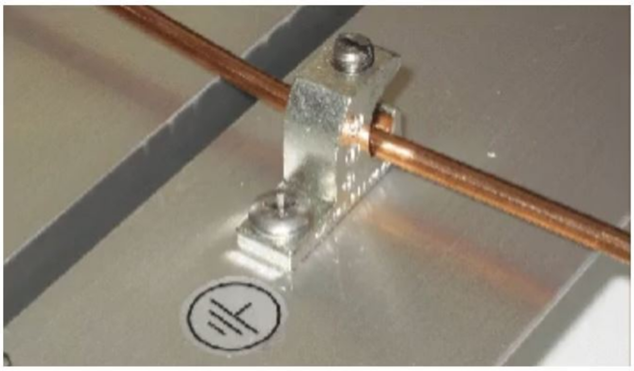
The male MC4 connector (positive) of one panel is inserted into the female MC4 connector (negative) of the next panel.

Make sure you wear electrical insulating gloves when making these connections. Connect modules with each other correctly. Do not skip any modules and pay careful attention that no module is connected to itself, this will cause a short-circuit of the module. When you have a design with both series-parallel connections, pay attention to how many panels are in series and how many strings are in parallel.



Source: Northern Arizona Wind and Sun

We also need to connect the grounding cables using grounding clips to the solar array frame and the mounting system (if it is metallic). Look through the solar panel manual for grounding instructions. Typically, you will need to use 10 mm2 (6 AWG) grounding cables. All the panel frames and mounting frames are connected together using grounding clips and grounding cables, then a grounding cable is used to connect the mounting frame to the grounding rods or vehicle chassis.



Source: Instructables

5. ***Connect the DC Combiner Box, Charge Controller, and Solar Array***

IMPORTANT- Before we connect the extension cables to the solar panel output cables, we make a connection to the DC Combiner Box. This is because once we connect the extension cables to the solar array it becomes live with electricity. We don’t want our cables and the busbar to be live as we need to work on them. So we finish all the other connections before connecting the DC Combiner box to the solar array.

Pay attention to the polarity- positive to positive and negative to negative.

First, we connect the extension solar cables to the fuses in the DC Combiner box and then onto the busbar. To connect it to the busbar, we need to fit lugs or crimp connectors on this end of the cable. Then

appropriately sized holes are drilled on the busbar. The cable fitted with lugs or connectors is then attached to the busbar using nuts and bolts. The connection between the busbar and the circuit breaker is also made.

Make sure the circuit breaker is in the OFF position.

Next, we make the connection from the DC Combiner Box to the charge controller PV input. Go through the manual of the charge controller to see how this has to be done.

DO NOT connect the solar array to the charge controller if the battery bank is not connected to the charge controller. Make sure the battery bank to charge controller connection is made already.

Once all this is done, we need to connect the extension cables with the output cables of the solar array. To connect the solar cables with the array output cables, we first need to fit MC4 connectors onto our extension solar cables at the array end. Watch a video tutorial online on how to fit MC4 connectors onto cables.

The basic steps are as follows-

I. Using a wire stripper, strip 3/8 inches (1 cm) of the solar cable insulation

II. Get a pair of MC4 connectors. The male connector will go on one cable while the female part goes on the other

III.

The metal terminal of the MC4 connector is crimped onto the cable using a crimping tool.

IV. Put the terminal directly into the connector

V. Use the MC4 assembly tool to slide the strain relief/ grommet and nut back onto the MC4 connector. Firmly tighten the nut.

Source: Leader Group; Sinovoltaics

Once you connect the MC4 connectors onto the extension cables you can connect the extension cables to the solar panel output cables.

6. *Connect the Inverter to Batteries and AC Distribution Box*

Make sure you read the inverter manual before this step.

Ensure the DC isolator and circuit breaker in the battery junction box are in the OFF position.

Pay attention to the polarity- positive to positive and negative to negative.

As usual, prepare the cables with the appropriate lugs using crimping tools. Then make the connection to the inverter according to the inverter manual. After this, connect the other end of the cables to the busbar in the battery junction box.

Next, the inverter output cables are connected to the AC Distribution busbar via the circuit breaker. As usual, use cable lugs or crimp connectors to connect to the busbar.

Also, make the grounding cable connections to the inverter according to the inverter manual.

7. ***Installing the Battery Monitor and any other Monitoring or Control Unit***

The battery monitor is installed according to the manufacturer guidelines in the manual. Similar to the charge controller, they are mounted directly on the wall or onto a wooden board that is attached to the wall. The battery monitor will have a cable connection to the batteries.

If you have any other monitoring, communication, or control unit that is used along with the charge controller, inverter, and/or battery, this must be installed as well. These units are installed according to the instructions in the manual. These units may also have an Internet connectivity feature that allows online monitoring. An example of such a component is the Victron Color Control GX which is used with Victron Energy charge controllers and inverters allowing them to be monitored via the Internet. Other brands may have their own monitoring solution with unique connection technique which can be confirmed with the supplier, website, and manuals.

8. ***Connect up your grounding system***

Consult with your component suppliers and go through the manuals for recommendations on grounding connections. Typically, all the grounding cables from the components and grounding busbars have to be connected together into an equipotential busbar. The equipotential busbar is then connected to the grounding rods or vehicle chassis. As the name suggests the equipotential busbar makes sure all the components are in the same voltage potential relative to the ground.

9. ***Connect up wiring to your appliances and sockets***

Last but not the least, we connect the cables to our lighting circuits and sockets from the AC Distribution Box via circuit breakers. This may be

done already for our vehicle or home- in which case you may need to make a connection between the inverter/AC distribution box to your consumer unit.

13 Starting up your System: System Commissioning

When you have completed the wonderful experience of installing your very own solar system, all that is left is to do some final checks and tests to ensure the safety and proper functionality of your system. These tests must be performed before you start up your system and claim your prize!

13.1 Commissioning Tips & Tricks

✓ First and foremost, wear appropriate safety gear and maintain all safety rules.

✓ Make sure you read through the manuals and instructions for solar panels, charge controller, inverter, batteries, etc. for essential information for commissioning and start-up.

✓ The first test we do is a visual check of all the components and connections:

- Make sure all the switches and circuit breakers are in the open or OFF position.
- Compare your installed system with your schematic diagram and planning template.
- Verify the mechanical connection integrity of the system; look for any loose clamps or hardware, missing junction box covers, and check whether all the components are securely mounted and fastened.
- Verify the electrical connections- look for any open solar panel connections, check whether the array wiring is neatly secured to the solar panels or mounting system, and verify conduit and wiring supports.
- Verify the proper polarity of cable connections- positive to positive and negative to negative. This can be done by measuring the voltage of each solar string with your digital multimeter. When the positive clamp of the meter is on the positive string terminal the reading will be positive.

IMPORTANT: Make sure the knob of the digital multimeter is set to “DC Voltage”. Having the knob mistakenly set on current or other parameters may lead to dangerous electrical blasts! If you are not comfortable, let the professional electrician do this.

- A check should be made to see if there are any missing fuses.
- Check if the grounding connections have been properly made.

✓ A professional electrician trained and experienced in solar power systems should inspect the system and the connections. This electrician should perform commissioning tests on the array, junction boxes, mounting system, battery
and wiring. Tests to be conducted include:

- Measuring the open circuit voltage of each string
- Checking battery voltage
- Verifying polarity
- Continuity tests on all connections
- Insulation tests on all wiring
- Measuring ground resistance and continuity of the grounding system (solar panel frame, mounting frame, inverter, charge controller, grounding rods, etc.).
- Voltage drop after each component, switch, and protection device.

✓ Perform any required modifications and remedial work. Make a note of the changes.

13.1.1 System Startup

Once again refer to the inverter, charge controller and battery manuals, and instructions for the startup procedure. It will be necessary to first close/turn ON the switches and circuit breakers between the charge controller and the battery. Only after this can you close/turn ON the switches between the solar array and charge controller. THIS IS IMPORTANT as reversing the order may blow up your charge controller.

Next, all solar string fuses need to be inserted, all combiner box/junction box switches and circuit breakers need to be on. The inverter is then

started up according to manufacturer instructions, which typically involves turning on the AC and DC circuit breakers and switches connected to the inverter and waiting 5 minutes for something to happen.

Generally, the inverter or other monitoring/control units will have a display that shows input and output voltage, current, and/or power. Some monitoring/control units also display if the system is performing correctly and the presence of any errors or faults.

Finally, make a note of any changes that were made compared to the original design plans and diagrams. If required, finalize the as-built schematic diagram.

14 Operation, Maintenance & Troubleshooting

Luckily for us, solar systems typically do not require much maintenance at all except for cleaning the solar panels. As long as we are operating the solar system according to the original plan and design it should be generating free electricity seamlessly! Other than that, we can ensure the system is running healthily over the long term by operating the system properly and scheduling routine inspections and maintenance checks.

In this chapter, we will take a closer look at the best practices pertaining to operating, maintaining, and troubleshooting solar systems. This chapter was inspired by Mark Hankins (2010).

14.1 Operating Your System

It is very important for us to operate the system within its planned design and limits on a day to day basis. There are a number of best practices that when practiced on a daily and weekly basis will ensure a healthy and long-lasting solar system.

- ✓ We need to stick to our energy use plan/load table that we formulated during the planning and design stage. Remember the solar system was designed to supply the loads for the particular duration used in the load tables. For instance, if you planned to use your air conditioner for 4 hours, then 8 hours of use may drain the battery to the point where the system shuts down until the battery can charge again.
- ✓ Similarly, do not connect greater loads than originally planned. If you do plan to add a new appliance or use an appliance for a longer duration than originally planned, you would need to calculatedly reduce loads from other appliances. Remember the energy generation from the solar system needs to be in balance with your energy use.
- ✓ Ensure that the batteries are well charged. This way the batteries will last longer and do not need frequent replacement. Make sure the batteries attain full charge from the solar system and/or backup sources (such as diesel generator or grid/shore charging) at least once a week.
- ✓ If you are faced with prolonged cloudy or dark periods without proper sunshine you may need to reduce your energy use unless you have backup sources to charge your battery.
- ✓ If your battery is in a low state of charge, you may need to reduce your energy use and allow the battery to fully charge from the solar array or other available sources.
- ✓ Make sure there is someone responsible for managing and monitoring the solar system.

- ✓ It is a good practice to keep a logbook to note down information on issues, maintenance schedules, component warranties, repair work, and so on. It will come in handy down the line. Remember you will have the system running for over 25 years!

14.2 Maintenance Best Practices

Solar power systems require very little maintenance, much less than a diesel generator or a car. The best way to take care of your system is to inspect your system regularly, to make sure components are kept clean, and to ensure all electrical connections are tight. Be sure to go through the manuals of all the components for maintenance recommendations.

It is always good to keep spare parts of components that require replacement such as fuses, mounting system pieces, and fasteners. Also, keep track of the shops where parts are available.

Shut down your system first! You should shut down the solar system before any maintenance work that requires you to touch the solar system, First of all, switch off circuit breakers in the DC Combiner box to disconnect the solar array from the charge controller. Then switch off the circuit breaker and isolator switch in the battery junction box to disconnect the batteries. Switch off the inverters and any other components with an ON/OFF switch.

- **Batteries:** Batteries are the components that require the most attention. The way you operate and maintain the batteries will directly affect their lifespan. You must pay attention to your batteries if you don't want to make a big investment to replace your expensive batteries anytime soon. Flooded lead acid batteries require the most maintenance, while lithium ion batteries and lead acid batteries require less maintenance.

Go through the manuals and maintenance recommendations from the battery manufacturer. Make sure you wear insulating gloves, a protective helmet, and safety glasses when maintaining batteries. Be careful when coming into contact with batteries, there is always a possibility of a short circuit if one manages to mistakenly create a connection between the terminals of a battery while cleaning or maintaining them. Wash your hands right after handling batteries as there may be traces of acid from the batteries.

- ✓ ***Inspection:*** Inspect your batteries once a month for signs of damage, leaks, corrosion, and loose connections.

✓ ***Cleaning:*** Battery cleaning must be performed once or twice a year. Make sure the battery racking is clean and dry. Then clean the top and outside of the battery with a cloth.

If the battery terminals are corroded with white deposits, they will need to be carefully cleaned with sandpaper or a wire brush. We recommend a professional or someone experienced with batteries to do this. If the terminals are highly corroded, they may need to be replaced.

✓ ***Flooded lead acid battery maintenance:*** Flooded lead acid batteries need to be filled with distilled water from time to time. Distilled water may be bought from petrol/gasoline stations. Do not use water from the tap or other sources.

Put on your safety goggles, remove the cap of one battery at a time for checking the liquid (electrolyte) level in the battery and carrying out maintenance. The level of liquid within the battery needs to be at the marked level or within 2 cm (¾ inch) of the top of the battery. If the liquid is below this level, add distilled water until it reaches the marked level or up to 2 cm (¾ inch) from the top of the battery.

This may need to be performed weekly or monthly depending on use. So, make sure you check the liquid level on a regular basis. It is always good to keep a stock of distilled water readily available.

- **Solar Panels:** Solar panels don't really require much maintenance except for regular cleaning. Inspection from time to time will also ensure everything is in order. Follow any maintenance recommendations specified in the manuals and documents of the solar panels and mounting system.

✓ ***Cleaning:*** Solar panels need to be kept clean to make sure maximum light can enter through the glass and allow maximum power to be produced. Clean any dust, bird droppings, leaves, or streaks on the panels. Cleaning needs to be done once or twice a month, especially during dry seasons. More cleaning may be required in dusty locations.

Solar panels must be cleaned with water and a soft cloth, sponge, or dust broom. Do not use solvents or chemicals for cleaning.

✓ ***Inspection:*** Inspection can be done when you go to clean your panels or once a month. Look out for signs of damage, discoloration, and cracks on the panels and on the wiring. Look for damaged solar cells. Ensure the wiring has not been chewed on or pulled out by

animals or other external factors. Also check the grounding cables and connections.

Pull on the panels to see if they are still firmly attached by the mounting system. Look out for loose nuts, rust, and corrosion on the mounting frames and fasteners. Make sure no plants or vegetation is growing around the panels that might cause shading. Also, look out for loose cables, cable ties, and cable conduits.

✓ ***Measurement:*** It makes sense to measure the current from the solar array strings once or twice a year. Using your clamp meter, you can measure the output current produced by each of the solar strings and solar panels. This is done by setting the clamp meter to measure DC current and placing the clamp around the positive output cable of each solar string or solar panel. This test is best performed during sunny conditions and the solar system must be ON and functioning. If a solar panel or string is not producing as much current as it should, it may need to be replaced.

- ***Inverter and Charge Controller:*** These components don't require much maintenance. Once again, make sure you read the manuals and documents for any maintenance recommendations. Keep an eye on the status of operation of these components, usually, they will have lights to depict their status.

Once or twice a year do some routine cleaning, visual check for any signs of damage, rust, corrosion, animals or invasive plants, etc. Check the status of the enclosures. Also, check if the cable and grounding connections are strong by gently wobbling them. If you have a display unit or remote monitoring feature, observe the values such as current, voltage, and power to see that everything is working as it should. It is also useful to check the status of operation and signs of clogging in the ventilation system or fans of the inverter.

Wiring, Junction Boxes, and Protection Devices: Once or twice a year, you should inspect and clean all the cabling and junction boxes. Look for signs of damage, animals, chemicals, water ingress, dust, dirt accumulation, and loose connections. Check that no bare wire is sticking out or visible. Check the insulation of all wiring for breaks, cracks, or places where it has been chewed by animals. Inspect the status of the enclosures. Look for loose or defective cables, cable ties, cable conduits, and cable ducts.

Check the status of all protection devices for any signs of damage or burn-fuses, circuit breakers, surge protection devices, residual current device,

isolator switches, and junction terminals.

You MUST make sure your solar system is completely shut down when opening the fuse holders or inline fuse connectors to inspect the fuses inside. Opening the fuse holders or inline fuse connectors when the system is live can lead to blasts! Blown fuses should be replaced with new ones of the same type and rating. Before we replace the fuse we should identify the problem that caused the fuse to blow (such as ground fault, short circuit, or overload). A professional electrician with solar experience can help identify the problem.

Check the status of the grounding system, which includes grounding cables, equipotential busbars, grounding rods, and the integrity of the overall connection.

If you have one or more components hooked up to the Internet via communication links, check the data cables and connections, monitoring and display units, status of the Internet connection, and any other associated equipment.

14.3 Troubleshooting

Solar systems usually run seamlessly without any issues when properly installed, operated, and maintained. However, due to the complexity of these systems that combine many different components, issues may sometimes occur. Don't worry though, most of these issues have simple solutions. Nevertheless, it is always handy to have a professional electrician with solar experience to contact, to examine more difficult issues.

We will first look at the simple solutions to basic problems which will be our first go-to option when issues arise. We will then go through the more detailed troubleshooting solutions for more complex problems.

Simple solutions

Let us look at the low hanging fruits we should go for at first when we face issues or unexpected system shut down.

- As mentioned earlier, it is important to have a logbook to record issues and maintenance work. Go through the logbook first.
- The recent weather may have clues to the issues. Cloudy or dark periods for several days or weeks may prevent the battery from getting charged. This would require us to reduce our energy use unless we have a backup source such as a diesel generator or grid/shore charging.

- The condition, age, and type of battery is also a big factor. Corroded battery terminals may need to be replaced. Lead acid batteries typically reach their end of life within 3 to 5 years, while lithium ion batteries can last for upwards of 10 years.
- Check if any circuit breakers have tripped or any fuses have blown. Remember when inspecting fuses, the system must be completely switched off according to the procedure specified towards the beginning of section 14.2 Maintenance Best Practices. Get your professional electrician to identify the issue.
- Check if all the wiring and connections are secure and in good condition. Inspect for signs of corrosion or breakage.
- Another low hanging fruit to be looked at is the cleanliness and condition of the solar array. See if the panels are dusty or shaded by an external element. Make sure no panels are missing or damaged.
- Have a look at your inverter and charge controller to see if they are functioning. Check if all the indicator or status lights and displays are working.

Comprehensive troubleshooting

If the simple solutions didn't help solve the issue, we go for a more detailed approach towards finding the problem.

A troubleshooting guide is presented below that details various issues along with their possible causes and solutions (Mark Hankins, 2010).

Issue	Cause	Solution
1. Low battery state of charge: "Battery low" indicator light on; charge controller or inverter automatically disconnects, or battery voltage is constantly low	• No solar charging	See Issue 2 (No charging from solar) and Issue 5 (Blown or missing fuse) below
• Battery liquid level is low (for flooded lead acid batteries)	Add distilled water to cells	
• Poor cable connection	Look for broken or loose wire and repair if needed	

Issue	Cause	Solution
• Defective battery	Measure the voltage of each battery using a multimeter. If there is a significant difference between batteries, replace or repair	
• Battery terminal is loose or corroded	Clean and tighten battery terminals	
• Overuse of battery	Reduce energy use; charge batteries using solar power or other sources	
• Battery is not taking in charge	Confirm the age and history of the battery. Check the manufacturer's information and manuals. Replace battery bank if it has exceeded expected cycle life.	
• Voltage drop between solar array and battery too high	Check voltage drop using a multimeter. Replace the cable with the proper diameter if required.	
• • Defective controller	Verify operation of the controller with supplier. Replace or repair if necessary.	
• Inverter draining battery	Run system without inverter until battery charges. Reduce AC load use till battery charges.	
2. No charging from solar: Solar charge indicator on the charge controller does not light up during sunny periods. No current in wires from solar array.	• Short circuit along cables from solar array	Locate and repair short circuit. If needed, get an electrician to do this.
• Loose connection in battery cables	Look for loose connections and repair	
• Solar panels covered in thick layer of dust or soot	Clean solar panels with water and soft cloth or dust broom	
• Damaged solar panel	Look for damaged solar cells, damaged glass, or poor connection inside panel. Verify with supplier and replace panel.	

Issue	Cause	Solution
3. Appliances not working: One or more appliances are not turning ON when connected or functions poorly. (Check for blown fuse first)	• Poor cable connection	Look for broken or loose wire and repair if needed
• Defective or damaged socket	Test socket with an electrical tester. Replace if faulty or damaged. Check fuse in socket.	
• Damaged appliance	Try appliance where there is a good power supply. If still not working- replace or repair.	
• Inverter not functioning (for AC appliances)	Turn inverter "ON". Inspect the condition of inverter. Inductive or capacitive loads may result in low power factor and shut down inverter- adjust the inverter's power factor according to the inverter manual (if the inverter incorporates this feature)	
4. Blown or missing fuse Fuse wire has melted. Fuse is missing or removed from the fuse holder	• Poor operation of appliance	Check for low voltage (for DC appliances) Check for output of inverter (for AC appliances)
• Short circuit along cables from solar array	Locate and repair short circuit. If needed, get an electrician to do this. Then replace blown fuse	
• Fuse is undersized (below the required rating)	Use fuse 25% larger than the total current in the circuit	
• Lightning strike or power surge	Replace fuse	
• Missing fuse		
Source: Mark Hangins (2010)		

If the problem still persists, it would be time to call in a professional solar electrician to have a look. In the event that something needs to be repaired or

replaced, make sure you take note of the warranty periods of your components such as solar panels, mounting system, battery, inverter, and charge controller.

15 Making a Budget for Your Solar Project

Finally, we will look at how we can prepare a budget for your solar system. We will present sample budgets for a mobile system and an off-grid home system. These sample budgets will give you clues on ways to list the components and their costs in one place, and estimate the total cost.

In our sample budgets, we present the required components and their indicative costs based on online market prices in the USA. However, obviously, the component types, quantities, and their costs may differ depending on your site, location, country, requirements, brands, suppliers, and so on. So, you will need to list your required components according to your design plans. Next, you will need to do some online research and/or speak to local suppliers to get the prices of components.

15.1 Sample Budget: 1.5 kW Mobile Solar System

The first sample budget we present is that of a 1.5 kW mobile solar system on a simple RV which is used over the weekend. It includes 6 pieces of 250 W polycrystalline solar panels (2 panels in series x 3 parallel strings), 2 units of 12 V - 260 Ah lead acid batteries, an 80 A PWM charge controller, and a 2000 W inverter/charger.

Note that we consider the load wiring to be pre-installed in the RV (we don't need to install them), so we don't include costs for wiring, protection, and other components for load circuits. We also account for spare cables, MC4 connectors, fasteners, etc.

Remember the components, quantities, and prices listed are just an example and may change depending on your location, site, requirements, and so on.

Item	**Quantity/Sets**	**Cost per Unit USD**	**Subtotal Cost USD**
Solar Panels and Mounting Structures			
250 W Polycrystalline Solar Panels	6	190	1140
Mounting System- Z Brackets	6 sets	20	120
Inverters, Charge Controller and Battery			
2 kW Inverter/Charger	1	800	800
80 A PWM Charge Controller	1	75	75
Battery Monitor	1	70	70
Internet Modem	1	50	50
12 V – 260 Ah Lead Acid Battery	2	450	900
Junction Boxes			
DC Combiner Box (Including Fuses, Circuit Breakers, Busbars, Surge Protection Device, Enclosure Box, etc.)	1	300	300

Item	**Quantity/Sets**	**Cost per Unit USD**	**Subtotal Cost USD**
Battery Junction Box (Includes Circuit Breaker, Dc Isolator, Busbars, Enclosure Box, etc.)	1	220	220
AC Distribution Box (Includes Circuit Breaker, Residual Current Device, Surge Protection Device Busbars, Enclosure Box, etc.)	1	150	150
Cables and Associated Materials			
Solar Cables- 4mm2 (12 AWG)	500 ft	40 (per 100 ft)	200
MC4 Connectors	12 pairs	11 (per 6 pairs)	22
Battery Cables 35mm2 (2 AWG)	30 ft	30 (per 10 ft)	90
AC Cable 6mm2 (10 AWG)	50 ft	35 (per 50 ft)	35
Grounding Cables 6mm2 (Solar Array, Charge Controller, Inverter, Junction Boxes)	200 ft	35 (per 100 ft)	70
Grounding Box (Includes Busbar, Lugs, etc.)	1	50	50
Cable Conduit	50 ft	40 (per 50 ft)	40
Cable Duct	35 ft	60 (per 50 ft)	60
RJ45 Cable (Communication Cable)	50 ft	8 (per 5 ft)	80
Tools and Small Materials			
Tools and Safety Materials	As Needed		
Marine Grade Shock Cord (Safety Line)	50 ft	10 (per 10 ft)	50
Small Material Allowance (Nuts, Bolts, Lugs, Connectors, Cable Clamps, etc.)	1	300	300
TOTAL			$ 4822

15.2 Sample Budget: 4.6 kW Off-grid Home Solar System

Next, we shall look at a 4.6 kW off-grid rooftop solar system for a family house. We include 16 pieces of 290 W monocrystalline solar panels (4 panels in series x 4 parallel strings), 3 units of 48 V 200 Ah lithium ion battery bank with around 28.8 kWh storage capacity, two units of 60 A MPPT charge controllers (with 250 V maximum voltage), and a 5000 W inverter/charger.

For this example, we presume that the house does not have wiring for lights and sockets installed, and we need to install them. This means we need to buy the relevant components such as circuit breakers and wiring for the load circuits going to the different rooms of the house.

Remember the components, quantities, and prices listed are just an example and may change depending on your location, site, requirements, and so on. As usual, we include spare cables, MC4 connectors, fasteners, etc.

Item	**Quantity/Sets**	**Cost per Unit USD**	**Subtotal Cost USD**
Solar Panels and Mounting Structures			
290 W Monocrystalline Solar Panels	16	300	4800
Mounting System- Roof Mount Kits	4 sets	55	220
Inverters, Charge Controller and Battery			
5 kW Inverter/Charger	1	2500	2500
60 A MPPT Charge Controller	2	640	1280
Battery Monitor	1	200	200
Internet Modem	1	50	50
48 V – 200 Ah Lithium Ion Batteries	3	5000	15000
Junction Boxes			
DC Combiner Boxes (Including Fuses, Circuit Breakers, Busbars, Surge Protection Device, Enclosure Box, etc.)	1	450	450
Battery Junction Box (Includes Circuit Breaker, Dc Isolator, Busbars, Enclosure Box, etc.)	1	350	350
AC Distribution Box (Includes Circuit Breakers, Residual Current Device, Surge Protection Device Busbars, Enclosure Box, etc.)	1	375	375
Cables and Associated Materials			
Solar Cables- 6 mm2 (10 AWG)	800 ft	50 (per 100 ft)	400
MC4 Connectors	18 pairs	11 (per 6 pairs)	33
Battery Cables 120mm2 (4/0 AWG)	40 ft	135 (per 20 ft)	270

Item	Quantity/Sets	Cost per Unit USD	Subtotal Cost USD
AC Cable 4 mm2 (12 AWG) (Inverter Output)	60 ft	45 (per 100 ft red + 100 ft black)	135
AC Cable 4 mm2 (12 AWG) (Load Circuits)	400 ft		
AC Cable 2.5 mm2 (14 AWG) (Load Circuits)	600 ft	30 (per 100 ft red + 100 ft black)	90
Grounding Cables 6mm2 (Solar Array, Charge Controller, Inverter, Junction Boxes)	500 ft	35 (per 100 ft)	175
Grounding Box (Includes Busbar, Lugs, etc.)	1	70	70
Cable Conduit	80 ft	40 (per 50 ft)	80
Cable Duct	300 ft	125 (per 100 ft)	375
RJ45 Cable (Communication Cable)	50 ft	8 (per 5 ft)	80
Tools and Materials			
Tools and Safety Materials	As Needed		
Small Material Allowance (Nuts, Bolts, Lugs, Connectors, Cable Clamps, etc.)	1	500	500
TOTAL			$ 27433

So, there we have it! We wholeheartedly congratulate you on reaching the end of the book! By now, you must an expert in off-grid and mobile solar systems! You have mastered the art of planning, designing, installing, commissioning, maintaining, and budgeting for your very own solar power system!

We sure hope that you enjoyed learning with us on this journey. More importantly, we hope you will apply what you've learned and benefit from free, clean, and abundant energy from the sun!

16 About The Authors

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