The Solar Photovoltaic Workbook

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HENRY PUBLICATIONS ™ SINCE 1985

ISBN 979-8-9878837-7-8

CODE ELECTRICAL
LEADER IN ELECTRICAL
EDUCATION WORLD WIDE

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Introduction

I have revised this book *The Solar Photovoltaic Workbook* as I have gained so much valuable knowledge since its first printing that I want to share with you.

I'm writing this book as a customer, for the customer and so the prospective PV installer can win the bid by **explaining the correct installation procedure per the manufacturer's instructions** in order to maintain the warranty and harvest the maximum power from the system and the customer will not be among the over 50% that are having their PV system installed *incorrectly* voiding the warranty without the customer's knowledge of it.

The problem today is too much material is being written that little or no maintenance is required after installing a PV system. After reading this workbook containing the Manufacturer Installation Instructions it should put an end to those fantasies.

As I write, I have over 65 years in the electrical industry of which several years involved inspection and electrical expert testimony in personal injury and death cases.

I learnt at an early age in the electrical trade that anything mechanical can fail. It requires maintenance and inspection to maintain quality and operation.

So you'll hear me say the words maintenance and inspection several times throughout this workbook. The word *maintenance* is mentioned 223 times in the National Electrical Code and the word *inspection* 61 times.

It's time for the PV industry to return to craftsmanship skills when installing a PV system that may operate 40-50 years exposed to the inclement outdoor weather.

The customer is investing a substantial amount of money in the PV system expecting a continued savings on their electric bill.

The system must be installed correctly to produce the maximum possible energy.

The system must be designed to the manufacturer's specifications which requires **maintenance, cleaning and inspection periodically, which requires access space to the modules. These are requirements in the product warranty**.

One must first understand that **heat is resistance** and will reduce the power output of the PV system. **Untorqued connections**, and modules mounted too close to the roof surface are examples of contributers of heat that will lower the PV wattage output.

It's not a matter of just spinning the net meter backwards as desired by the customer to save money on the electric bill. It's a matter to ensure the customer the meter is spinning backwards at a maximum possible rate and it will continue in the future to harvest the maximum power as the system was installed correctly to the manufacturer's product specifications which include **torquing** the connections mechanically and electrically to the required inch-pounds or foot-pounds, cleaning of the modules, maintenance, and required inspection of the entire system periodically for corrosion, loose connections, wiring damaged by rodents, etc.

When I ask an installer if they torqued the connections as required, the reply is "no one does it that way." I've always maintained, **"wrong is wrong, even if everyone does it that way. And right is right even if no one does it that way."**

I'm not your average customer, so I'll expect you to do it the right way when installing my system. This workbook will teach you the right way.

(continued)

HOME OWNER

CONTRACTOR

Tips on how to pick a solar PV contractor, questions the home owner should ask.

Most customers will acquire three or more bids from solar PV contractors. They may or may know that it's noted that 50% of PV installations are installed correctly and 50% are not installed correctly. **Never pick a company only on price.**

Screen your solar contractor carefully

First of all, **the lawsuit** demonstrates the need to hire **qualified** contractors. Any type of bad home electrical work poses a fire risk, and much of the work of installing solar panels is electrical.

•It's not a matter of how many solar PV systems one has installed, the question that should be asked is how many have you installed **per the manufacturer's specifications** in order to **maintain the warranty**. A solar PV system is an investment for the long term. Prefer local companies that have been in business for a long time, a reputable company.

•The tightening of all mechanical and electrical connections throughout the **entire** PV system **requires torquing to the manufacturer's listed specifications**. This starts with the installation of the rail system and continues with the module T-bolts and midclamp bolts, ground connections, all wiring to terminal connections at the deck box, inverter, back-fed circuit breaker, load center connections, meter base connections, everything requires using torque tools set to the prescribed inch-pounds or foot-pounds.

How many PV installers are following the manufacturer’s listed specifications for installing the components? **How many even have the required torque tools?** Ask them!

•A space with a minimum of 16" is recommended between the arrays to be able to reach the defective module in the middle without removing several panels which would increase the labor cost to the home owner of the service call. This space is needed for cleaning, maintenance and inspection.

•Ventilation space under the panels with standoffs of 6".

•OSHA reqires safety fall protection when you can fall **6 feet** or more. **Permanent anchorage** must be installed when installing the PV rail system and then the safety harness can be used, and also for **future work** on the roof such as maintenance, cleaning, module replacement, etc.

•The benefit of **microinverter** is that it mitigates one of the causes of solar panel fires. This is because a microinverter converts DC power to AC power directly at each solar panel, resulting in AC power traveling down from your roof to your basement electric panel instead of DC power. A good solar installer will recommend one that balances costs with performance.

A PV Installation must be above inspection and beyond the Code

Recently I e-mailed a person to inform him the photo that appeared in an electrical magazine had the PV modules installed *incorrectly*. His reply, via his personal solar contractor was the inspectors signed it off and stated there wasn't any violations.

I have been employed as an electrical inspector in the years past and have written a book on *Electrical Inspection*. What one must understand is a correctly installed PV installation **goes way beyond the inspector and the Code**.

Let's start at the beginning, why did the prospective customer call the PV installer? To reduce their electric bill, simple as that!

Guess what, the inspector enforces the Code, which is for safety and has nothing to do with reducing your electric bill!

If you read the National Electrical Code, it states their intent in the very beginning of the book:

Section 90.2(A) Practical ***Safeguarding*** of persons and property.

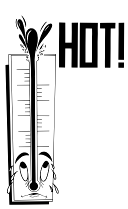
Section 90.2(B) Adequacy. Compliance therewith and proper maintenance in an installation that is essentially free from hazard ***but not necessarily efficient***.

Section 90.2(A) Intention. This Code is ***not intended as a design specification*** or an instruction manual for untrained persons.

In reality, PV modules will operate in a wide range of temperatures that are specific to the project location. ***To properly design a system***, it is important to know the performance of the modules at the specific temperature extremes. The temperature coefficients, which are determined by Nationally Recognized Test Labs, are used to calculate the performance of the modules at these temperatures.

In Table 690.7(A), the Code recognizes the cold temperatures by requiring a correction factor. The reason is cold temperatures actually raise the voltage of the module. The Code has a 600 volt maximum as does the insulation of most wires and with several modules in series you can reach extremely high DC voltages. So the Code steps in for ***safety*** purposes, not designing. With colder temperatures you have higher voltages and also more power (watts).

•STC = Standard Test Condition



The opposite is true with heat. Higher temperatures cause the modules to have less voltage and less power output (watts). But the Code does not recognize the higher temperatures as the modules heat is not a safety item, it's an ***efficiency*** item.

Excessive **heat** can cause problems as the modules now with a lower voltage may not meet the minimum DC voltage required to start the inverter.

Mounting the modules too close to the roof surface blocks the air flow to help cool the modules.

The increase in **heat** lowers the output power of the modules.

In my early studies of the installation of PV systems I became immediately concerned about filling the roof with modules and how could you follow the manufactuer's specifications which requires cleaning, maintenance and inspection of the mechanical and electrical components. I was told by an experienced instructor of the Code that section 110.26 does not apply as the PV modules cannot be ***serviced*** in the field. The comment was ,"The NEC does not and should not address maintenance procedures."

The reason for inspection is to check for corrosion, looseness of mechanical connections, inspection of the wiring for rodent damage and signs of loose connections, etc. The reply was, rodent damage would come under ***good workmanship*** and proper use of materials suited to the environment and protected from physical abuse. But I have yet to see the DC wiring between the modules connected in series in metal conduit in any published articles?

When I ask how would you remove a defective module in the center of the roof without removing several modules to get to the defective one? The reply was, "Yep, you may have to remove multiple modules to get to the defective one, ***but the code doesn't care***."

I bet the customer would care when they have to pay $$ the service bill! The first step we take in our designing a PV system is to ***allow space between the arrays*** for cleaning, inspection and maintenance which is required. I guess some people haven't taken the time to read manufactuer's installation instructions. I was told that I needed to read section 110.26 carefully so I would understand that it doesn't apply to equipment that does not require service or can be de-energized? I've been in the electrical industry 65 years now and after reading these types of replies, my last question is "*who's teaching the teacher*?"

A space with a minimum of 16" is recommended between the arrays to be able to reach the defective module in the middle without removing several panels which would increase the labor cost to the customer of the service call.

The question today with the roof being filled with panels how would a firefighter use his saw when the change states: ***except directly below the roof surface covered by PV modules***?

California fire code requires roof access for safe fire suppression and rescue operations. Solar panels must set back ***4'*** from the edges and peaks of the roofs with space between the arrays. This reduces the area for solar panel installation but provides room for **emergency personnel** to work around the array. It also allows for roof-peak venting in case of a **fire**. Now this rule makes sense. But, now the PV salesmen don't like it because now they can't fill the roof with modules.

How do you clean the modules you can't reach? You must provide access space to each module and NOT fill the roof with modules.

CLEANING - In order to harvest the maximum power, clean the module surface with water and a soft cloth or sponge to remove the scum and bird droppings that the rain won't wash away. Remove any leaves or weeds.

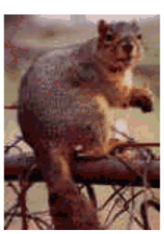
Cleaning is recommended a minimum of twice a year.

SOLAR MODULE INSPECTION CAMERA

NOTE: Remember, the manufacturer requires inspection to the underside of these modules.

How can you inspect them when mounted close to the roof?

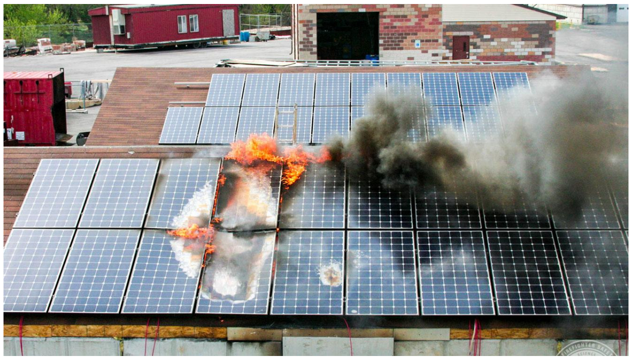
•**Maintenance inspection** --While damage to solar panel wires can happen because of other reasons - **such as squirrels chewing on them** - the occurrence of seven fires at installations by the same installer does suggest that substandard work could be to blame.



Solar panels only need maintenance two to four times a year, but check your solar companies manual for panel specific maintenance care.

Just like the 44,000 electrical fires that happen every year, a solar panel fire is the result of a malfunction.

But when solar panel equipment is poorly installed, in some cases this can result in electrical faults that cause arcing. Arcing can ignite the encapsulant layers that surround the solar cells in a panel, or the backsheet at the rear of the panel. Both are made of plastics and are flammable.



Rapid shutdown means that firefighters need a way from the ground to flip a switch and kill the power at the wires that surround a solar array. For a firefighter who might need to **swing a metal axe on a roof** with solar panels, this is very important for safety.





The customer after receiving several estimates for a solar PV system should not be looking only for the lowest cost but ask the questions about the installation being installed correctly to endure the many years that it will be exposed to the weather **and will the installation maintain the Limited Warranty as required by the product manufacturer**.

This is because warranties invariably contain a clause that says it will be rendered void if the **instructions in the installation manual aren't followed**.

Solar Panel Warranties Can be Voided Without **professional installation**. Work performed by a contractor who lacks industry **certification** can nullify a performance warranty.

Ask about warranties

There are many different components in a photovoltaic system, and each is covered by a different warranty from their manufacturer. It's crucial that the installer fully explain each one.

• The installer should provide a warranty of the workmanship and components of the system, and cover the labor and replacement costs of any failing components.

• Photovoltaic panels have their own warranty, and often this is specified in two parts: one warranty covering materials and workmanship, and another warranty period covering their power output. Solar panels normally degrade over time, producing a little less power each year. (This degradation should be less than 1% per year.) The panel warranty will certify that it will continue to produce a given percentage of the original power output after a number of years. A 25 year power warranty is typical, and the product warranty should be at least 10 years and is sometimes as long as 25 years.

• The inverter system is a critical part of the system, and will have its own warranty period. 10 to 25 years is typical.

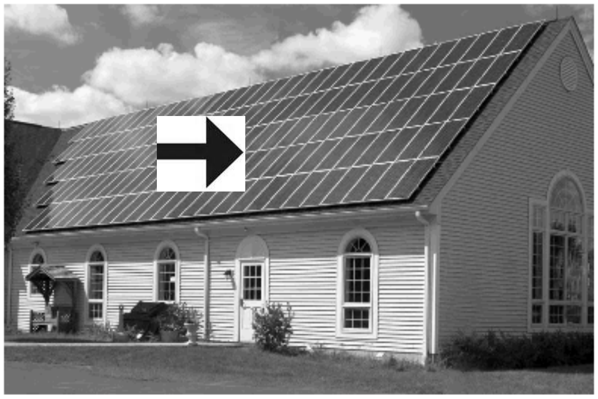
•1 The racking system needs to hold up to potentially extreme weather for a couple decades. You want to make sure it has a strong warranty - at least 20 years.

MAINTENANCE - I had *permanent* anchorage installed on my roof for future connection of the **safety harness for maintenance and service work.** OSHA requires a safety harness when 6' above the ground when performing the key word is *work*.

Workers engaged in residential construction 6 feet or more above lower levels must be protected by a personal fall arrest system, per OSHA Part 1925.

"Personal fall arrest system" means **a system used to arrest an employee in a fall from a working level**. It consists of **an anchorage**, connectors, a body belt or body harness and may include a lanyard, deceleration device, lifeline, or suitable combinations of these.

Notice how many insllers violate the OSHA law by not wearing the personal fall arrest system,safety equipment required by law.



Can you imagine the cost of a service call to replace a defective module that you can't reach without removing several modules to service it.

NOTE: *The Limited Warranty does NOT include the costs of removal or reinstallation for the product being repaired or replaced.*

•Ask your PV installer if he is going to install ***permanent anchorage*** installed on your roof for **future connection** of the **safety harness for maintenance and service work.**

HOME OWNER

The property owner is **not** knowledgeable in the electrical PV solar practices **and depends on the electrician to install a safe electrical system. But, did they?**

There is one warning. The solar installer must have done the job **correctly**. The customer must ask the installer certain questions before signing a contract.

You could write a book on "**qualified person**."

Which PV installer would you choose?

It's your choice, qualified, licensed, professional, advanced, experienced, competent, certified, verified, reputable, etc.

The word reputable actually has a good deal of reputability itself, since it's been in standard use since the 17th century.

Having a good reputation "a reputable company."

There is a difference when hiring an *experienced, qualified, knowledgeable and reputable* electrical PV installer compared to a licensed electrical installer.

It's not a question of how many solar PV systems they have installed, the real question I want to know as a customer is how many have you installed according to the product manufacturer's specification so that I have a Limited Warranty.

As a customer, I don't want to pay to have several modules removed to gain access to the defective one, don't leave me with future problems that could have been avoided.

We can trace all energy used on our planet back to the source...the nearest star, our Sun. The history of solar energy is as old as humankind. In the last two centuries, we started using Sun's energy directly to make electricity.

In 1839, Alexandre Edmond Becquerel discovered that certain materials produced small amounts of electric current when exposed to light.

Photovoltaic, or PV for short, is the word that describes converting sunlight into electricity: photo, meaning pertaining to light, and voltaic meaning producing voltage. It took, more than 100 years, however, for the concept of electricity from sunlight to become more than just an experiment.

When certain semiconducting materials, such as certain kinds of silicon, are exposed to sunlight, they release small amounts of electricity. This process is known as the *photoelectric effect*. The photoelectric effect refers to the emission, or rejection, of electrons from the surface of metal in response to light. It is the basic physical process in which a solar electric or photovoltaic (PV) cell converts sunlight into electricity.

Sunlight is made up of *photons*, or particles of solar energy. Photons contain various amounts of energy, corresponding to the different wavelengths of the solar spectrum. When photons strike a *PV cell*, they may be reflected or absorbed, or they may pass right through. Only *absorbed* photons generate electricity. When this happens, the energy of the photon is transferred to an electron in an atom of the PV cell (which is actually a *semiconductor*).

With its new found energy, the electron escapes from its normal position in an atom of the semiconductor material and becomes part of the current in the electrical circuit. By leaving its position, the electron causes a *hole* to form. Special electrical properties of the PV cell - a built-in electric field - provide the voltage needed to drive the current through an external load (such as a light bulb).

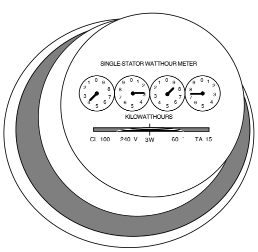
Photovoltaic (PV) technolgy converts one form of energy (sunlight) into another form of energy (electricity) using no moving parts, consuming no conventional fossil fuels, creating no pollution, and lasting decades with very little maintenance.

Let's begin by identifying the types of PV systems.

Type of System	Back Up Power if Utility Fails	Sell Back / Net metering
Stand-alone, battery based	YES	NO
Utility-interactive, battery based	YES	YES
Utility-interactive, NO batteries	NO	YES

The Stand-alone, battery based is mainly used in a remote area that has no utility nearby. An example would be a cabin in the mountains. You would produce DC voltage from the solar power and the appliances, lights, etc. in the cabin would be DC.

The Utility-interactive, battery based produces solar energy during the day and spins your utility meter backwards (net metering) for you to use free electricity during the night and with the battery back up will also provide limited electricity if the utility fails. This system provides enough electrical power to provide emergency lighting and **minimal** comforts during prolonged electrical outages.



The Utility-interactive, NO batteries spins the meter backwards during the day. Utility companies are becoming more accepting of the Utility-interactive PV system with buyback or net metering capabilities. Having a batteryless system not only does away with the considerable expense of buying and periodically replacing batteries; also avoided are the hassles of maintenance, as well as the need to make sure that the energy demands placed on them balance the energy production, lest they become too drained.

So there are two basic types: bill reduction and blackout protection.

Now let's start by identifying the major elements of a PV system.

Solar Module

An Array

Combiner Box

DC disconnect

Inverter

Charge controller

Batteries

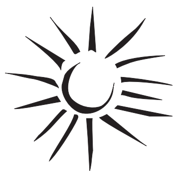
Panelboard

Sometimes the word "panel" is used when referring to a module. More commonly, the term panel refers to an assembly of two or more modules that are mechanically and electrically integrated into an ARRAY.

Sometimes "panel" is used as an alternate term for module. More commonly, the term panel refers to an assembly of two or more modules that are mechanically and electrically integrated into an **array**.

PV modules are rated (power, voltage, current) at a **Standard Test Condition** (STC) temperature of 77°F (25°C). Surfaces (including PV modules) mounted in exposed outdoor locations are subject to widely varying temperatures that are a result of the ambient temperatures, solar exposure, and cooling by radiation and convection.

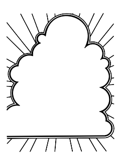
Solar Module



A typical PV module mounted outdoors in a well-ventilated area and exposed to 1,000 W/m^2 (**m^2 is 10.76 or 11 square foot**) of **solar irradiance** with no wind blowing can be expected to operate at 54-63°F above the ambient temperature. If the ambient temperature is 104°F, the typical PV module will operate in the 158-167°F range on hot sunny days during the solar peak period.

On the other hand, a PV module operating in cold, windy weather may have the heat removed from the module so rapidly that the sun never increases the module temperature more than a few degrees above ambient temperatures. With winter ambient temperatures as low as 40 degrees below zero, modules can operate at these temperatures.

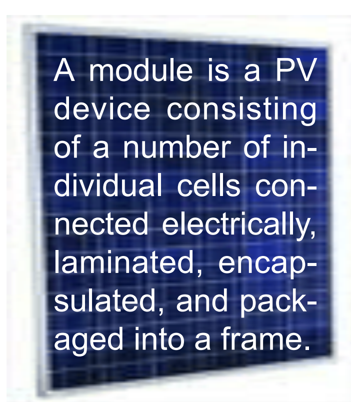
An unshaded roof with a "true south" orientation is often one of the premier sites for a solar-electric system.



Direct sunlight does NOT have to be shining on the module for voltage to be on the output terminals. Current may be extremely low, but nearly full voltage can be expected in dim light.

Photovoltaic (PV) modules have something in common with batteries, they both can supply power even at times when it is not wanted.

There is no way to turn off a PV module device, other than completely covering the top surface so that no light reaches the cells.

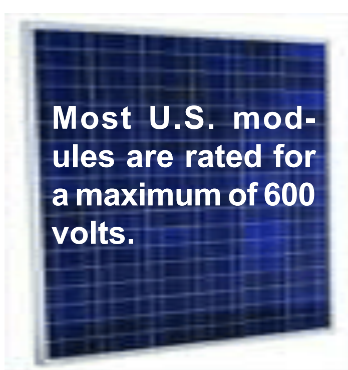


PV systems are low-density power generators, so large surface areas are required to produce appreciable amounts of power.

The required area for mounting an array is typically increased to account for spacing between modules, panels, or rows, for better access to all parts of the array.

Electrically, the voltage, current, and power output values are the most important considerations because they define the total number of modules needed to meet the desired energy production requirement.

Groups of modules are combined electrically and mechanically, typically first into strings, to achieve the desired array voltage. Strings of series-connected modules may be called panels or subarrays. Connecting modules into series strings before making parallel connections makes it easier to expand the array in the future, replace individual modules, and troubleshoot problems within the array.



The Roof

PV modules must be securely mounted to a supporting structure. Mounting holes are provided in the frames of PV modules, and have been tested under simulated high wind loads to ensure that the module can withstand normal and environmental conditions. The hardware used to attach modules to a racking system must be appropriately sized and also be weather-resistant. Stainless steel hardware is most commonly used. Hardware to secure PV modules to a building's roof must be robust and connect the mounting rack directly to the structural elements of the roof, such as the trusses or rafters. Attachment to only the roof sheathing will NOT provide adequate strength. All penetrations must be sealed with an appropriate sealant for the roofing material.

A PV array may add up to 10 pounds per square foot of dead weight to the roof structural members.

Added loads are particularly important for some of the heavier glass-on-glass modules, and on roofs that already have several layers of shingles.

Measure the angle of the roof for both wind-loading estimates and to determine if an elevated mounting rack will be needed.

The roof may be subjected to both uplift and down-force wind loads.

Standoff-mounted arrays are far the most common, and least expensive method for installing arrays. Standoff mounts allow air to circulate beneath the array, keeping modules cooler and reducing heat gain into the building.

Materials used for mounting hardware must be suitable for the ambient environment and compatible with other materials that may be in contact.

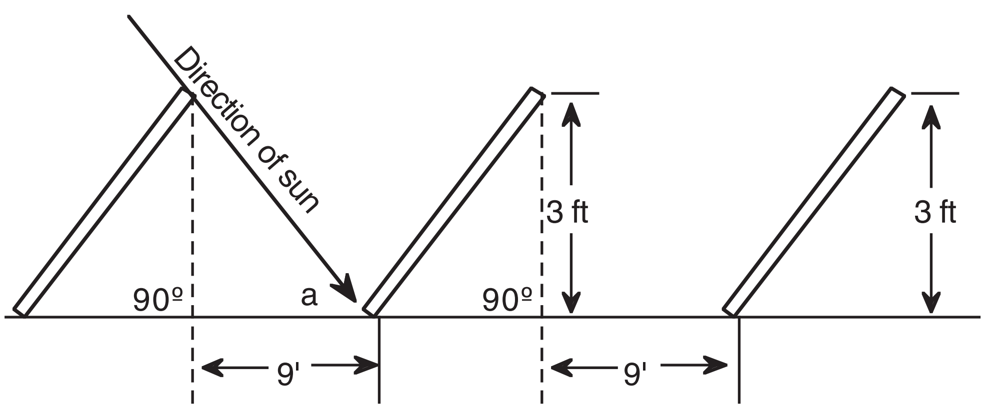
A common structural material used for commercial array mounts is corrosion resistant aluminum such as 6061 or 6063 alloy aluminum. **Aluminum develops a thin oxide coating very quickly, and this coating prevents further oxidation**. Anodizing can increase the corrosion resistance for aesthetics or for areas with extreme corrosion rates. Stainless steel is generally too expensive for structural members, even though it is highly resistant to oxidation. The combination of corrosion-resistant aluminum structural members and stainless steel fasteners is a practical solution to minimizing the cost while maximizing long-term structural reliability.

Maintenance? Basically, remove all sources of shade on the modules, and rinse the array to remove accumulated dust, dirt, and other debris such as bird droppings. Debris such as leaves collecting beneath and around the PV array should be removed to minimize the fire hazard risk. Squirrels have been known to cause damage to the insulation of exposed wiring.

Even electrical systems need to be maintained from time to time. With proper metering, an informed owner can easily determine if their PV system is operating properly or not.

For easiest maintenance access, a walkway should be provided between each row of modules. However, this consumes valuable roof area, so a balance needs to be made to the array. Often, only 50% to 80% of the roof area that has a suitable orientation can be used for mounting modules when room for maintenance, wiring paths, module replacement, etc. are taken into account.

Inter-row shading is when a row of modules shades an adjacent row of modules. A 6" shadow from an adjacent module is capable of shutting down a whole section of modules and can even shut down the entire PV system. A simple rule for minimum spacing between rows is to allow a space equal to 3 times the height of the adjacent module. In the southern half of the U.S., a closer spacing may be possible, but not less than 2 times the height of the top of the adjacent module.



Most standoff array mounts are designed so the support rails can be attached to the roof by brackets that can be lag-screwed into the rafters or trusses from the roof surface. For roofs with adequate attic access and when it is extremely difficult to mount standoffs from the roof surface, it may be necessary to install 2x6 blocking boards (spanners) in the attic between the roof trusses. The 2x6 boards provide 3" of wood into which a lag screw can penetrate.

The allowable withdrawal load is the force required to remove a screw by pulling in line with the screw without a twisting force. Pilot holes must be drilled for lag screws, typically in the range of 60-75% of the lag screw shank diameter.

The mounts need to be fastened solidly to the roof trusses or rafters, NOT to the roof decking.

Screw Diameter "	White Oak	Southern Yellow Pine	Douglas Fir	White Spruce
1/4"	381	281	232	192
5/16"	469	346	285	237
3/8"	538	397	327	271
Numbers represent pull-out strength in pound/inch of thread				

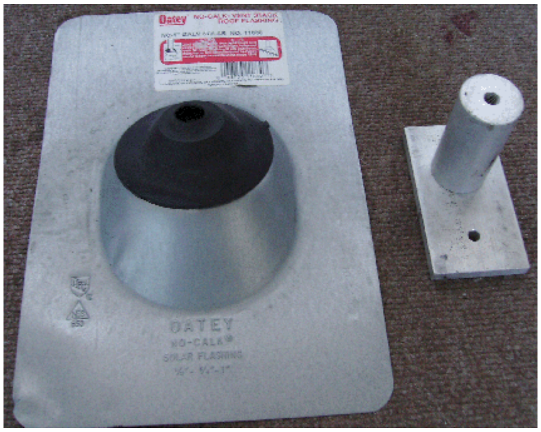
Local building codes may vary and each jurisdiction may have specific requirements.

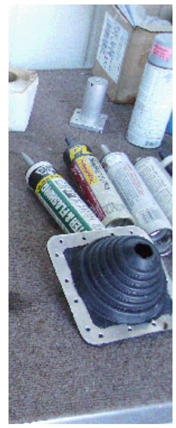
The minimum wind speed requirement in Florida is 100 mph (3-second gust).

Consult with a licensed professional for verification of the load requirements for your protection if this information is not provided by the system supplier.

Roof penetrations must be secure and weathertight. The weather sealing of attachments and penetrations through building surfaces should use accepted roofing industry practices and materials that meet or exceed the lifetime expectations for the PV system.

Polyurethane, elastomeric, butyl rubber, and asphalt-based compounds are some of the more popular sealants. Basic latex, acrylic, or silicon caulks are generally unacceptable, due to their tendency to degrade and lose adhesion to roofing materials.





Falls are the leading cause of deaths in the construction industry. Because most PV systems involve climbing ladders, or working on rooftops, it is essential that PV installers are familiar with OSHA fall protection regulations. OSHA requires that fall protection be used for walkways and ramps, holes and excavations, roofs, and wall openings where an employee or **worker can fall 6 feet or more**. Training is required on how to properly use Personal Fall Arrest Systems (PFAS), including the **anchorages**, lifelines and body harnesses.

Using a metal ladder in an environment that has electrical energy could result in electrical shock and cause the user to be thrown off the ladder.

Another danger of electrical shock is a person's reaction when shocked.

Aluminum is a good conductor of electricity. A fiberglass ladder is an insulator.

A metal ladder gives electricity a path to ground.

TRACKING SYSTEMS

Tracking mounts can increase the array output by 20 - 30% over a year. Tracking mounts are most cost effective in areas with minimal cloud cover.

An array on either a tracking mount or on a rack mount will be subject to a larger wind load.

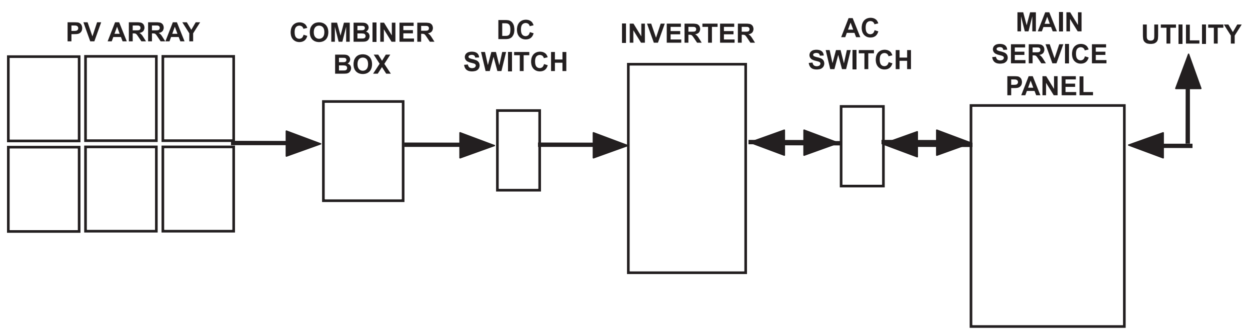
The initial cost and maintenance for a tracking system are the keys to evaluating the value of a tracking system relative to a fixed system.

Tracking systems require periodic maintenance if they are to deliver more energy than a fixed system.

When a PV array rack is located at ground level, normally the greatest concern would be physical damage to the array and wiring by vandalism.

The most cost-effective use of a two-axis tracking mount would be in areas of low wind, latitude greater than 30°, and minimal daytime summer cloud cover.

THE UTILITY - INTERACTIVE SYSTEM



95% of all PV systems being installed
are utility-interactive systems.

In most of the United States, a 167°F (75°C) temperature correction factor is suggested for conductors near PV modules that are mounted roughly 4" or less from a roof surface. However, 4" or less is NOT sufficient clearance to allow optimum airflow behind the modules mounted in an array.

Those conductors could be delivering energy for 40 years or more, so carefully applying these temperature-correction factors helps ensure that the insulation does not suffer premature degradation.

PV modules and mounting racks are typically made of aluminum and are NOT compatible with copper conductors.

Since PV modules operate in extreme outdoor conditions, there is always an abundance of ultraviolet (UV) radiation from the sunlight and wind, rain, snow and ice depending on the location. The Code allows single-conductor, insulated cables to be installed as connections between PV modules and from the modules to a **transition box** under the PV array, where a more conventional wiring system starts to the **combiner box**. The use of **wrong** conductors for **exposed** locations such as THHN/THWN, RHW, THW, or others that are **intended for use in conduit**, will result in rapid deterioration of these conductors that have no UV resistance. Conductors marked USE-2, with or without RHW-2 markings, should be used for exposed module interconnections. Newer cables marked "PV Wire," "PV Cable," "Photovoltaic Wire," or "Photovoltaic Cable" are coming to the market, and they too will be acceptable since they have a thicker jacket and superior sunlight resistance compared to USE-2. Where this new cable is used in conduit, the conduit fill will have to be calculated manually because of the thicker jacket.

Conductors permanently attached to the PV module are part of the listed module assembly and have been certified by UL as meeting the necessary safety requirements.

PV modules are typically connected in series strings. After making several connections, the positive and negative conductors at the ends of each string lie some distance apart, to bring these two points to a common location, a single conductor is used.

Transition Box

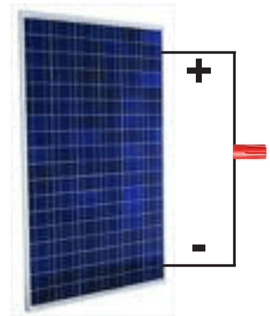
In general, these exposed, single-conductor cables, with attached conductors, will be longer than necessary when the modules are mounted side by side. The cables should NOT be allowed to droop, which could expose them to abrasion damage from wind and ice. Control this extra length by gathering the excess cable and connectors and fastening them to the module racks. Fastening hardware should be strong - stainless-steel pipe clamps in various sizes with EDPM rubber inserts are effective, but other options are available, including clips specifically designed to be used in conjunction with PV modules. Be wary of plastic cable ties - especially the white nylon variety - they do NOT resist heat and ultraviolet light exposure well.

WARNING LABEL ATTACHED TO SOLAR MODULE

WARNING
ELECTRICAL HAZARD

PLEASE OBEY THE INSTRUCTIONS MENTIONED BELOW FOR ACTUAL USE OF THIS MODULE.

BE CAREFUL IN HANDLING POLARITY OF INSULATED OUTPUT WIRES. NEVER TOUCH THE END OF THE OUTPUT WIRES WITH BARE HANDS WHEN THE MODULE IS IRRADIATED. COVER THE SURFACE OF THE MODULE BY SUFFICIENTLY THICK CLOTH OR SOMETHING SUITABLE TO PREVENT INCIDENT LIGHT, AND HANDLE THE WIRES WITH RUBBER GLOVED HANDS NOT TO RECEIVE ELECTRIC SHOCK. DO NOT DROP TOOLS OR HARD THINGS ON THE GLASS OF THE SOLAR MODULE. DO NOT SCRATCH THE BACK FILM BY HARD THINGS. DO NOT WEAR METALLIC JEWELRY WHICH MAY BECOME CAUSE OF ELECTRIC SHOCK DURING INSTALLATION. WHEN PART OF SOLAR MODULE IS SHADOWED A HOT SPOT MAY BE CAUSED. THEREFORE DO NOT SHADOW CELLS. INSTALL MODULES AND GROUND FRAMES IN ACCORDANCE WITH APPLICABLE LAW OF EACH COUNTRY. CONSULT THE GOVERNMENT OFFICE CONCERNED FOR PERMIT INSTALLATION AND INSPECTION REQUIREMENTS. PRODUCTS SHOULD BE INSTALLED AND MAINTAINED BY QUALIFIED PERSONNEL. ELECTRO-OPTICAL CHARACTERISTICS DEGRADE WHEN GLASS BECOMES DIRTY. DO NOT POUR LIQUIDS ON MODULES WHEN CLEANING. DO NOT PRODUCE SPARKS NEAR FLAMMABLE VAPORS. FOLLOW SAFETY PRECAUTIONS OF THE BATTERY MANUFACTURER IF BATTERIES ARE USED WITH MODULES. DO NOT EXPOSE MODULE TO CONCENTRATED SUNLIGHT WITH MIRRORS, LENSES OR OTHER SIMILAR MEANS. CONSULT MANUFACTURER FOR PROPER INSTALLATION ON SPECIAL VEHICLES SUCH AS BOATS AND CAMPERS. KEEP MODULE AWAY FROM CHILDREN.



A photovoltaic module will produce its maximum current when there is essentially NO resistance in the circuit. This would be a short circuit between its positive and negative terminals.

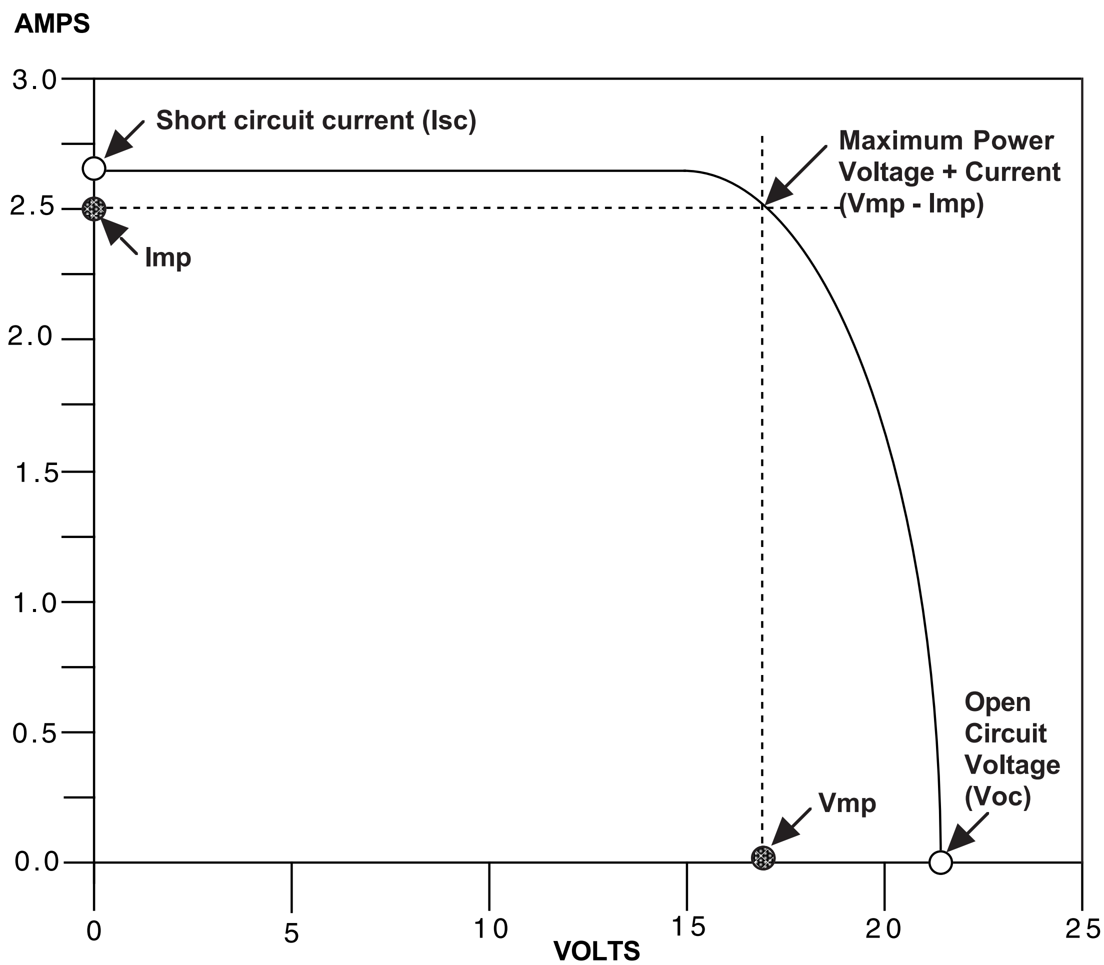
This maximum current is called the **short circuit current**, abbreviated Isc. When the module is shorted, the voltage in the circuit is zero.

Conversely, the maximum voltage is produced when there is a break in the circuit. This is called the **open circuit voltage,** abbreviated Voc. Under this condition, the resistance is infinitely high and there is NO current, since the circuit is incomplete.

These two extremes in load resistance, and the whole range of conditions in between them, are depicted on a graph shown below called a I-V (current-voltage) curve. Current in amps is on the vertical axis. Voltage, in volts, is on the horizontal axis.

As you can see in the graph, the **short circuit current** occurs on a point on the curve where the voltage is zero. The **open circuit voltage** occurs where the current is zero.

A Typical Current-Voltage Curve



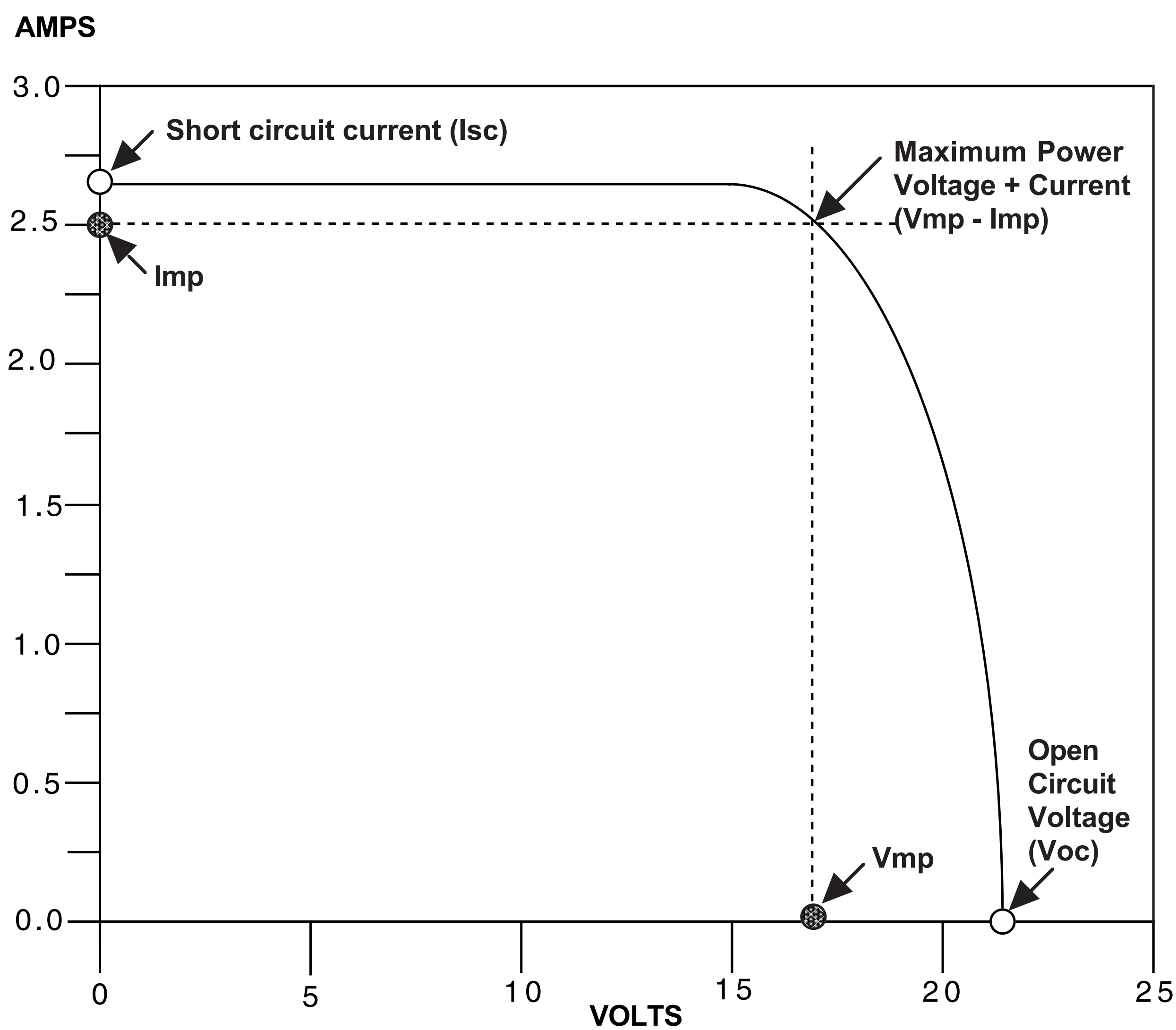
At the **short circuit current** point, the power output is zero. At the **open circuit voltage** point, the power output is also zero, but this time it is because the current is zero.

There is a point on the "knee" of the curve where the maximum power output is located. This point is where the voltage is 17 volts, and the current is 2.5 amps. The maximum power is 17 volts x 2.5 amps = 42.5 watts.

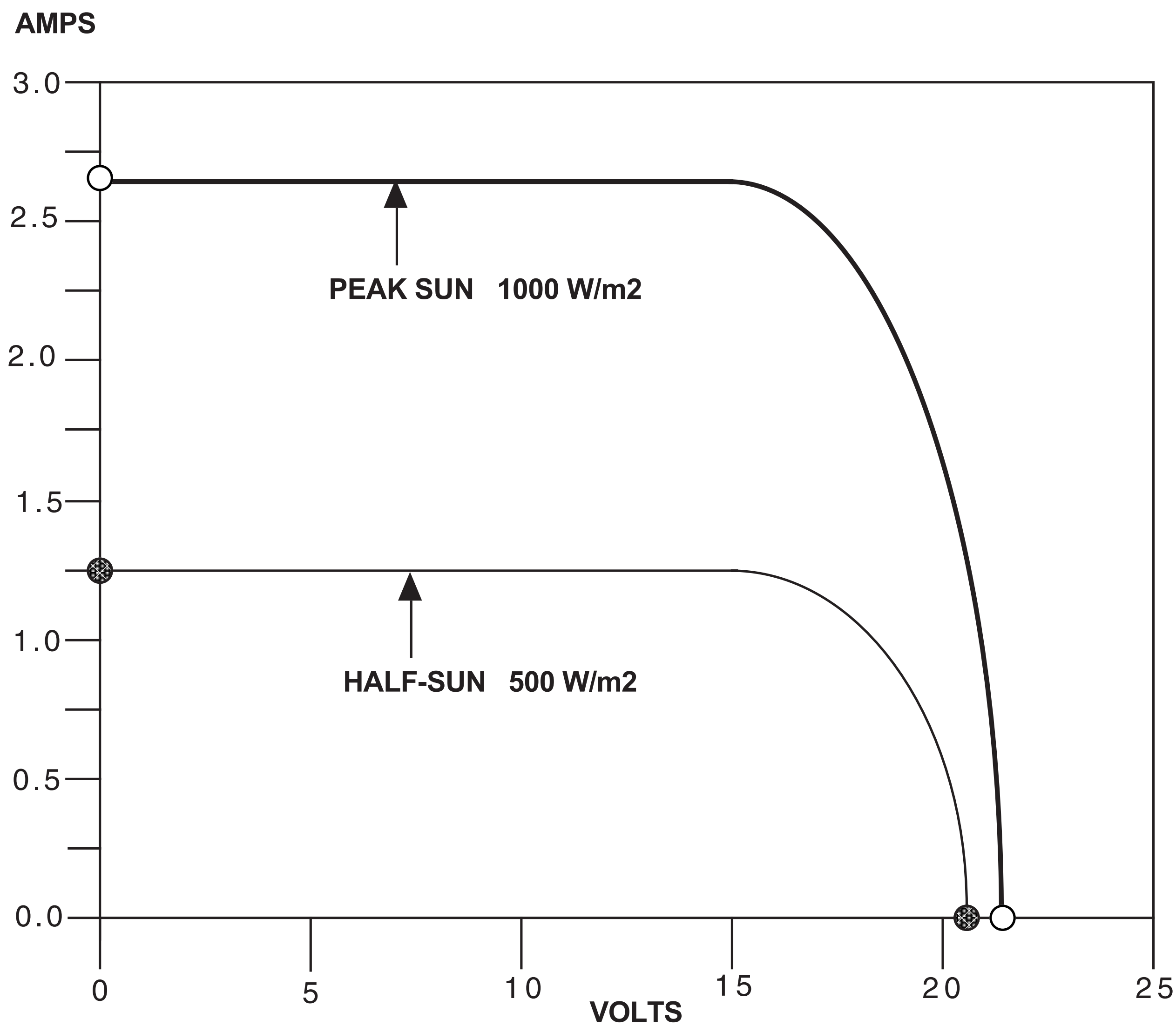
The power (watts), at the maximum power point is described as "maximum" or "peak" among other terms. Maximum power is abbreviated Imp.

The current-voltage (I-V) curve is based on the module under standard conditions of sunlight and module temperature. It assumes there is NO shading on the module.

A Typical Current-Voltage Curve

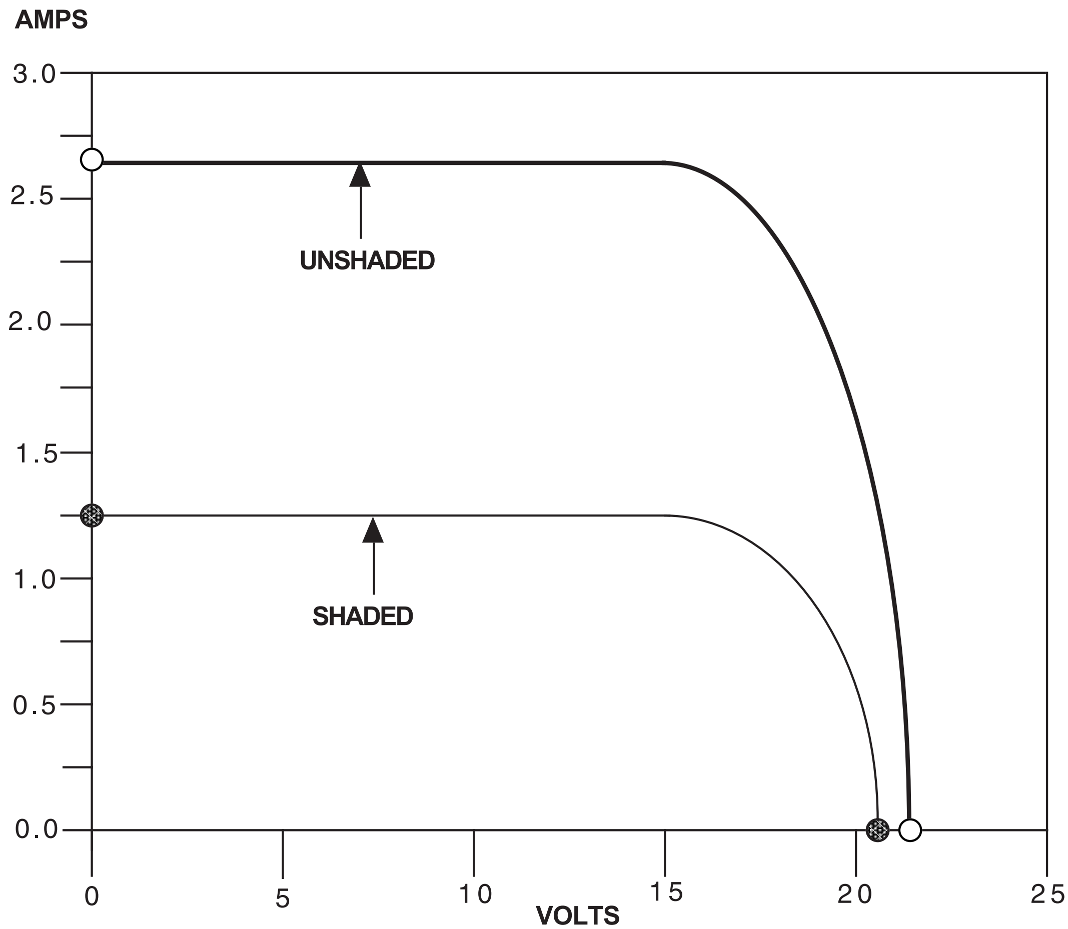


Standard sunlight conditions on a clear day are assumed to be 1,000 watts of solar energy per square meter or **11 square feet**. This sometimes is called "**peak sun**." Less than the peak sun will reduce the **current output** of the module by a proportional amount. If only one-half sun (500 watts per square meter) is available, the amount of current is roughly cut in half.



Because photovoltaic cells are electrical semiconductors, partial **shading** of the module will cause the shaded cells to heat up. They are now acting as inefficient conductors instead of electrical generators. Partial shading may ruin shaded cells.

Partial module shading has a serious effect on module power output. For a typical module completely shading only one cell can reduce the module output by as much as 80%. One or more damaged cells in a module can have the same effect as shading.



Module temperatures affect the output voltage inversely. Modules should NOT be installed flush against a surface. Air should be allowed to circulate behind the back of each module so it's temperature does NOT rise and reduce its output. An air space of 4-6" is usually required to provide proper ventilation.

THE COMBINER BOX

A combiner box is a PV junction box.

It is a normal practice to connect modules in series (**called a source circuit**) to get the proper voltage and then connect each series string of modules in parallel through a PV combiner box to increase the current to get the desired power level (watts). These combiners usually contain fuses or circuit breakers that are required to protect the conductors from the modules from fault currents and the individual modules from reverse currents. The reverse currents may originate from parallel-connected strings of modules, from reverse currents from batteries if the system has batteries, or from backfeed currents from a utility-interactive inverter. The ratings of the fuses or breakers must be consistent with the ampacity of the conductors connecting the modules and the maximum series fuse marked on the back of the module. The combiner might be viewed as a branch circuit load center connected in reverse acting like a PV source panel.

To connect multiple strings to each DC input terminal, you will need one or more string combiners. A string combiner, connects a number of strings in **parallel**, protects each string with an overcurrent fuse or circuit breaker and combines the strings into a single unit. This output will then be connected to one of the DC inputs on the inverter.

The PV source-circuit combiner is found on **larger residential systems and on most large commercial systems**. PV systems that have a DC rating above about 6 kW may have sufficiently large numbers of modules that more than 2 strings of modules are required to get the desired array power. Since module voltages range widely and module power ratings can vary from 40 watts to 300 watts, there are no hard and fast rules relating the need for a DC combiner to a specific number of modules in an array.

The rated output voltage of the PV modules and the inverter DC input characteristics determine how many modules may be connected in a series string. The power rating of each module and the power rating of the inverter determine **how many strings** can be connected in parallel. Normally 2 strings can be connected in parallel without requiring a combiner box containing overcurrent devices.

690.9 Overcurrent Protection.

Article 690 is one of the fastest changing parts of the NEC due to the ever growing popularity and rapid advancement of PV technology. The exam could be based on the 2017, 2020, or 2023 NEC. this book is based on the 2023 NEC

690.9(A) Circuits and Equipment. PV system dc circuit and inverter output conductors shall be protected against overcurrent. Circuits sized in accordance with 690.8(A)(2) are required to be protected against overcurrent with overcurrent protective devices. Each circuit shall be protected from overcurrent in accordance with 690.9()A)(1), (A)(2) or (A)(3).

690.9(B)(1). Overcurrent devices shall be rated not less than 125% of the maximum currents calculated in 690.8(A).

Informational Note: Some electronic devices prevent backfeed current, which in some cases is the only source of overcurrent in PV system dc circuits.

If the PV system consists of a single string of modules (or possibly two strings of modules) and is directly connected to the load **without battery storage** or other source of overcurrent, then **NO overcurrent protection is required** if the conductors are sized at 156% of the short-circuit current.

Some utility-interactive inverters are NOT capable of back feeding utility currents into the faults in the PV array. With these inverters, one, two, and possibly more strings of modules may be connected to the inverter with **NO** overcurrent device at the inverter input.

Fuses are generally required in the DC sections of a utility-interactive PV system for 2 reasons. First, all ungrounded conductors must be protected from overcurrents. Second, each PV module must be protected from reverse currents that exceed the value of the module protective fuse that is marked on the back of the module. Overcurrents may result from a short circuit in the wiring, and reverse currents may result from either a short circuit or a shaded module or modules. In most cases, a single overcurrent device will satisfy both of these requirements and, **in many small residential PV systems, NO overcurrent device is required at all**.

These overcurrent devices are required **only** when there are sources of overcurrents that could damage either the wiring or the module during shading or fault conditions. In the utility-interactive PV system, with a listed inverter, the only source of currents or overcurrents in the DC part of the system originate in the modules themselves. The inverter is NOT able to provide any current into the DC PV array, so it is not a source of currents other than a short transient current as the input noise filtering capacitors discharge.

In a single string of PV modules (a series connection of several modules), the only current in question is the current generated by the modules in the string. This current is, at a worse-case maximum, 125% of the rated module **short-circuit current** (Isc) marked on the back of the module. All circuit conductors will be sized at **156.25%** of the same short-circuit current. Therefore, the conductors have NO source of high overcurrents that would exceed their ampacity and they do NOT need overcurrent protection. Currents generated within a string of modules can**not** produce reverse currents in that string and, since there are no external sources of currents, no overcurrent device is needed to protect the PV module. The result is that in a utility-interactive PV system with a **single string** of modules, NO overcurrent device is needed in the DC circuit.

When there are 2 strings of modules, it is possible for one string to attempt to force currents back into the other string when that string is **shaded**. The unshaded string can produce up to 125% of the rated short-circuit current. All wiring in each string is sized at **156.25%** of that same current so NO overcurrent devices are required to protect the module wiring. Most PV modules have a marked, module-protective fuse that is well in excess of the **156.25%** of the rated **short-circuit current**, so again, there is NO requirement for an overcurrent device to protect the modules. With 2 strings of modules connected in parallel, NO overcurrent device is needed in the DC wiring.

When 3 or more strings of modules are connected in parallel, the situation may be different and a calculation must be made. If we assume that one string of modules is shaded, then the 2 unshaded strings of modules may attempt to force reverse current into the shaded string. Each of the unshaded strings can source up to 125% of the rated short-circuit current, so 2 strings can source up to 2 x 125% = 250% of the rated short-circuit current. If this 250% current is greater than the value of the maximum module protective fuse marked on the module, then an overcurrent device must be installed in the ungrounded conductor of each string, and the value will typically be **1.56 Isc** or larger, up to the value of the maximum protective fuse. A minimum value of **1.56 Isc** will protect the module from reverse currents and will also protect the conductors that have also been sized at **1.56 Isc**. If a larger value of series overcurrent protective devices is used (up to the allowed maximum protective fuse value), the ampacity of the conductors connecting the modules must be adjusted accordingly.

When there are more than 3 strings, the same calculation applies. Just take the number of strings in parallel and subtract one. Use this number times 1.25 x Isc to get a number that will be compared to the value of the module protective fuse. If the calculated number is larger than the protective fuse value, then one overcurrent device will be required on each of the series-connected strings of modules. The overcurrent devices are usually mounted in a DC combiner box.

While PV modules produce volts, amps, and watts, they are considered to be **current sources** and operate differently than the normal **voltage sources** commonly experienced in the 120/240 volt AC circuits.

A voltage source can have very high available short-circuit currents. If it were not for the overcurrent devices in the load centers and main disconnects, the typical utility transformer feeding a residence could deliver short-circuit currents approaching 10,000 amps. The larger 480 volt AC transformers can deliver even higher short-circuit currents. A typical 12 volt battery can send several thousands of amps into a short circuit.

PV modules as current-limited current sources have a **limited** capability to produce high currents. A typical 208 watt PV module might have an operating current of 7.5 amps and be able to **deliver a short-circuit current of only 8.1 amps**. The amount of current a single PV module can deliver is limited by the size of the cells in the module, the method of internal wiring, and the brightness of the sunlight falling on it.

On most modules, the short-circuit current at STC will be only 10-15% higher than the operating current.

When modules are connected in **series** to form a string of modules, the operating and short-circuit currents do NOT change. However, the voltage that each module produces does add up in the string and **many typical residential systems operate with voltages in the 400 to 600 DC volt range**.

PV systems can and do operate over 480 volts DC, but unlike a 480 volt AC feeder (a voltage source) the available short-circuit current in a typical residential system will be less than 10 to 20 amps compared to 10,000 amps AC. At this DC voltage, shock hazards definitely exist, and arcs are possible, arc-blast hazards are NOT possible since the available current is insufficient to produce them. However, even in residential systems, installation errors can result in damaged equipment. **Arcs** involving direct currents (DC) are somewhat more difficult to extinguish than arcs in alternating currents (AC) because the DC arcs do not self-extinguish 120 times per second as AC arcs do.

Fortunately, most residential PV systems rated at power levels of 2,500 to 5,000 watts have DC currents in the 5 to 15 amp range and are proportionately less dangerous from an arcing point of view.