A SunCam online continuing education course

Solar Power II

Design for Grid-Tie Systems – an Introduction

by

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COURSE DESCRIPTION

This is a Grid-Tie Solar Power (Photovoltaic or "PV") course. If you don't understand the differences between an Off-Grid, On-Grid, and a Grid-Tie system, then you should take the first course (Introduction to Solar Power Design for Small Structures) also offered by SunCam. But a brief explanation is…

> **Off-Grid / On-Grid / Grid-Tie –** Terms used to identify whether a user is connected to a power company providing AC power. An **Off-Grid system** would be a structure not connected to any external electrical service (normally provided by a power company). An **On-Grid system** would be a structure connected to a power company's electrical service. A **Grid-Tie system** means that the structure can use the solar energy when it's available and when the solar is not available, the system may or may not automatically switch to the electricity from a power company (the Grid)… depending on the design.

Originally, solar power was used almost exclusively in areas without reasonable access to electrical power lines… as in space, small islands, and remote areas of the country. However, in recent years, new technological advances in inverters, the ever increasing efficiencies of solar panels, and the declining costs of commercially available solar panels has spurred an interest and a desire for solar power for both residential and business uses… even when local power lines are readily available. The previous courses focused on stand-alone solar power designs (Off-Grid) for small structures without any reasonable access to the power company's electrical lines. Primarily because of an Off-Grid structure's simplicity, it provides an excellent model for an introduction to solar/photovoltaic designs. But due to the number of requests SunCam has received for a Grid-Tie course, this course was developed to meet that demand and provide an introduction to Grid-Tie systems. So, it is now the newest addition to the solar design courses available on SunCam.

What this course is NOT… This is not a course that explains *how* to design a solar powered (photovoltaic) system. For that, take the course "Solar Power Design for Small Structures" also offered by SunCam or you may have difficulty with this course.

What this course IS… This is a course that begins where the first course "Solar Power Design for Small Structures" ends and introduces you to the components needed to connect a solar PV system to the power grid. Then it provides a quick refresher of the design process.

Unfortunately, a Grid-Tie system can be more difficult to design because of the many variables incurred due to "owner preferences". In addition, you must also address the "user preferences". Hopefully, the owner and the user are the same. However, if they are different, does the owner understand how the user impacts the design… which impacts the cost… which impacts the return on the investment? Nothing is ever simple anymore! But because of the many variables in a Grid-Tie design and the fact that the solar design process is covered in the first course, we are limited in this 4-hour course to focusing on the Grid-Tie elements.

Now to get started…

So you want to design & construct a Grid-Tie solar power system. Why? No, really… why? Before you start this endeavor you need to understand the answer to that question. There are many reasons to use a Grid-Tie system and you need to know the *real* reason the owners are coming to you and what their expectations are. The reason is likely one of the following…

1. To reduce the electric bill
2. To connect an existing solar PV system to a recently available power system
3. To protect against brief power outages
4. To provide power during extended power outages caused by storms like hurricanes, ice storms, snow storms, fires, etc.
5. Or… the owner simply wants to join the "green" power movement

So… what is the real objective? That answer will have a direct impact as to how you design the system and on the client's satisfaction with the constructed system.

Then, you must also address the local power company's requirements for connecting to their system which will vary from power company to power company. But first, let's briefly discuss the owner's reason for a Grid-Tie system.

1. Reducing the electric bill – Reducing the electric bill sounds simple enough. But then the next question is how much reduction is desired? It's fairly easy to reduce the electric bill by $20 a month… just design a system that powers only a few appliances. If that accomplishes the goal, you don't even need a Grid-Tie system. Just install a dedicated panel that powers only specific circuits. The net effect is you reduce the monthly bill. But that's probably not what the owner has in mind or is going to be happy with.

If the goal is to reduce the electric bill by a specified percentage… say 20-25 percent, then a simplistic approach is to provide all the power the owner needs but only during the daylight hours. This approach definitely needs a Grid-Tie system *but without batteries*. So you only need to supply enough watts to meet the daytime needs and all other times the power will be supplied by the power company. Therefore, you only need to focus on analyzing the daytime wattage requirements and no more since you don't need to simultaneously recharge any batteries. Why is this approach only reducing the power by 20-25% since daytime is about 12 hours? Well think about it… the sun may rise at 6:30 am but the sun's rays aren't hitting the solar panels effectively except from roughly 10 am to 3 pm. Hopefully, you remember this from the previous courses. So, if you aren't getting effective radiance except for 4-5 hours, you probably can't expect a 50% electric bill reduction with a small bank of solar panels.

To reduce the electric bill by more than this requires producing *much more power* than the owner is using such that there is excess power that may be "sold" to the power company… provided the power company will purchase the owner's excess power. More on that later….

2. Connecting to a recently available power system – If you have an existing off-grid solar power system that you wish to connect to a new power system, this is relatively easy to do. However, it will require replacing your old inverter with a new Grid-Tie inverter and adding an electrical disconnect.

3. Protecting Against Brief Power Outages – Many think protecting against brief power outages during the day is easy enough… just add some solar panels to a Grid-Tie inverter and *voila*… you have power when your neighbors don't. However, what many don't understand about a standard Grid-Tie system is that when the Power Company's grid goes down, so does the power produced by the solar panels. That is shocking to some. *But just tell the owners they can jokingly tell their neighbors that they* *turned the power off to show empathy with their neighbors' plight.* ;-) We'll discuss this more later in the course. So… the owner must add an AC-Coupled inverter and batteries to the system to really make the neighbors envious. But this is where it gets tricky… What's an AC–Coupled inverter and how many batteries do you add? Well, that depends on the answers to another set of questions:

1. How long does your typical power outage last? 30 minutes, an hour, 2 hours?
2. What needs to be powered by the PV system until the electricity is restored?
3. Can you isolate the circuits that need to be powered until the electricity is restored?
4. Is the use of a generator available?

The answers to these questions will guide your design criteria. Providing short term emergency power is not inexpensive but it is not exorbitant either. This is similar to providing a UPS battery backup to your computer. But it does require special equipment which we will discuss later in the course.

4. Provide Electricity During Extended Power Outages – Protecting against power outages for short durations is easily addressed as discussed above…but what if you need power for extended periods of time. Obviously, this design becomes a little more complicated… and costly... because you will want to power more appliances, equipment, and essentials that will make life more bearable until the power is restored. To do this, you first need to determine the daily power required to meet your essential needs…. refrigerator, freezer, heat, water pump, lights, etc. Your hot tub probably won't be on the list... but if you want it, then include it. For some, everything in the building will be "essential". Regardless, this list will be used in your design calculations with the number of days you need to be protected. Even if you expect the power company's service to be out for 10 days, you probably only need 2-3 days of battery capacity since the sun will likely shine long before the electrical power is restored.

And if you have an emergency generator available, you can recharge your solar batteries as may be needed. Remember, the generator doesn't need to power your entire essential needs list. It only needs to recharge your batteries and it can do so when needed and for as long as needed. Just make sure the generator is secured because generators have a tendency to "grow legs and disappear" after a severe storm event.

And, yes, you still need one of those AC-Coupled inverters….

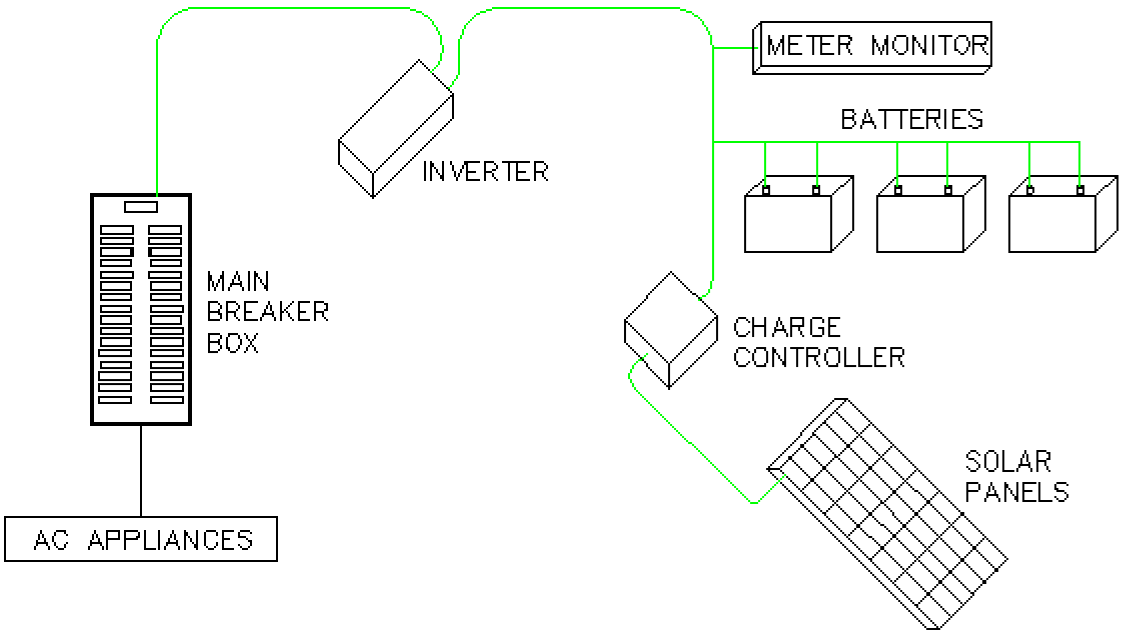
5. The owner simply wants "green" power – Perhaps the owner simply wants to experiment with solar power or wants a starter system that he can expand. Does he want emergency power available? Regardless of the owner's motives, this reason requires more time since you need to interview… *and educate*… the owner about what the expected costs will be and what the expected return on investment will be before you can set the goals of the system. Otherwise, you can expect an unhappy client because neither of you agreed to… or established… the expected outcome. Misunderstandings can lead quickly to unhappy clients and unpaid invoices.

Once you have determined and agreed upon the goal for your design, you need to begin the design process. For this course, we will start "at the beginning" with a basic Off-Grid system and then add the components needed to build a Grid-Tie PV system for more complex conditions and optional features.

THE BASICS

A typical solar PV power system… Grid-Tie or not… is comprised of solar panels (a.k.a. photovoltaic or PV panels), a charge controller, a power inverter, a meter or monitor, electrical distribution system (or the electrical wiring), and batteries… though the batteries might not be included in some Grid-Tie systems as we'll see later in the course. Like most technologies, there are multiple manufacturers for each component offering different levels of quality, features, and, of course… price.

The typical off-grid system configuration is shown below (**Figure 1**). This is the basic system and I mean basic… in the sense that it's only source of power is from the sun. Even if a generator is included, it is intended only as a backup. So you basically have a battery-powered system in which the batteries are recharged by the sun. So… no sun and no batteries *means* no power. Again, pretty basic.



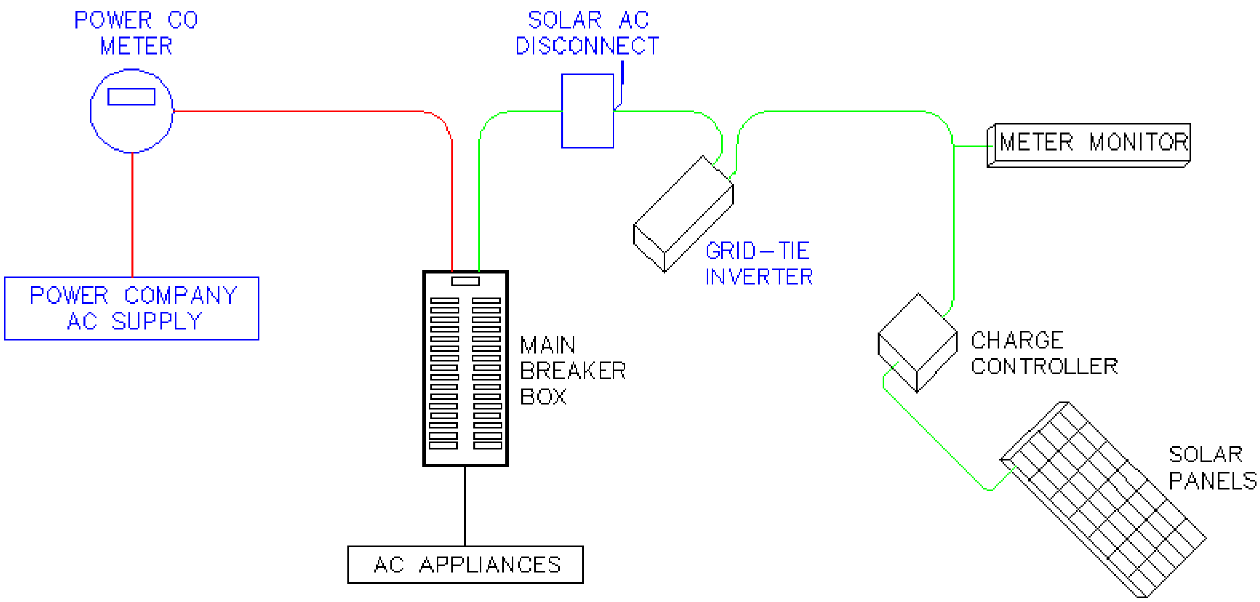
BASIC OFF–GRID
SYSTEM COMPONENTS

Figure 1

The Off-Grid system is the simplest of the solar power systems to design and understand as shown in **Figure 1** above. All of the power is provided by the sun and the batteries. When the sun sets, all power is provided by the batteries until… the batteries are depleted. Then everything shuts down. Simple, agreed?

But let's now look at the Grid-Tie system since this is the system you're interested in and is what we'll be discussing in this course. Obviously, there are a few prominent differences you will immediately notice between Off-Grid (**Figure 1** above) and the Grid-Tie systems (**Figure 2** below). First is the addition of the Power Company's electrical service (AC supply) and their meter. Second is the addition of a Solar AC Disconnect. Third is the replacement of the standard inverter with a Grid-Tie Inverter... and ***there are*** differences between the two inverters which we will discuss later. And fourth is the absence of batteries.

Review the basic Grid-Tie system below (**Figure 2**)…



BASIC GRID–TIE
SYSTEM COMPONENTS

Figure 2

*For the purposes of clarity for this course, the solar-powered wiring is shown in **green** and the Power Company's wiring is shown in **red**.* The colors have nothing to do with positive, negative, or ground wiring… they just indicate Grid power or **Solar power**. **Blue** indicates the items of current discussion.

All Grid-Tie systems **must** have a connection to a Power Company's electrical lines (the Grid). Because of that connection, batteries aren't required for every Grid-Tie system. Think about it… if the solar panels aren't providing the necessary power, then the Power Company will… day or night. So the batteries *are optional* in a Grid-Tie system. And if the owner is trying to keep costs down for his installation, the batteries are typically the first cut made.

Now that you've been introduced to a Basic Grid-Tie system… but before we get too far into the design aspects… let's turn our focus to the basic components that make up a

Grid-Tie system. Obviously, most of the components are found in the Off-Grid systems but there are some additions and differences as well… for example, both have inverters but the inverter used in an Off-Grid system cannot be used in a Grid-Tie system. A convenient analogy is the term "automobile". There are many types of automobiles… a car, a bus, a truck… and each will drive from Point A to Point B. But a car isn't going to carry 40 passengers or large cargo. And the term "inverter" is much like the term "automobile".

System Components

Solar Panels (Required) – A manufactured photovoltaic panel is comprised of silicon crystals that are used to convert the sun's rays into electricity. They supply the electricity for charging the batteries and for use by the appliances either directly (DC) or through an inverter (AC). Multiple panels are used to produce more electricity than is consumed, and then, any excess energy that is produced is stored in the batteries for nighttime and emergency use or sold to the power company. The panels are available in different sizes, voltages, and amperages. They can be wired in series, in parallel, or both... depending on how the system is designed.

A polycrystalline panel

Charge Controller (Required) –The charge controller is the "brains" of the system. It monitors the electricity produced by the solar panels and then regulates the electricity to the inverter or to charge the batteries and prevent them from becoming overcharged. Proper charging is critical to prevent damage to the batteries and thereby increasing the batteries' life and performance. Though different technologies are available for selection, stick with the Maximum Power Point Tracking (MPPT) charge controllers.

TriStar Solar Charge Controller

Batteries (Optional) – Batteries are optional for a Grid-Tie system but are required for a Grid-Tie system with an emergency backup. The batteries simply store the excess electrical power from the solar panels for later use. Without the batteries, you would only have power when the sun is shining. The power would be interrupted at sunset or reduced each time a cloud passed overhead. The batteries are available in different voltages and varying amp-hour ratings and are selected based on the design requirements of the system.

Fullriver AGM battery

Inverter (Required) – The inverters convert the DC volts produced by the solar panels (or from the energy stored in the batteries) into AC volts. The inverters can also be used to charge the batteries by connecting them to a backup generator or other DC electrical source. Choosing the right inverter for the demand and power requirements of the system is critical for the components to function properly. ***Note that for a Grid-Tie system, the inverter must be a "Grid-Tie Inverter".*** Surprised? An Off-Grid inverter will not work for a Grid-Tie system. And there are two types of Grid-Tie inverters… a standard Grid-Tie and the AC-Coupled.

Image SMA Solar Technology AG

Monitor meter (Optional) – Though a monitor meter is optional, it is highly recommended. It is used to monitor the power being generated by the solar panels, the user's current consumption rate, and the condition of the batteries if installed. The various monitors available in the market today can provide detailed information on the system status. They will monitor the system's performance, provide you with the information you need to help locate the source of any system problems

Morningstar Remote Meter

when they occur, protect the batteries, and allow you to minimize a generator's use by indicating when it may be shut off (typically… when the batteries are approaching a full charge).

Generator (Optional) – A gas-powered generator is a good economical insurance policy to keep the batteries charged during those extended power outages that can last for days after a storm event. Or it can provide the additional power needed for those temporary high power demands. Without the power company's supplied AC power or sunlight or batteries, a generator is the only thing that will keep the electricity available for your modern conveniences. To avoid problems with your solar system components, get a True Sine Wave generator. And don't forget the fuel for the generator. A generator will require gasoline, diesel, propane, or natural gas. And there are EPA and local codes regulating the storage of fuel that you must address as well.

Emergency Generator

Before beginning any design… always contact the Power Company serving the local site to determine their specific requirements for connecting to their grid and determine their process for design approval and inspections. Also, you will want to find out how their power buy-back program (Net Metering) is set up and what their rates are. They may use a single bi-directional meter or they may use two meters. Either way, you need to know all of their requirements.

Then there are the code requirements that must be addressed. NEC Part VI of Article 690 defines the requirements for marking the Grid-Tie system and the information that must be posted. See NEC Sections 690.53 and 690.54. And the Power Company may have additional markings that they will require.

Now… refer back to the **Basic Grid-Tie System** design (shown again below in Figure 2 for ease of access) and let's look at some of the design options.

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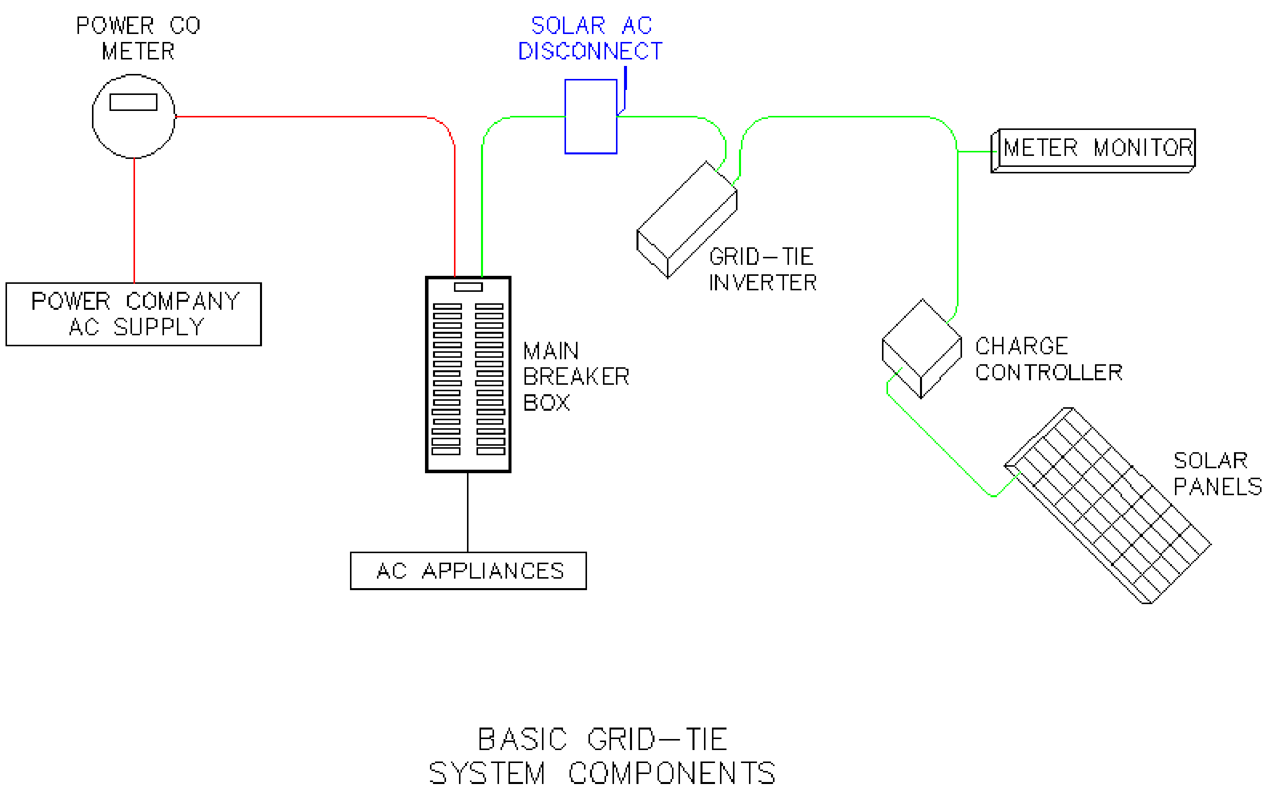


Figure 2

AC power is supplied to the Main Breaker Box from two sources. The first source is the solar PV system which provides DC power to the Grid-Tie inverter which converts it to AC power to supply the Main Breaker Box.

The second source is the AC power from your Power Company which is supplied to the Power Company's meter and then to the Main Breaker Box. The Power Company's meter simply measures the building's power consumption which is used for billing purposes.

Preferably, the Power Company meter is bi-directional to record the power being sold to the owner or the power purchased from the owner… at the same unit cost per kilowatt. Alternatively, there may be two meters required… one for buying power and one for selling power which can be at different cost rates.

The ***solar PV system***… as shown in **blue** in **Figure 2**… has DC power supplied by the solar panels routed to the Charge Controller which regulates the power output sent to the Grid-Tie Inverter. A Meter Monitor is *usually* added to monitor and report the solar power generation for performance and maintenance purposes. The Grid-Tie Inverter then converts the DC power into AC power before connecting to the Main Breaker Box (or Main Distribution Panel).

A ***Solar AC Disconnect*** is required by most Power Companies to insure there is no power being back-fed to the Power Company's supply lines that could harm their repairmen working to restore power during a power outage. This AC Disconnect is a visual safety measure for the repairmen's benefit and it must be accessible to their crews on the ***outside*** of the building so they can lock it in the "Off" position. This provides assurance that no power from the solar system can be fed to the Main Distribution Panel or back-fed to the Power Company grid. The Grid-Tie Inverter is required to provide the same protection but it does so without the visual aspect (see IEEE 1547). Once the power is restored, the Grid-Tie inverter will sync with the grid's phase frequency within about 5 minutes and then reconnect to the Grid.

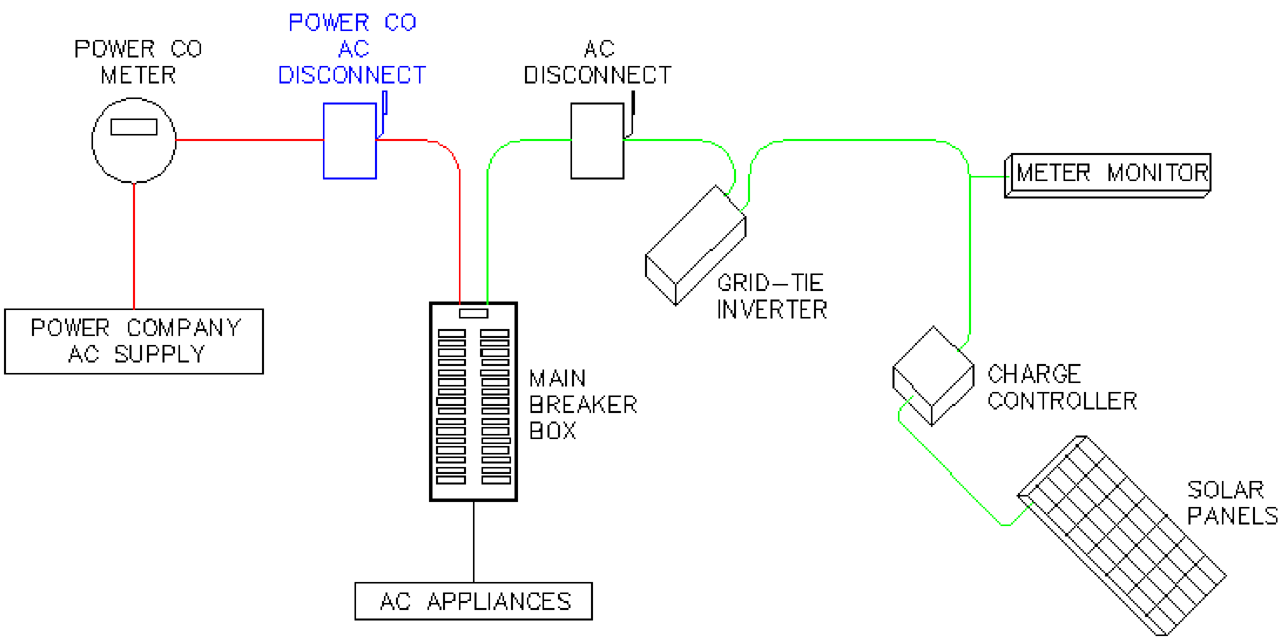
Now you're asking*…"But doesn't that prevent the structure from having electricity to run appliances when the Power Company is experiencing a power outage?"* And my answer is… You are correct! Then your next question is *"Then why have a solar PV system installed?"* The solar PV system will still provide power when the grid is available which will reduce or eliminate the Power Company's electric bill. However, if you want electricity during a power outage, a different inverter and wiring is needed. And we'll discuss that scenario later in the course.

The ***Main Breaker Box*** is the typical breaker box (also called a circuit breaker box, main distribution panel, electrical panel box, etc.) found in commercial buildings and residences. It routes the AC power supplied by the solar PV system or the Power Company to the appliances needing the power.

Remember, ***batteries*** are optional and expensive… to purchase or to replace. Consequently, many PV systems don't include them. However, the owner can easily add batteries at a later time once there is funding and a desire to add them.

Adding a Power Company Disconnect Box (Figure 3)

Some power companies require an additional (a second) **AC Disconnect** between the Power Company Meter and the Main Distribution Box as shown in **Figure 3** below.



ADDITION OF POWER COMPANY AC DISCONNECT
Figure 3

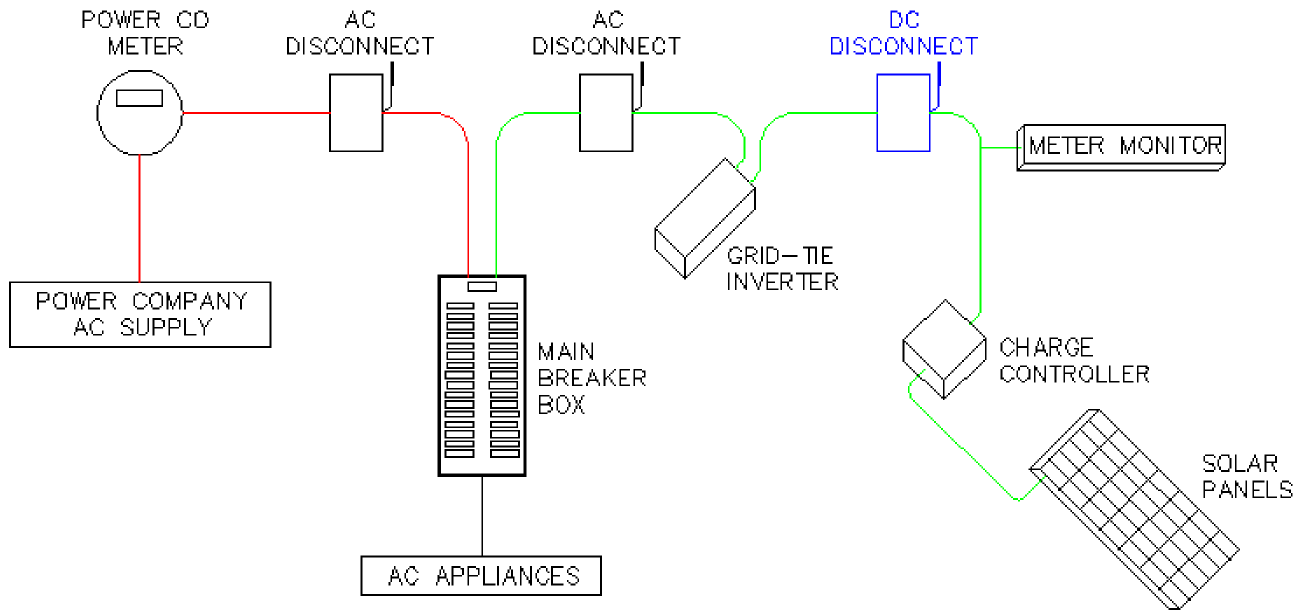
This second AC disconnect provides a positive means to totally isolate the structure's electrical system from the Power Company. The Main Breaker Box can also be used to shut down power inside the building insuring that any electrical repairs occurring in the structure can be completed safely. Once again, the Power Company AC Disconnect provides a visual indication to repairmen that there is no power to the Main Breaker Box and that no power is being back-fed to the Power Company's grid.

So now you're saying *"Well, can't I just pull the Power Company AC Disconnect to prevent power from reaching the Power Company grid and keep the Solar AC Disconnect turned on? Won't that provide the structure the electricity the owner so desperately craves? Simple solution, right?"*

And the answer to all of these is "No." The Grid-Tie Inverter requires power from the Power Company Grid to enable it to send power to the Main Breaker Box. As stated earlier, emergency power is not available using a standard Grid-Tie Inverter. So, if the Power Company is experiencing a power outage, the owner will not have power even on a brilliantly sunny day… with a ***standard*** Grid-Tie Inverter. But there is a solution on the way…

Adding a DC Power Disconnect Box (Figure 4)

The DC Disconnect is another component that a Power Company may not require but is a good addition for the owner. It's a simple way to prevent the DC power produced by the solar panels or generator (discussed later) from getting to the inverter. Like the other disconnects, it provides a visual indication that power from the solar panels and batteries have been shut off and the solar PV power is totally isolated from the inverter and the rest of the system.



ADDITION OF
DC DISCONNECT
Figure 4

For any repairs or work on a structure with a Solar PV system, ALL sources of power must be disconnected from the structure. This includes the Power Company grid, the solar panels, the batteries, and a generator, if one is connected. Likewise, if repairs are occurring on the Grid-Tie Inverter, then both the AC and DC Disconnects need to be turned off.

Adding a Battery Bank (Figure 5)

As we discussed previously, a battery bank is optional for a Grid-Tie system since anytime electricity isn't available from the sun, electricity is available from the Grid. And batteries are expensive and require maintenance and monitoring. Therefore, many owners opt to not include them. Additionally, they recognize that they will be buying electricity from the Power Company every night but their power needs at night are normally lower than during the day. So they are still reducing their monthly electrical bill. If the owner wants to reduce his electrical bill as much as possible, that will require batteries.

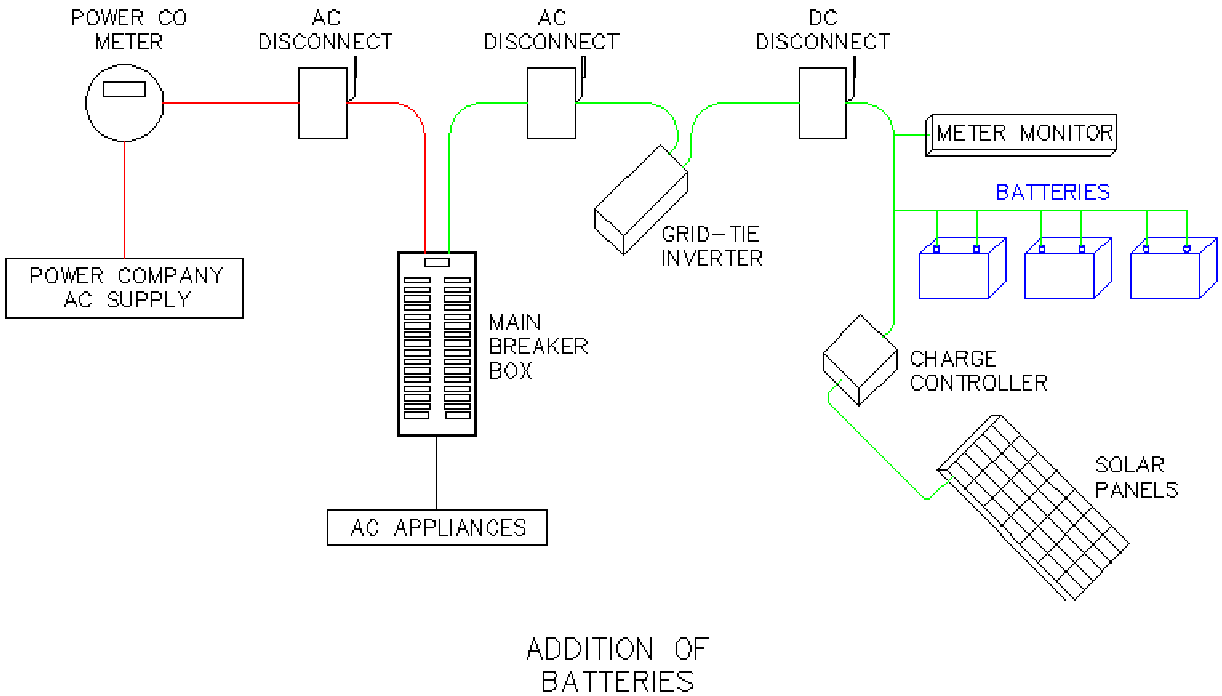


Figure 5

Just as in an Off-Grid solar system, the batteries are used to provide power to the inverter when the solar panels aren't meeting the demand… usually at night. However, the number of batteries needed vary by the design criteria. If your design has too few batteries to meet the demand throughout the night, it's really no problem since the system will automatically switch to the Grid supplied power to make up the difference. But now you're buying power again.

Having too many batteries simply means the system's installation and maintenance costs are higher than necessary but the system still functions… but you're still not buying electricity from the Power Company.

For the designer, determining the "right" number of batteries for each system is a function of cost vs. benefit. When designing a basic Grid-Tie system, the designer needs to ensure the owner understands that during a power outage in the local area, he WILL NOT have any power available in his building. And then he may likely respond with "But I just spent thousands for a solar power system! Why doesn't it work…?"

Now you get to respond that the NEC codes won't allow basic Grid-Tie systems to do so… but… you know how to make it work during power outages; however, it's going to cost….

Increasing Efficiency by Adding a DC Power Circuit (Figures 6 & 7)

To maximize your system's efficiency, adding a DC circuit for specific appliances is a simple solution. Simply put… it takes power to convert power. Any time that you convert power from DC to AC, you lose a percentage of that power in the form of heat. And then when you convert the AC back to DC, you lose power again. It even sounds inefficient, doesn't it? Many, if not most, electronic appliances really operate on DC power even though they have an AC power cord. Why? Because the manufacturers know that Power Companies provide AC power to their users. So the manufacturers include a transformer in the electrical cord (like most laptop computers) or it's installed within the equipment case itself.

Also, because of the growing number of solar PV systems in the U.S. and the world, there is a growing supply of DC powered equipment. You can easily find DC powered lights, fans, water pumps, air conditioners, etc. on the internet or at retail distributors.

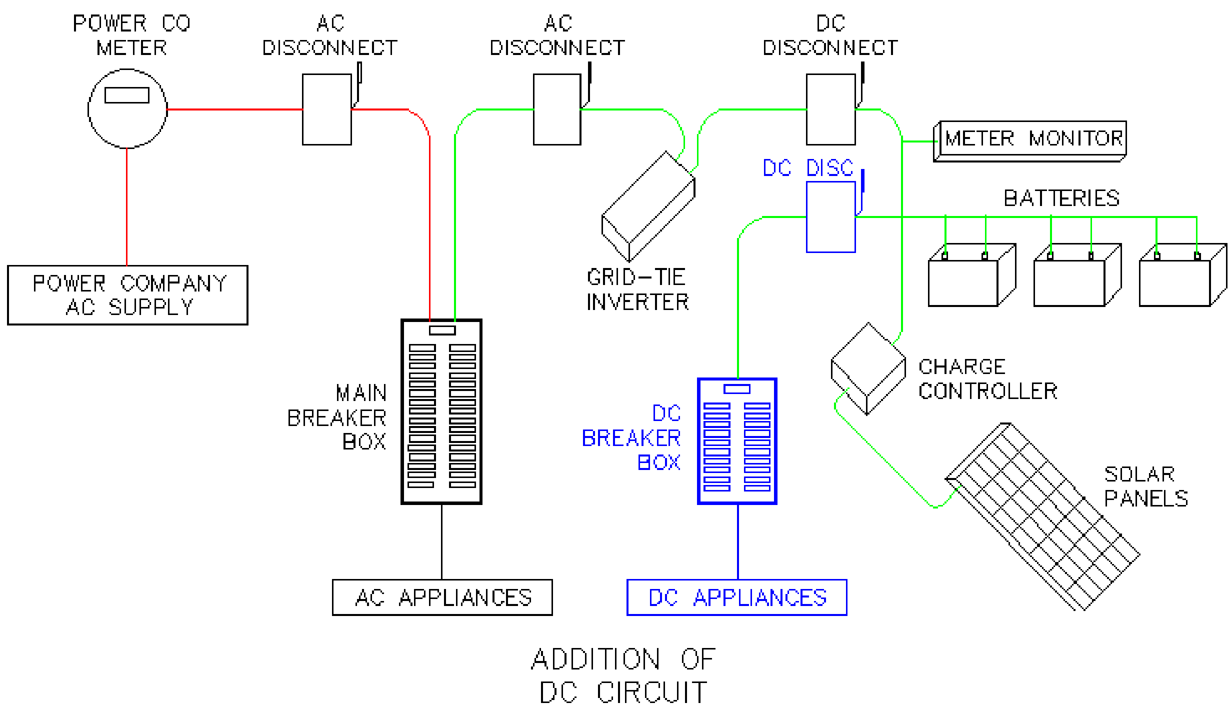
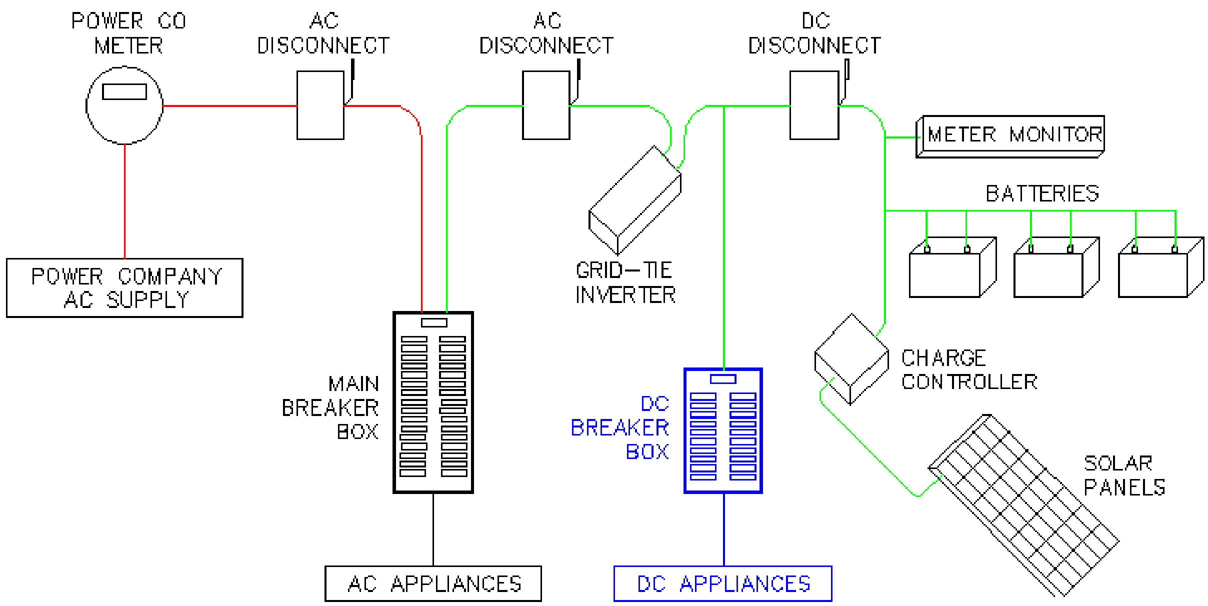


Figure 6

When installing a DC circuit, there are two options as to how it will be connected to the solar PV system. Obviously, the connection will be made before the inverter, but does it go before or after the DC Disconnect box? Either is acceptable, but let's look at the pros and cons of each.

Option 1: (shown in Figure 6 above) Personally, I prefer this option since it makes the connection prior to the DC Disconnect box for the inverter and I also prefer to add an additional DC Disconnect for the DC Breaker Box. The two reasons are 1) the second Disconnect box provides a quick visual confirmation that the DC Breaker Box is deactivated and requires that two safety switches (the DC Disconnect and the DC Breaker Box master switch) are activated before power is available to the DC circuits in the building and 2) the ability to have the building's DC circuits functional even when the AC circuits are disabled. Obviously, the second DC Disconnect could be omitted but the cost savings are minimal and you eliminate a factor of safety.

*Note… in Option 1, we're only talking about the **DC circuits** in the building. The AC circuits are still dependent on the Grid-Tie inverter.*



ADDITION OF
DC CIRCUIT

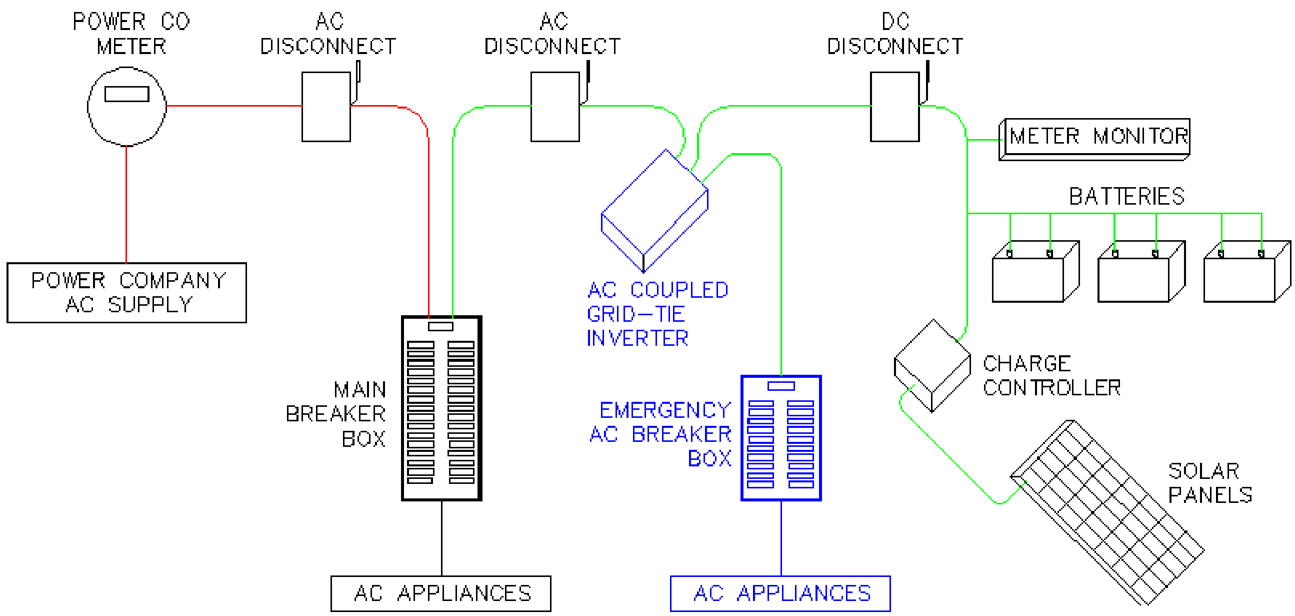
Figure 7

Option 2: (shown in Figure 7 above) If the DC Breaker Box is connected between the Solar Disconnect box and the Grid-Tie Inverter, you lose both AC and DC power when the DC Disconnect is turned Off. The system still has the same visual safety factor, it still has the dual disconnect switches (DC Disconnect and the DC Breaker Box master switch), and you save the cost of an additional DC Disconnect. But when this DC Disconnect is turned off, the building is totally dependent on the Power Company for electricity since the DC power for the Grid-Tie Inverter and the DC circuits is also turned off. And that seems to be a “high” price to pay… for the small cost savings of not purchasing another DC Disconnect.

Addition of Emergency Power Panel (Figure 8)

At last… the design you've been waiting to see… the Grid-Tie Solar PV System with Emergency Backup Power (**Figure 8**)… *as promised*. All of the previously discussed systems are in use today but owners are always interested in this particular system for the simple reason that they will have power available under any situation. However, many choose not to add the emergency power option for a couple of reasons. First, is the additional cost of the installation and second is the difficulty with the installation in an *existing* building. And these costs have to be weighed against the expected frequency of power outages or the need for an uninterruptible power supply (UPS)… perhaps for medical reasons.

Note that one added benefit to installing an AC-Coupled Grid-Tie Inverter is that the owner won't have to explain to his neighbors why his solar powered building doesn't have electricity during a power outage and listen to them laughing as he tries to explain it. That one reason may outweigh all other considerations for the installation!



ADDITION OF
EMERGENCY BACKUP
POWER CIRCUIT

Figure 8

It seems counter-intuitive that a solar powered building would be without power during a local power outage. But if you don't install an inverter with that capability… specifically an AC-Coupled Grid-Tie Inverter, that's exactly what you have.

If you're dealing with the construction of a ***new building***, it's easy to install the Emergency AC Breaker Box and to run the wiring for those circuits that need to be dedicated for backup power as shown in **Figure 8**. For new construction, this cost is relatively minor.

The design requires that an AC-Coupled Grid-Tie Inverter be used and installed similarly to the standard Grid-Tie Inverter. The primary difference is the additional wiring connections for the emergency power circuit that feeds the Emergency AC Breaker Box. Only those building circuits connected to the Emergency Breaker Box will have electricity during a local power outage. And the plans and design calculations should be clearly defined and tested when the system is installed. The testing is easily performed by simply pulling the Power Company's AC Disconnect lever. That should shut off all power to the building except for the emergency power circuits. Pulling either of the AC Disconnects should give the same results. But the Power Company's AC Disconnect totally isolates the building's electrical systems. After pulling that lever, if you still have power throughout the building, you have a defective Grid-Tie Inverter that must be corrected immediately… unless the entire building is powered by the Emergency AC Breaker Box.

For installation of an Emergency AC Breaker Box in an ***existing building***, the cost can be significant… especially if access to the Main Breaker Box and to the new Emergency AC Breaker Box is going to be difficult. All of the existing circuits that need emergency backup power will need to be moved from the Main Breaker Box and rerouted to the new Emergency AC Breaker Box. But simply moving the terminal ends from the Main Breaker Box to the Emergency Breaker Box may have unintended consequences that result in having more loads on the emergency power than planned. For example, a single circuit in the Main Breaker Box may be wired to include lights and electrical outlets in multiple rooms that you did not want on emergency backup power. So, now you have to rewire those rooms or provide additional power and batteries for those unnecessary loads. Again, these costs can add up significantly.

SOLAR SYSTEM DESIGN REVIEW

Next we will review the steps needed to design a Grid-Tie Solar PV system. We will quickly review all of the components and the entire design process but focus on discussions of the considerations that are different from a basic Off-Grid system. If you need more detailed instructions, take the “Introduction to Solar Power Design for Small Structures” course.

SOLAR SYSTEM SIZING

Step 1A: (Shortcut for EXISTING structures) Everyone loves a shortcut and **if** you’re adding a solar system to an existing structure, a good way to size your solar PV array is by using the *yearly* average of your *daily* electric usage. For some, this can be found on the building’s monthly billing statement or obtained from the Power Company. Others will have to do it the hard way by taking a year’s worth of monthly electric bills and calculating the average daily consumption. While this may seem “hard”, it’s actually much faster and easier than taking an inventory of every electrical item in the building and calculating it that way. Anyway, take the average daily use and divide it by a factor of 5 (the southern half of the U.S. will use 5 and the northern half of the U.S. will use 4). This factor is the average solar radiance hours for your area. If you’re in another part of the world, you’ll need to determine the solar radiance hours for your specific area. This will give you the approximate number of kilowatts needed for the solar panel array.

For example, a structure in the southern U.S. with a yearly power usage of 10,000 kwh, the calculations are…

10,000 kwh/yr / 365 days/yr = 27.40 kwh/day
27.40 kwh/day / 5 hr/day = 5.48 kw solar array size

So the minimum solar array size for a $0 yearly net electric bill is a 5.48 kw PV system… assuming the Power Company’s power purchase price is the same as their sell price for those times when the peak usage exceeds the daily average. For some power companies, the sell price and the purchase price are different and you will need to factor that into your design calculations.

Remember, this is just for a quick estimate of what is needed ***assuming*** *the building usage remains the same*. The danger with this comes when you use less than a year’s data. Why? Because… power consumption in the summer months can be substantially different as compared to the winter months. So, missing some months’ data can cause a significant impact to the average daily use. Once the solar PV system is installed, some months may show a credit on the bill and others will show charges due. But after a year's use, the credits and charges should almost equal.

This also assumes that the power consumption remains the same once the users 'believe' they have free electricity. Too many times, the users' power consumption increases once they have "free" power. *Surprised*?

Now, if you only want to reduce your power bill by a set percentage you can easily factor that in for your PV system sizing. For example, if you want to reduce the electric bill of the same structure above by 20%, then your calculations become…

10,000 kwh/yr * 20% / 365 days/yr = 5.48 kwh/day
5.48 kwh/day / 5 hr/day = 1.1 kw solar array size

These quick calculations (assuming you know the yearly power consumption for the structure) can be used to determine the cost-benefit analysis for multiple electric bill percentage reductions for the structure.

For every solar system you design, you must account for every demand the end user has for power. And if your system has an AC-Coupled Grid-Tie Inverter, you will need to account for every demand for power on that system separately and jointly. Separately for when there is a local power outage that must be supported by your emergency backup panel and jointly to determine the solar panel bank requirements, as well as the battery bank requirements for the percentage of the yearly power that you are trying to reach.

If your design is for an EXISTING structure, you can now skip to **Step 3.**

If your design is for a NEW structure, proceed with the sizing calculations for new structures…

Step 1B: (Required for NEW structures) Know your end users. Know what they will be using or adding and how they will be using the electricity in the structure... now and in the future. Not knowing this information is setting your system up for failure.

Obviously, the calculations above for determining the solar array size doesn't work for new structures and you'll have to do it the hard way… by calculating every power demand for every hour of every day. And don't forget to add a buffer.

Again, if your system has an AC-Coupled Grid-Tie Inverter, you will need to account for every demand for power on that system separately and jointly as you did above.

Step 2: For the reasons previously stated, you must quantify EVERY item that will require power. You will need to know the wattage of each appliance and the hours it will be used each day for both the normal usage and… don't forget to separate out the emergency power usage. This will provide you with the amp-hours you will use for the solar array design.

Total Building Power Demand:

Appliance	Quantity		Watts		Hrs/day		Watt-Hrs
Lights	20	*	15	*	10	=	3,000
Ceiling Fans …	X	*	XX	*	XX	=	X,XXX
Computers….	X	*	XX	*	XX	=	X,XXX
							Y,YYY watt-hrs/day

Emergency Power Demand (if applicable):

Appliance	Quantity		Watts		Hrs/day		Watt-Hrs
Lights	20	*	15	*	10	=	3,000
Refrigerator …	X	*	XX	*	XX	=	X,XXX
Computers….	X	*	XX	*	XX	=	X,XXX
							Z,ZZZ watt-hrs/day

You will continue this appliance list for every item you expect to be used and then provide an additional buffer based on your best estimate of the end users daily power demands. Not surprisingly, people will ***ALWAYS*** use more electricity than you expect when it's "free".

DISCUSSION ON SOLAR PANELS

While the solar panels are basically the same as before, manufacturers are continuing to increase their efficiency. Today, the biggest factor affecting the solar panel arrays is space limitation. There is only so much rooftop area and/or ground space available … especially in urban areas. Many times, available space is extremely limited or non-existent or prohibitively expensive. As such, the more limited the space, the more efficient the panels need to be.

STC Ratings – Solar panels are rated under Standard Test Conditions (STC) by the manufacturers at 1000 watts per square meter of solar irradiance at 25° C. If the temperature is different than 25°C (77°F) or the sunlight intensity is different, then your panel will perform differently than the specifications stated. If you have high power demands but have limited space, you'll need to select panels with the highest ratings.

Note of interest… The current solar PV systems are increasingly more efficient such that if it's cloudy, your solar array may still produce up to as much as 70% of its rated power. This will provide you with an unexpected buffer (safety factor) in your calculations. That's a good thing!

Monocrystalline solar panels are the most efficient and, therefore, the most expensive. The solar panels are made with *monocrystalline* cells. These solar cells are made from very pure silicon and are manufactured through a complicated crystal growth process. The advantage of *monocrystalline* panels is that because of their higher efficiency and wattage, they require less installation area for the same output. A 250-watt panel in 2014 will run about $270.

Polycrystalline solar panels (or *Multi-crystalline* solar panels) are made with *polycrystalline* cells which are less expensive yet only slightly less efficient than are the *monocrystalline* cells. This is because the cells are not grown in a single crystal form but rather in a large block containing many of the crystals. These panels are very popular today because they deliver only slightly less efficiency than the *monocrystalline* panels but at a more moderate price. A 250-watt polycrystalline panel in 2014 will run about $250.

Amorphous solar panels are very different from the *monocrystalline* or *polycrystalline* cells because they're not really crystals. Instead, they are made from a thin layer of silicon deposited on a sheet such as metal or glass or even a flexible material to create the solar panel. However, one advantage of *amorphous* solar panels is that they can be made into long sheets of "roofing" material and can cover large areas of a roof. So, if you have a large area available that is unusually shaped for standard panels, using *amorphous* solar panels can provide significant savings and additional power.

Solar Panel Considerations

Shadows are a solar panel's enemy. Therefore, it is critical to minimize or eliminate any shadows that can impact the solar panel array… especially during ***peak*** sunlight hours (10 am to 3 pm). You will find that some solar panel manufacturers will advertise panels that can withstand shading but they do so by using internal diodes which also reduce the power produced slightly.

Temperature is another issue that must be addressed. Solar panel efficiency decreases as temperature increases. So the solar panels should be mounted in such a way as to allow for air flow around the individual solar panels to help with their cooling.

Wind is yet another issue that needs to be considered. Wind can aid in cooling the panels in the hot sun but too much wind… i.e. hurricanes, gales… can damage the panels with flying debris or actually ripping the panels from their mounts.

Access to the panels must also be evaluated when considering where to install the solar panels. To maintain peak performance from the system, the panels need to be checked and cleaned on a regular basis.

SOLAR PANEL MOUNTS

Solar panels should face true south in the U.S. but many don't. And there is a difference between true south and magnetic south. In some areas this can make a significant difference in the correct alignment and in the power produced. Check the magnetic variation for the installation's location for proper alignment of the panels. Obviously, this is not as critical for tracking mounts as it is for fixed mounts.

The proper angle of inclination (tilt) is another consideration to obtain *maximum* panel output. The actual inclination for your location, if needed, can be obtained through various online website sources. A good rule of thumb is to set the angle of inclination equal to the location's latitude. See **Figure 9** below.

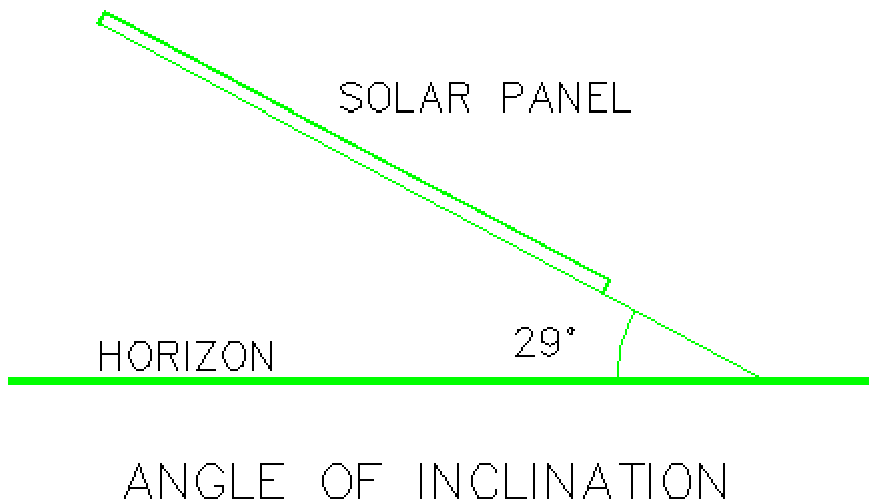


Figure 9

If your solar panels' performance isn't as you expected, the alignment and angle of inclination may be why.

Fixed solar panel mounts are the simplest and least expensive way to mount solar panels. Typically, they will be attached to a building's roof or they may be ground mounted on a series of posts, frames, and supports. However, ground mounted panels are more susceptible to shading issues and impact damage.

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

Tracking solar panel mounts allow the solar panels to follow the path of the sun during the day which maximizes the direct solar light that the panels can receive. Two styles of trackers exist… a one-axis and a two-axis. A one-axis tracker will track the sun from east to west at a fixed angle of inclination. The two-axis tracker will track the sun's east to west movement as well as the seasonal declination movement of the sun.

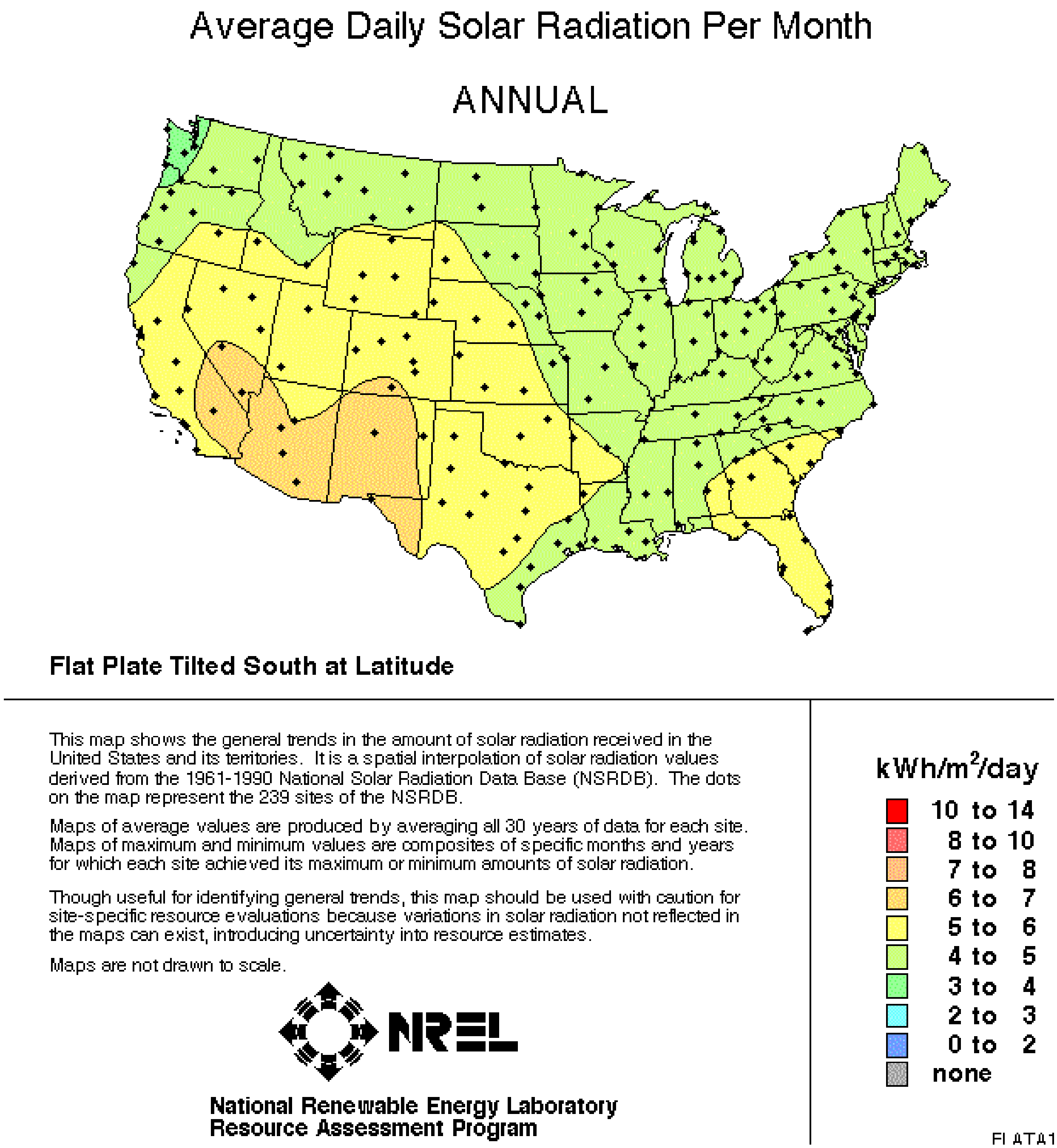
An alternative to the tracking mounts is to consider purchasing additional panels instead… provided you have the room to install them.

DISCUSSION ON SOLAR EXPOSURE

The yearly average of the approximate hours of daily sunshine in the Southeast U.S. is about 5 to 6 hours. The northern states average about 3 to 5 hours per day and the Southwest will see 5 to 7 hours per day. See the map below from the National Renewable Energy Laboratory Resource Assessment Program for the number of hours in your location or visit their website for more information at http://www.nrel.gov/gis/solar.html .

The solar exposure map is based on the average number of hours you can expect to receive the sun's rays for a particular location. The map does not take into account solar obstructions in the form of adjacent buildings, trees, terrain, signs, etc.

See the **Average Daily Solar Radiation Per Month** diagram from the **National Renewable Energy Laboratory (NREL) Resource Assessment Program** on the next page.


Average Daily Solar Radiation Per Month
ANNUAL
Flat Plate Tilted South at Latitude
This map shows the general trends in the amount of solar radiation received in the United States and its territories. It is a spatial interpolation of solar radiation values derived from the 1961-1990 National Solar Radiation Data Base (NSRDB). The dots on the map represent the 239 sites of the NSRDB.
Maps of average values are produced by averaging all 30 years of data for each site. Maps of maximum and minimum values are composites of specific months and years for which each site achieved its maximum or minimum amounts of solar radiation.
Though useful for identifying general trends, this map should be used with caution for site-specific resource evaluations because variations in solar radiation not reflected in the maps can exist, introducing uncertainty into resource estimates.
Maps are not drawn to scale.
NREL
National Renewable Energy Laboratory
Resource Assessment Program
kWh/m²/day
10 to 14
8 to 10
7 to 8
6 to 7
5 to 6
4 to 5
3 to 4
2 to 3
0 to 2
none
FLATA1

Step 3: (required) Solar panel sizing is your next step. But with a Grid-Tie system, this becomes more complex because of the "owner preferences" which we discussed at the beginning of this course. Since you have the Grid available, you have more flexibility in sizing the solar array. Even a small array will provide owners a savings on their electric bill.

If you are providing an AC-Coupled Grid-Tie System with Emergency backup power, the solar array must be sized for the emergency power demands or the system will shut down. Consequently, these calculations are critical for an emergency backup during power outages. So the emergency power demand will determine the absolute minimum size of the solar array.

If you need 27.4 kwh per day in the southern U.S., then your calculations are…

Watt-hrs / sunlight hrs = watts needed → 27,400 / 5 = 5,480 watts

Then evaluate the following 100, 200, and 250 watt panels for our example project.

Watts req.		Panel watts		No. of Panels req.
5,480	/	100	=	55
5,480	/	200	=	28
5,480	/	250	=	22

It is generally better to stick with pairs of panels rather than an odd number of panels because of mounting and wiring simplicity… especially if you're working with panels in series to obtain higher voltages.

Step 4: (required) Select solar array voltage. Selecting the most efficient voltage involves an evaluation of the distance from the panels to the charge controller and the costs of the voltage options available. Remember, increasing the voltage decreases the wire diameter size required and that can be a significant cost differential in itself.

Step 5: (optional) Account for bad weather days. Only if you are providing an emergency power backup will you need to perform a bad weather analysis. Again, this is different from an Off-Grid system because you have the Grid available to you. However, an emergency backup system will require determining the number of days the owner needs to provide electricity without sunlight. Of course, this determination can be adjusted with the availability of an emergency generator.

If you need 5,480 watts per day, then your 3 day system requirements are…

5,500 watt-hrs * 3 days = 16,500 watt-hrs

If you need a 5 day backup, then your 5-day system requirements are…

5,500 watt-hrs * 5 days = 27,500 watt-hrs

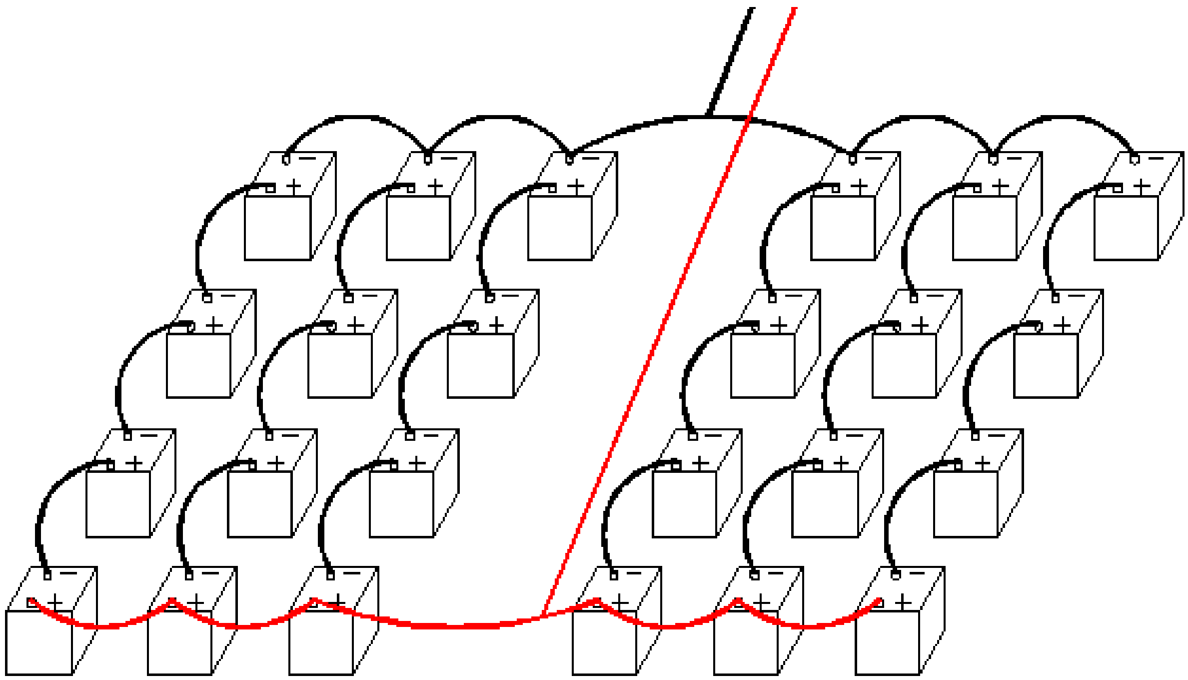
It adds up quickly, as you can see.

Step 6: Determine the battery bank size. Batteries are only needed for a Grid-Tie system (AC-Coupled) with an emergency power backup. Batteries provide the power for those times when there is no sunlight for the solar panels to function and there is no Grid power available. Since you want to avoid damaging these expensive batteries, you never want to reduce your battery charge below 50%. Some believe you shouldn't reduce the charge below 80% to extend their useful lifespan.

Using 27,500 watt-hrs, you should at least double (to avoid battery damage) the 27,500 watt-hrs to 55,000 watt-hrs and then determine the required amp-hrs:

P = E * I or P / E = I
27,500 watt-hrs * 2 = 55,000 watt-hrs
55,000 watt-hrs / 12 v = 4,583 amp-hrs

So, our 12 volt batteries need to be capable of delivering 4,600 amp-hrs to our structure. Using 105 amp-hr 12-volt batteries, you will need 4,583 / 105 = 44 batteries.



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Step 7: Select a Charge controller. A charge controller is necessary to safely charge the batteries and provide power to the inverter. The more direct the sunlight becomes, the more voltage the solar cells will produce and that excessive voltage could easily damage the batteries. Basically, a charge controller is used to maintain the proper voltage on the system.


Morningstar Charge controller

MPPT charge controllers allow your solar panels to operate at their optimum power output voltage, improving their recharge performance by as much as 30% or more and are the standard for controllers. Using 200-watt panels @ 6.06 amps/panel, we will have:

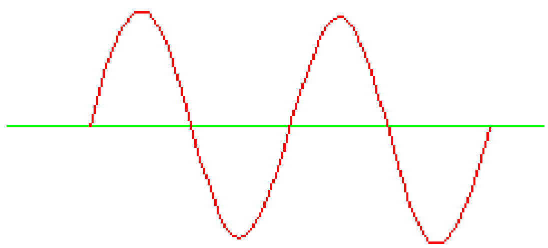
6 panels / 2 (2 panels is 48 volts) = 3 banks * 12.12 amps = 36.36 amps

Therefore, we need a charge controller capable of handling approximately 45 amps.

DISCUSSION ON GRID-TIE INVERTERS

Selection Considerations.

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



PURE SINE WAVE

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

True Sine Wave inverters produce the closest pure sine wave of all power inverters and in many cases can produce cleaner waves than the power company itself. They will run any type of AC equipment and are, consequently, the most expensive. Also, most appliances will run more efficiently and use less power… which is another good reason to use a True Sine Wave inverter. So, unless you have an unusual situation where you are certain that a True Sine Wave inverter isn't needed, always specify a True Sine Wave inverter.

Inverter Input Voltages. What should be used… a 12, 24, or 48 volt inverter? The main consideration in deciding on the voltage from the batteries to the inverter input is the distance between your solar panel array and your batteries. The higher the voltage, the lower the current… which means the smaller the electrical wiring can be. Remember, the Grid-Tie Inverter must be rated for the battery output voltage to avoid damage.

Inverter Stacking is using multiple inverters to provide more AC power or higher voltage (i.e. 240 VAC). For example, if two compatible inverters are stacked in series, you can double the output voltage. This would be the technique used to provide 240 VAC.

On the other hand, if you configure two inverters in parallel, you can double your amperage. Two 4000 watt inverters in parallel would give you 8000 watts (8KW) of power.

Step 8: Inverter design. (Required) Again, using your design calculations, you will need to select a Grid-Tie Inverter that meets the system demands. And if you have an inverter with an emergency backup, you will need one that can handle your emergency power demands. Check the inverter specifications closely to ensure your selected inverter can meet both requirements. And don't allow your emergency power capacity to be near or at the calculated power demand or you will certainly overload the inverter when it is most needed.

Assuming a structure is using a peak of 3600 watts, you will select an inverter capable of handling about 4,000 to 4,500 watts (including a 10-20% buffer) with the same nominal voltage as your battery bank. And you will choose a Grid-Tie inverter that provides True Sine Wave outputs as we discussed previously. A 5kw Grid-Tie Inverter will run about $2,000. If you are also providing emergency backup power, you will choose an AC-Coupled Grid-Tie Inverter that also meets the backup power requirements. A 5kw AC-Coupled Grid-Tie Inverter will run about $2,500.

DISCUSSION ON METERS AND MONITORS

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

If you have a solar system with an emergency backup, you may want a meter/s capable of monitoring the emergency power supply as well. Again, check your product specifications closely.

Step 9: Meters & Monitors. (Required) Depending on the charge controller and inverter chosen, you may or may not need an "independent" meter or monitor. However, you **do need** some way to accurately measure performance. Meters can monitor and display important outputs like how much electricity is being produced from the solar array, how full the battery bank is, what the battery voltages are, as well as amps, amp-hours, and other data… depending on the unit, of course. The 2014 prices run about $150 to $250 for a good monitor.

TS-M-2 Monitor Meter on Morningstar TriStar MPPT-60 charge controller

Also, MidNite Solar currently has a system available that allows you to monitor your solar system performance remotely on your Android phone. And others are likely doing the same.

DISCUSSION ON GENERATORS

(Optional) Generators are best used for backup power during long periods of little or no sun. Ideally, if and when you need to run the generator, you want to use your Meter Monitor to determine how long to run it to provide the batteries with both the Bulk stage charge and the first portion of the Absorption charging stage. Then shut it off! Once in the latter portions of the Absorption stage, the current will begin dropping as the batteries approach a full charge. As the current drops, the generators' excess power will simply be wasted. Therefore, using a generator in the latter portion of the Absorption phase is obviously very inefficient and wasteful of energy and fuel. Any time you're running the generator, then also run anything else with large electrical loads (like power tools, air conditioners, etc)… anything that would normally put a real drain on your batteries.

If you charge the batteries up to about 85% to 90% capacity with a generator, not only will that prevent the batteries from becoming too deeply discharged but then only a short period of sunlight is required to complete the battery charging.
Most solar inverters have a battery charger built in. This allows the generator to simultaneously charge the batteries while also providing power to the AC loads. This is a much more efficient use of the generator and it minimizes the wear on the generator and the batteries.

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

Step 10: Generators. (Optional) For most small to medium-sized structures, a 4,000 to 7,000 watt generator will work nicely and they are moderately priced. Generators can be found in the $350 to $1000 price range depending on brand & features. Additional features like auto-start capability, diesel fuel, LP fuel, etc. are available depending on user preferences.

GRID-TIE SOLAR POWER SUMMARY

As we have seen, there are the same basic components found in every solar Grid-Tie PV system. These are the solar panels, charge controllers, monitor meters, Grid-Tie inverters, AC disconnects, and the electrical wiring. Depending on the system size and options, additional items that the system may include are an AC-Coupled inverter and a generator.

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

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

In 2014, complete solar systems… panels, controller, Grid-Tie inverters, mounts, etc… can be readily purchased as kits. A 2,150 watt kit that provides 10.75 kwh can be purchased for about $7,000. A much larger system, a 20,640 watt kit that provides 103.2 kwh can be purchased for about $53,000 today. Obviously, this doesn't include labor as these are just for the parts.

And don't forget about the benefits of the electricity generated by a green system. The cost savings can be significant over the lifespan of the system. And having a reliable power supply available when there is a local power outage can be a real life-saver for those relying on critical medical equipment. For most of us, since we are connected to a seemingly endless source of electricity through an on-grid electrical supplier, we don't give much thought to the electricity we use… until we receive the electric bill or experience another power outage.

And always remember these two formulas as you will repeatedly use these…

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

So don't just sit there… go do it! And, if you do design and construct a system, I'd love to hear from you… and send pictures. If you grant me permission, I may even include your photos and description in a future course.

Business powered by the sun!

