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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.

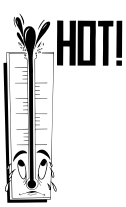
Section 90.2(B) Adequacy. Compliance therewith and proper maintenance in an installation that is essentially free from hazard ***but not necessarily efficient***.

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.

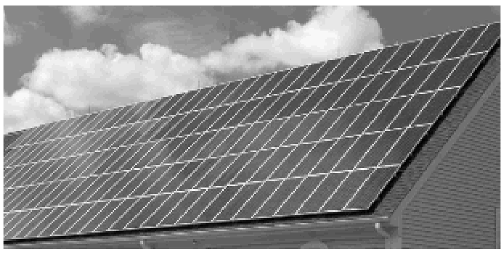
Excessive **heat** can cause problems as the modules now with a lower voltage may not meet the minimum DC voltage required to start the inverter.

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.

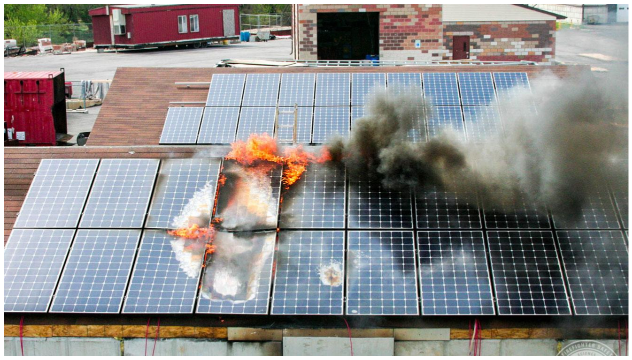
How can you inspect them when mounted close to the roof?

•**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.

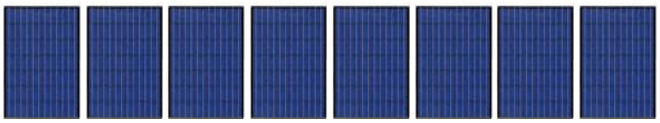
"Personal fall arrest system" means **a system used to arrest an employee in a fall from a working level**. It consists of **an anchorage**, connectors, a body belt or body harness and may include a lanyard, deceleration device, lifeline, or suitable combinations of these.

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

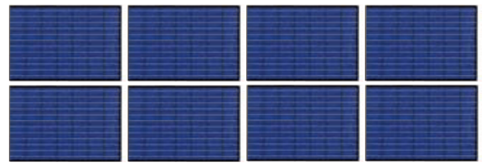
As a rule of thumb, crystalline modules with 10% efficiency will generate about 10 watts per square foot of illuminated module area.

By multiplying the usable and available roof area in square feet by 10, the size of the PV array (in watts) that can be installed can be estimated. Example, a roof with dimensions of 16' by 55' = 880 sq.ft. x 75% (for access) = 660 sq.ft. x 10 watts per sq.ft. = 6,600 watts or 6.6 kW.

Portrait orientation



Landscape orientation



PV source and output circuits get their voltage directly from series connected solar cells which increases voltage. **Cold** temperatures also increases voltage.

PV output circuits are PV source circuits connected together in parallel at a dc combiner. Since voltage is determined by series connections and not parallel connections, PV output circuits have the same voltage as the PV source circuits that are combined to make the PV output circuit.

ARRAY EXAMPLE

A 4 kW residential system at 130% = 4,000 watts x 130% = 5200 watts. By using a 205 watt panel this would require a minimum of 26 panels (5200w ÷ 205w = 25.36 panels).

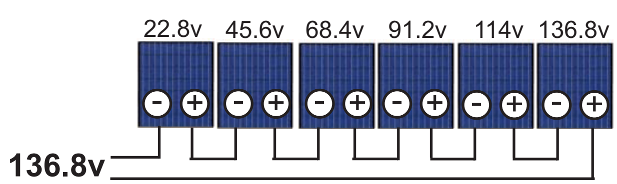
This example will have **28** panels @ 205 watts each.

28 x 205 watt modules = 5,740 watts 5.74 kW

Name plate on back of module

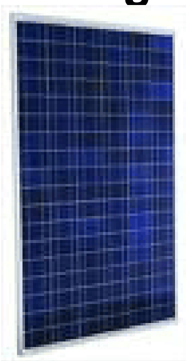
Name plate	
205 watts	**18.4 volts x 11.15 amps = 205 watts**
Vmp = 18.4 volts	**Vmp = Maximum Power Voltage**
Imp = 11.15 amps	**Imp = Current Maximum Power**
Voc = 22.8 volts	**Voc = Voltage open circuit**
Isc = 12.10 amps	**Isc = Short-circuit current**

When modules are connected in series the **open-circuit** voltage adds, but the **short-circuit current** remains the same at 12.10 amps. With just 6 modules connected in series you have already reached over 120 volts.



In reality, the power produced varies depending on how much sunlight is hitting the panels, what the ambient temperature is, and several other variables. On a cool day with high irradiance, the panel may actually produce more than its “maximum” power.

Voltage



The voltage of a solar panel is not fixed, and will vary depending on the intensity of the sunlight hitting the panel. It is also heavily affected by temperature. As the temperature of the cells in a panel increase, the voltage decreases. This also causes the power output of the module to decrease. The amount that the voltage changes with each degree change in temperature is called **temperature coefficient**, and **can be found on the solar panel datasheet**.

A solar panel datasheet will give several different voltage values. The two main ones are:

Voc (at STC) – Solar Panel open-circuit voltage at STC. This is the voltage the solar panel can be expected to show across its terminals when it is not connected to any other device, under standard test conditions (STC). This value is used in string length calculations.

Vmpp (at STC). Solar Panel voltage at the maximum power point. The maximum voltage the panel will produce at STC when connected to an inverter with maximum power point tracking (MPPT).

When solar panels are connected in **series** into what are called **strings**, their voltages are added together. When they are connected in **parallel**, the voltage stays the same.

The total voltage of a string must not go over the maximum voltage allowed at the input of the inverter or charge controller being used. The solar panels themselves also have a maximum system voltage that must not be exceeded. Typically the maximum voltage of the system is either 600V or 1000V (or 1500V in utility-scale systems).

Typically residential systems will be 600V. The NEC sets this as the legal limit for dwellings with 1-2 families.

Note that 1000V solar panels can still be used in a 600V system. This is the maximum voltage they are designed to handle, so the 600V system will stay well below their maximum.

When solar panels are connected to an inverter or charge controller, and are exposed to sunlight, current will flow. The higher the irradiance hitting the module, the higher the current it will produce.

In solar, current is important for sizing the cables and protection equipment (fuses and circuit breakers). As electricity is fed through cables, they heat up. If more current is fed through a cable than it is designed for, perhaps due to a fault, it can get too hot and be damaged or start a fire. To prevent this, fuses or circuit breakers are used which break the circuit before the current can go above the limits of the cable.

Two important solar panel currents to be aware of are Isc and Impp.

Isc (at STC) – Short circuit current at STC. This is the amount of current that can be expected to flow when the positive and negative leads of the panel are connected together under standard test conditions. It is the maximum current that the panel can be expected to produce under STC.

Impp (at STC) – The maximum current a solar panel will produce at STC when connected to an inverter with maximum power point tracking (MPPT).

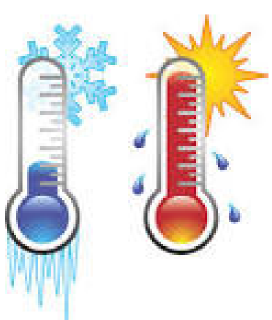
One aspect of designing a solar PV system that is often confusing, is calculating how many solar panels you can connect in **series per string**. This is referred to as **string size**.

String size is important, because if you connect too many panels per string, you run the risk of **damaging your inverter**. On the other hand, if you have too few panels per string, **the inverter may shut off during the hottest days** of the year, **meaning you miss out on valuable generation time**.

Calculating string size when using string inverters or charge controllers. If you are planning to use DC optimizers or Micro-inverters in your system then this information does not apply. Optimizers and micro-inverters have specific rules around how many panels can be connected to them, and how they can be connected together. **The rules vary between manufacturers and components, and can be found in the manufacturer design guidelines and product datasheets**.

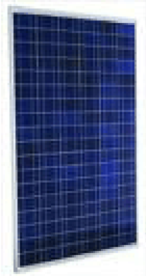
The **maximum number of solar panels** you can connect in a string is determined by the maximum input voltage of your inverter or charge controller. You can find this value on the inverter datasheet.

If the maximum input voltage of your inverter is exceeded on a **cold** day, the inverter can be damaged. Even if the inverter is not damaged by over voltage, having too many panels in a string may void the inverter warranty, so that you are not covered for other inverter issues.



To make sure you don't exceed the maximum voltage of your inverter, the first thing you need to understand is how the **voltage of the solar panels changes with temperature**.

Voltage



Remember, the voltage of a solar panel is not fixed. As the temperature of a panel increases (heat), its voltage decreases, and **as its temperature decreases (cold), its voltage increases.**

The rate at which the **open circuit voltage** of a solar panel will change as its temperature changes is defined by the **Temperature Coefficient of Voc**. You can always find this value on the solar panel datasheet.

The temperature coefficient will be given in %/°C, (**percentage per degree celsius**). That is, is the percentage that **Voc will rise**, for every degree celsius the temperature of the panel **drops**. Table 690.7 of the NEC requires a correction factor for ambient temperatures below (**cold**) 25°C (77°F).

For example, if you have a solar panel that has a Voc (**at STC**) of 40V, and a **Temperature Coefficient of 0.27%/°C**. Then for every degree celsius **drop** in panel cell temperature, **the voltage will rise** by: 40V x 0.27% = 0.108V

Since STC is at 25°C, **then at 24°C, the new Voc would be 40.108V.**

Example: Assume you had the following values:

Voc (STC): 41.5V
Temperature coefficient of Voc : -0.26 %/°C
Expected low temperature: -5°C

First, find the difference between STC temperature (25°) and your expected low temperature

25°C – (-5°C) = 30°C

Multiply this by the temperature coefficient. 30°C x 0.26% = 7.8%

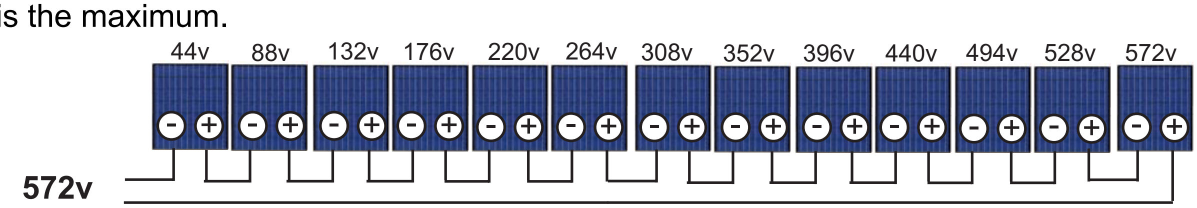
Now increase Voc (STC) by this percentage 41.5V x 7.8% = 3.237v + 41.5 = 44.73v

Once you have the max Voc of one panel, all you have to do is divide your inverter maximum voltage by this value, and then **round down** to the nearest whole number.

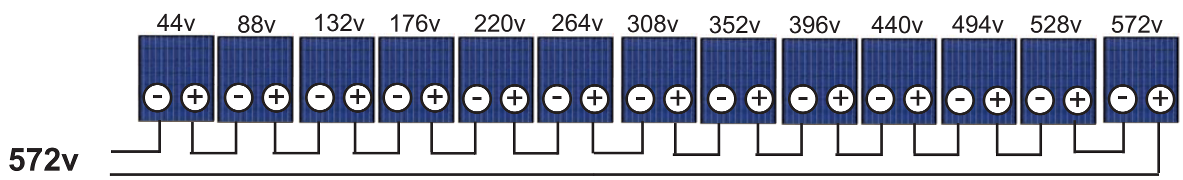
For example, using the example above with a **600V inverter**:

600V ÷ 44.737V = 13.41 panels   13 panels x 44 volts per panel **572 volts**.

So this means if you connected 13.41 panels to your inverter you would be right at the inverter's 600 voltage limit. Now obviously you can't have 0.41 of a panel, so you always round down to the nearest whole number. In this case, 13 panels per string is the maximum.



Now that you know what the **maximum string size** you can have is, you also need to calculate the minimum string size. Safety and inverter warranty are not a concern here like with maximum string size, but your inverter has a minimum **input voltage of 600 volts** which it can run at, and you want to make sure your inverter will continue to run on the hottest days of the year, or else you will be losing valuable generation.



Example: Connected in one **series** string. Voltage = 28 modules x 22.8 volts = **638.4 volts.**

As temperature drops (cold), voltages increase. To avoid damaging equipment, design voltage needs to stay below an inverter's maximum input voltage, you run the risk of damaging the inverter with high voltage as well as the voltage rating of wiring, switchgear, and overcurrent devices.

Table 690.7(A) of the NEC requires a correction factor for ambient temperatures below (cold) 25°C (77°F). Multiply the **rated open circuit voltage** by the correction factor.

The rated **open circuit voltage** is **22.8v** x 28 modules = **638.4 volts**. In Central Florida with a record cold of **14°F** the correction would be 638.4v x **1.14 (Table 690.7(A)** = **727.7 volts**. Which **exceeds** the 600 volt maximum permitted on the residential PV system wiring, etc.

Table 690.7(A) Voltage Correction Factors for Crystalline and Multicrystalline Silicon Modules.

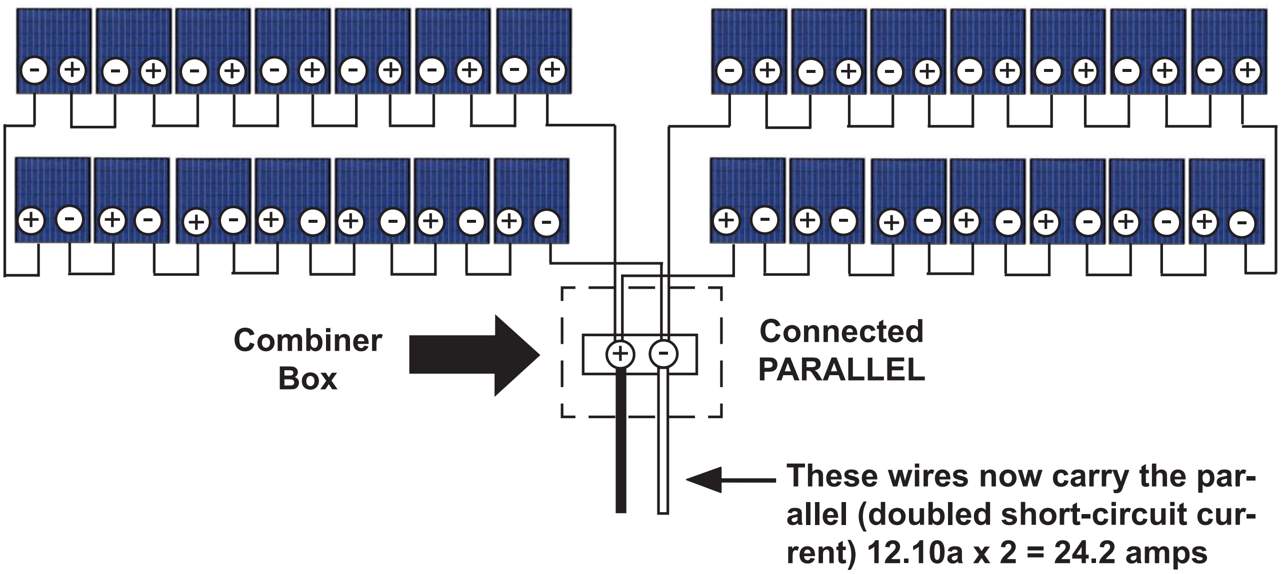
Correction Factors for Ambient Temperatures Below 25°C (77°F). (Multiply the rated open circuit voltage by the appropriate correction factor shown below.)

Ambient Temperature (°C)	Factor	Ambient Temperature (°F)
24 to 20	1.02	76 to 68
19 to 15	1.04	67 to 59
14 to 10	1.06	58 to 50
9 to 5	1.08	49 to 41
4 to 0	1.10	40 to 32
-1 to -5	1.12	31 to 23
-6 to -10	1.14	22 to 14
-11 to -15	1.16	13 to 5
-16 to -20	1.18	4 to -4
-21 to -25	1.20	-5 to -13
-26 to -30	1.21	-14 to -22
-31 to -35	1.23	-23 to -31
-36 to -40	1.25	-32 to -40

But, since parallel connections of strings do **NOT** affect the open-circuit voltage, the number of **strings connected in parallel** should be considered for the short circuit current.

By connecting two series strings **in parallel** the 638.4 volts **is now half**, 319.2 volts and the **current is doubled**, 11.15a x 2 = 22.3 amps.

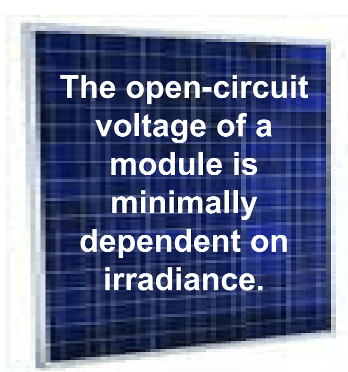
The maximum system voltage is 319.2 x 1.14 (T.690.7(A) = **363.8 volts**

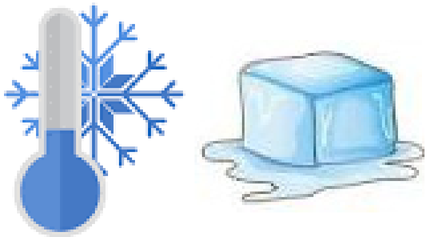


Name plate on back of module

205 watts
Vmp = 18.4 volts
Imp = 11.15 amps
Voc = 22.8 volts
Isc = 12.10 amps

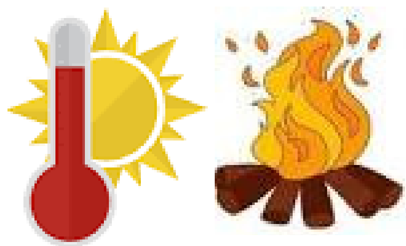
Isc = Short-circuit current



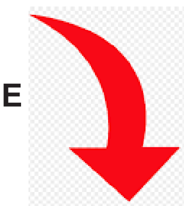


COLD INCREASES VOLTAGE

Table 690.7(A) shows the correction factors for temperatures **below** 25°C (77°F). If the temperatures are **ABOVE** 25°C (77°F) **a correction is also necessary**.



HEAT DECREASES VOLTAGE



The maximum power voltage and maximum power current are the module voltage and current levels for which the module delivers the maximum possible power for a given irradiance and temperature level. **As the module temperature increases (heat)**, the module current increases slightly while the **maximum power voltage (V_{mp}) decreases** by a ***Temperature Coefficient*** approximately **0.5% per °C**, resulting in a **maximum power decrease** of approximately **0.5% per °C.** Conversely, as the temperature of the module **decreases**, the voltage and power **increase** by approximately **0.5% per °C**. Crystalline silicon-based PV modules achieve their highest voltages at the lowest temperatures.

Module cell temperature **is rarely** at STC (**Standard Test Conditions**) temperature of **(cold) 25°C** (77°F) and an irradiance of 1000w/m^2 at the same time. An operating cell temperature of (**heat)** 50°C (**122°F**) is more common. Modules that lose **.5% per °C**, this corresponds to a typical performance that is 12.5% below the value tested under STC.
50°C - 25°C x ***Temperature Coefficient* .5%°C** = 12.5%

Example: If the maximum power voltage of a crystalline silicon PV module is 17.1 volts at STC, then at 50°C (heat) (122°F) (module temperature) and 1000W/m^2 incident on the **module**, the maximum power voltage of the module will be closest to ____ volts.

Solution: *50°C - 25°C = 25°C x* ***.5*** *= 12.5%*
17.1v x 12.5% = 2.1375 or 2.14 *17.1v - 2.14 v = 14.96 or* ***15 volts***

The Temperature Coefficient of Voc, you can always find this value on the solar panel datasheet.

Most solar PV modules have a temperature coefficient of around **-0.3% to -0.5%.**

Typically, solar panels based on monocrystalline and polycrystalline solar cells will have a temperature coefficient in the -.44% to -.5% range. Sunpower (Monocrystalline) does the best in this regard with a temperature coefficient of –0.38%.

The reason for the misuse of the table comes from not reading the heading which states the ampacities shown for the various conductors are correct if you don't: (1) install over three current carrying conductors in a raceway or cable (2) exceed 30°C or 86°F in ambient temperature.

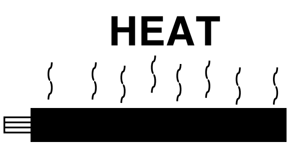
(1)

Table 310.16. Ampacities of Insulated Conductors Rated 0-2000 Volts,
60° to 90°C (140° to 194°F) **Not more Than Three Conductors in Raceway or Cable or Earth** (Directly Buried),
Based on Ambient Air Temperature of 30°C (86°F).

(2)

Common sense would remind you that normally you are installing more than three conductors in a conduit and also the surrounding temperature of these conductors would be above 86°F. The **normal** ampacities listed in the table must be corrected if either condition (1) or (2) is present.

The conductor ampacity is the current carried **continuously** without increasing the temperature of its insulation beyond the danger point. The conductor ampacity varies with the type of insulation and the method of installation.



Except for mechanical abuse, the greatest hazard that conductors must endure is **heat**. Conductor insulation can be damaged by excessive heat in various ways, depending on the type of insulation and the degree of overheating. Continued exposure to excessive heat causes insulation to become soft, perhaps to melt, and in extreme cases to burn.

This heat comes from two sources: From the ambient air surrounding the conductors or from the current the conductors must carry. There is a point where an increase in current causes excessive heat even though conducting materials such as copper or aluminum have a low resistivity.

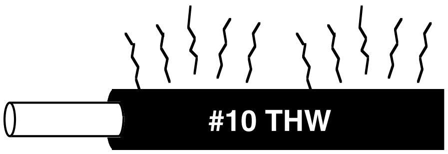
For many years natural rubber was used to insulate conductors, but age along with heat caused such rubber insulation to dry out, to crack, and to become brittle. Today we have better quality rubber and thermoplastic materials that not only permit thinner insulation on conductors but also withstand temperature better resulting in higher ampacities of conductors.

The maximum temperature permitted for conductor insulation is called the **temperature rating** of the conductor. **Table 310.16** shows the **maximum** temperature that the insulation type is permitted to reach. That maximum temperature will be reached when a conductor is loaded to its full ampacity in an ambient temperature of 30 degrees C or 86 degrees F.

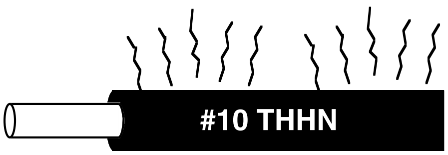
The type letter on the insulation indicates its insulation, maximum operating temperature, and application provisions.

RHW insulation, the "R" indicates rubber insulation. The "H" indicates 75°C - 167°F maximum operating temperature (insulation rating). The "W" indicates moisture resistant.

THHN insulation, the "T" indicates thermoplastic insulation. The "HH" indicates 90°C - 194°F maximum operating temperature (insulation rating). The "N" indicates nylon covering.



The #10 THW has a maximum operating temperature of 75°C which is 167°F.



The #10 THHN has a maximum operating temperature of 90°C which is 194°F. A "HH" rated insulation will allow more heat to be dissipated faster than an "H" rated insulation thus raising the ampacity (the current the conductor can carry safely without damage).

The maximum operating temperature is the insulation rating of the conductor and must not be exceeded. Proper designing is a very important factor.

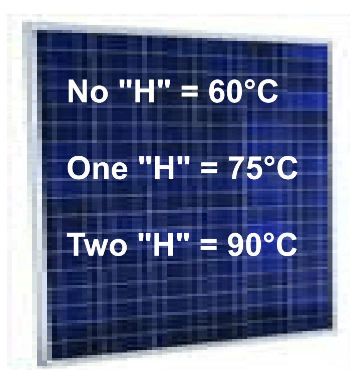
You must first understand what words mean; such as ampacity, ambient temperature, insulation rating, etc.

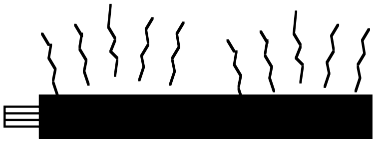
#10 TW 30 ampacity
60°C - 140°F temperature rating

A #10 TW conductor has an ampacity of 30 amperes. The insulation rating is 60°C or 140°F.
This does *not* mean that a TW insulation can be installed where the ambient temperature reaches 140°F.

What this means is: If a #10 TW conductor is loaded to the allowable ampacity, 30 amperes in an ambient that has a temperature of 30°C or 86°F, the temperature of the *insulation* will reach 60°C or 140°F.

Table 310.16 the table of ampacity is aimed at designating a level of current that will permit the conductor to reach its thermal limit, but not exceed it.

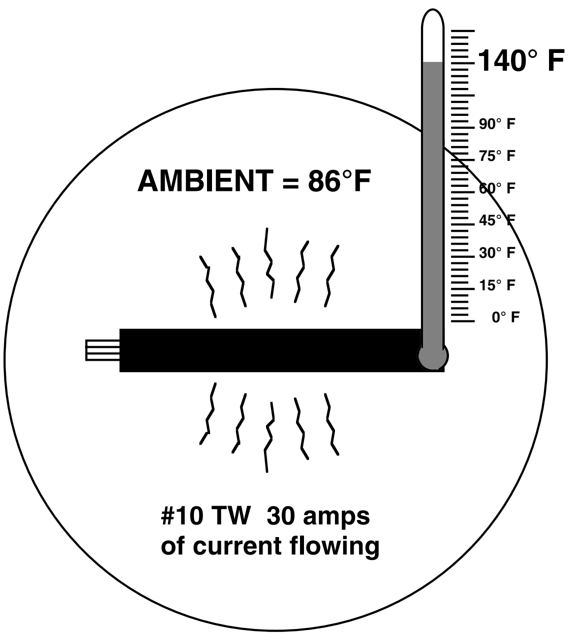




#10 TW 30 amps
of current flowing

The 30 amps of current flowing produces heat in the conductor which must dissipate through the insulation to the ambient.

With the ambient temperature at 86°F and with 30 amperes of current flowing through the conductor, a thermometer placed on the *insulation* would read 140°F which is maximum operating temperature for this type insulation (TW).



For a #10 TW conductor, any current above 30 amps or any ambient temperature above 86°F will cause insulation damage, as you will exceed the maximum operating temperature of the conductor; 140°F.

Maximum operating temperature = Full ampacity at 86°F.

140°F - 86°F = 54°F for the 30 amperes of current flow in the #10 TW conductor.

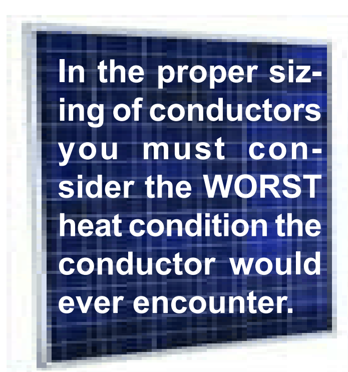
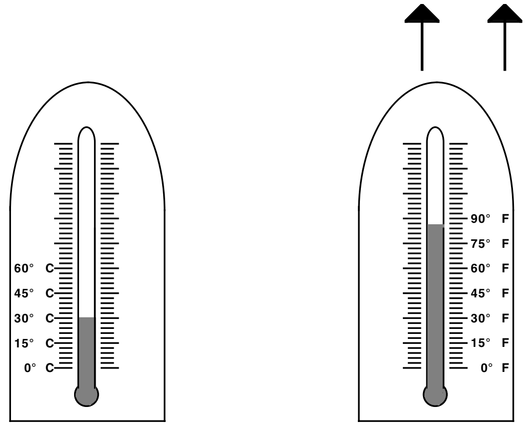


Table 310.16. Ampacities of Insulated Conductors Rated 0 -2000 Volts,
60° to 90°C (140° to 194°F) Not more Than Three Conductors in Raceway or Cable or Earth (Directly Buried),
Based on Ambient Air Temperature of 30°C (86°F).



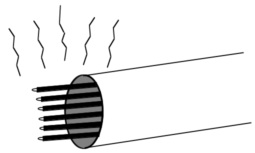
30°C **86°F**

For ambient temperatures above 30 degrees C or 86 degrees F **multiply** the **ampacities** by the appropriate correction factor shown below. Remember, correction factors change with different temperatures and different **types of insulations**.

Article 690 Solar Photovoltaic Systems has it's own Table 690.31(A)(3)(2) for correction factors which is typically the same as Table 310.16 except it includes a 105°C (221°F) insulation temperature rating.

Table 690.31(A)(3)(2) CORRECTION FACTORS

Ambient Temp. °C	Temperature Rating of Conductor 105°C (221°F)	Ambient Temp. °F
30	1.00	86
31-35	.97	87-95
36-40	.93	96-104
41-45	.89	105-113
46-50	.86	114-122
51-55	.82	123-131
56-60	.77	132-140
61-70	.68	141-158
71-80	.58	159-176



When there are more than three current-carrying conductors in a raceway or cable, the ampacity of each conductor must be reduced as indicated in **Table 310.15(C)(1)** to compensate for heating effects and reduced heat dissipation due to reduced ventilation of individual conductors.

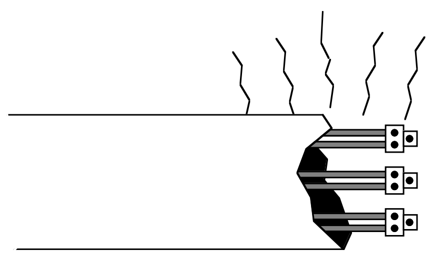
Table 310.15(C)(1). Adjustment Factors.

(a) More than Three Conductors in a Raceway or Cable. Where the number of conductors in a raceway or cable exceeds three, the ampacities shall be reduced as shown in the following table:

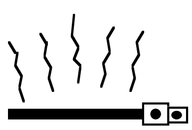
Number of Conductors	Percent of Values in Tables as Adjusted for Ambient Temperature if Necessary
4 through 6	80
7 through 9	70
10 through 20	50
21 through 30	45
31 through 40	40
41 and above	35

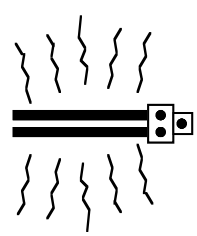
Example: A conduit contains six #8 TW current carrying conductors. The normal ampacity is 40 amps x 80% from **Table 310.15(C)(1)** = 32. The maximum current that can be passed through the #8 TW conductor without subjecting it to insulation damage is 32 amps.

Adjustment factors also apply when paralleling conductors per Section 310.10(G)(4).



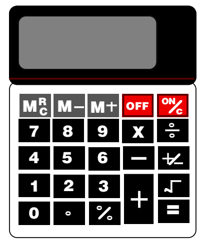
It is wrong to think since you connected two conductors in parallel on one lug that you now only have one conductor. Heat is measured by $W = I^2R$. In parallel you have **two** conductors carrying current producing heat.



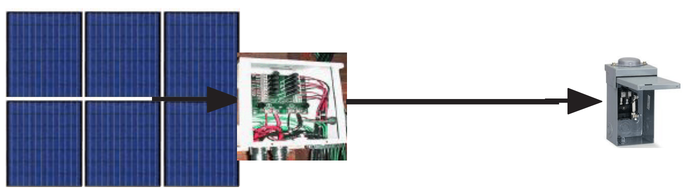


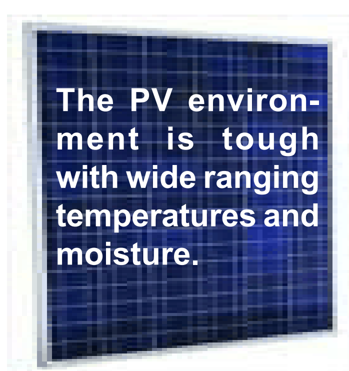
Next Temperature Corrections for Ampacity

Now open your Code book and turn on your calculator!

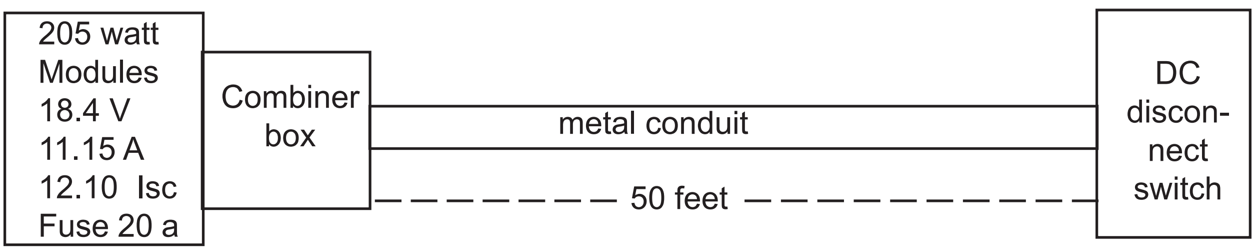


Continue with the circuit size, the wire from the array combiner box to the DC disconnect switch.





EXAMPLE #1



Name plate on back of module

205 watts
Vmp = 18.4 volts
Imp = 11.15 amps
Voc = 22.8 volts
Isc = 12.10 amps ← **Isc (amps short-circuit)**

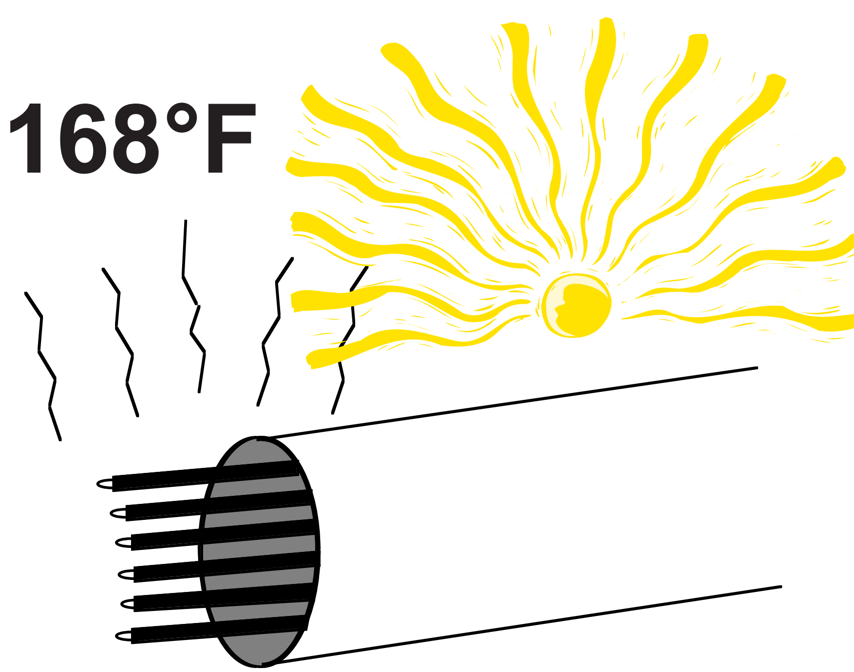
The required ampacity of the conductors from the source circuit combiner box to the DC disconnect switch **50' away**, generally depends upon the maximum PV module short-circuit current from the module. It is possible for the modules to operate at 125% of the STC short-circuit current rating for 3 hours or more. Example, if a module has a short-circuit rating of 12.10 amps. The continuous current rating of the module is 12.10a x 125% = 15.125 amps. Because conductors for continuous load must be sized at 125% of the continuous current, the **source circuit wiring** and overcurrent protection must be sized an additional 125% of continuous current 15.125a x 125% = 18.9 amps. This is the same as using a **156.25%** factor, 12.10a x 156.25% = 18.9 amps.

•Since the two strings are connected in parallel at the combiner box the Isc becomes 18.9 a x 2 = 37.8 amps. The conductors are sized on the Isc doubled 18.9 amps x 2 = **37.8 amps** Isc. So the wiring is calculated at 37.8 amps.

In almost all cases, wiring behind modules will be exposed to elevated temperatures. The NEC recognizes that conductors installed in conduit exposed to direct sunlight, as common in PV systems, can operate at temperatures that are 60°F above the ambient temperature **if the conduit is 3/4" or less above the roof surface**.

The 60°F shall be added to the outdoor temperature to determine the applicable ambient temperature for application of the correction factors in Table 310.15(B)(1)(1) or Table 310.15(B)(1)(2).

This means that a conduit in an outdoor ambient temperature of 104°F should actually be based on a **168°F operating temperature** with the conduit laying on the roof or above the roof 3/4" **or exposed to sunlight**.



We need a conductor with a corrected ampacity of at least **37.8 amps**.

Suppose you select a #10 THWN-2 which has an ampacity of 40 amps x **.41(correction factor for 168°F)** = 16.4 amps. A #10 THWN-2 with an allowable ampacity of 16.4 amps is not enough to satisfy the required ampacity of 37.8 amps.

The next larger size wire is a #8 THWN-2 which has an ampacity of 55 amps x .41 = 22.55 amps.

The next larger size wire is a #6 THWN-2 which has an ampacity of 75 amps x .41 = 30.75 amps.

The next larger size wire is a #4 THWN-2 which has an ampacity of 95 amps x .41 = 38.95 amps.

The ampacity of the conductor, after the application of these "conditions of use" factors must be equal to or greater than the continuous current of 37.8 amps. Since the #4 THWN-2 has a reduced ampacity of 38.95 amps it is greater than the 37.8 amps of continuous current, this meets the initial NEC requirements for ampacity.

Selecting 90°C insulation is an advantage in designing when applying the derating factors (correction factor and/or adjustment factor) to the normal ampacity of the conductor. But, you can NOT load the conductor to this 90°C ampacity per section 110.14(C). This is an everyday violation in the field.

Next we have to apply those often overlooked **terminal temperature limitations (110.14(C)** because the high PV module temperatures require the PV installer to use 90°C rated conductors. While the modules all have terminals rated for use with 90°C conductors, the combiner boxes and most other fused disconnects and overcurrent devices have terminals that are restricted to use with 60°C or 75°C rated conductors. Some of the combiner boxes do NOT have temperature markings, and since the overcurrent devices are usually below 100 amps, a conductor temperature ampacity of 60°C must be assumed per 110.14(C) of the NEC.

Conductor sizing must be determined to where the conductors will terminate and the rating of the termination.

If a termination is rated for 60°C, this means that the temperature at that termination may rise up to 60°C when the equipment is loaded to its *ampacity*. Any additional heat at the connection above the 60°C conductor insulation rating could cause damage to the conductor insulation.

If the temperature rating of the equipment is not considered and the 90°C wire is loaded to the 90°C ampacity it will lead to overheating at the termination and *premature opening* of the breaker.

Electrical equipment such as circuit breakers, panelboards, receptacles, switches, terminal blocks, wire nuts, lugs, etc. have *temperature ratings* that must be observed.

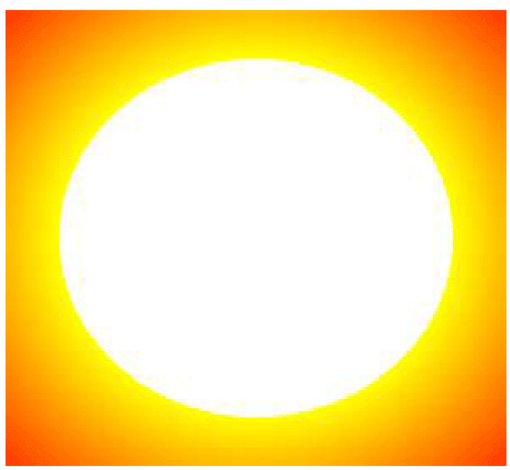
The best way to select the minimum size conductor for ampacity is to use the formula below.

Formula: Required conductor size = $\dfrac{\text{Ampacity required}}{\text{Correction factor}}$

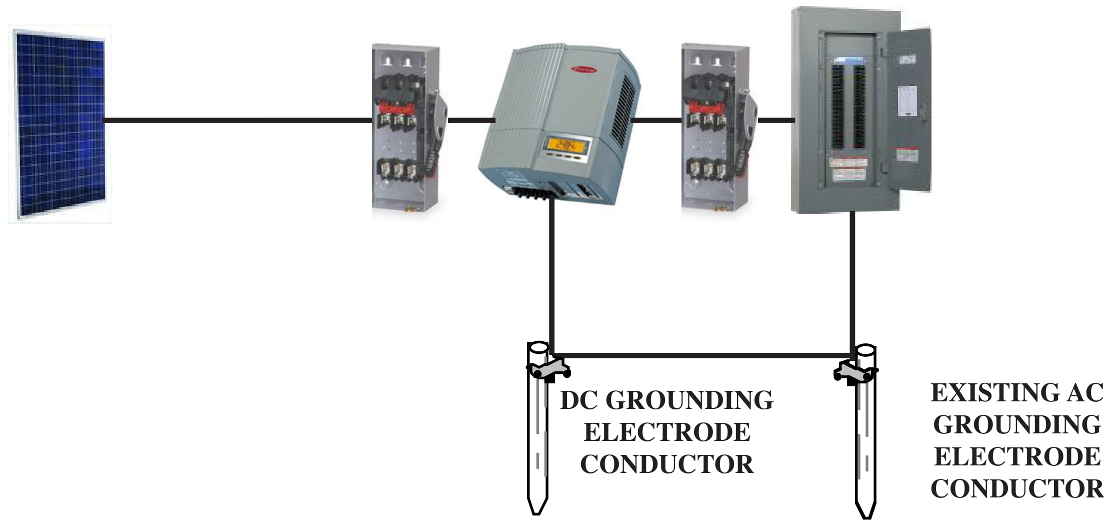
Example: $\dfrac{\text{37.8 ampacity}}{.41}$ = 92.19 required ampacity T.310.16 THWN-2 **#4 = 95 a**

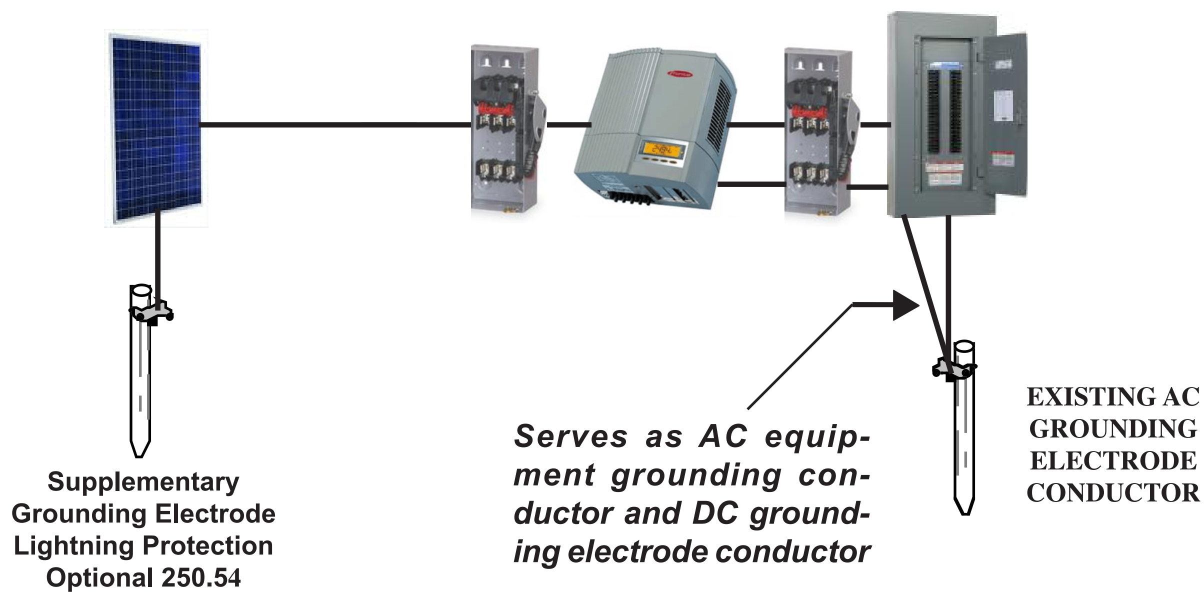
Now you must go to Table 310.16 and from the **60°C column** select a conductor that has an ampacity of at least 92.19 amps. The required conductor would be a **#2** which has a 95 ampacity.

It becomes evident that 310.15 correction factors for temperature are critical in calculating ampacities of wiring for PV systems.



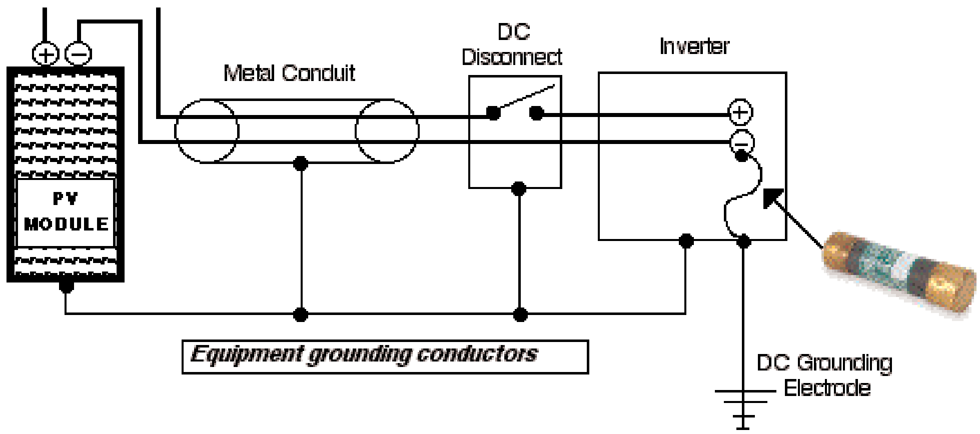
The DC and AC grounding electrode conductors are either connected to separate grounding electrodes which are then bonded together or are connected to a single grounding electrode system.





In this connection the conductor connected at the inverter connects to the other equipment to the ground rod. It serves as both the DC grounding electrode conductor and the AC equipment grounding conductor. All grounding terminals and lugs (equipment-grounding and grounding electrode conductor) are electrically connected together in the inverter. This connection can be used on smaller string inverters where the AC equipment grounding conductor is #8 or smaller. This connection is NOT appropriate for 10 kW and larger three-phase inverters.

In any ground-fault on the DC side of the PV system, ground-fault currents from **any** source, PV modules or batteries in stand-alone systems, must eventually flow through the DC bonding connection on their way back from the energy source through the fault and back to the energy source. This includes single ground faults involving the positive conductor faulting to ground or in the negative conductor faulting to ground. In ground faults involving the negative grounded conductor, the fault creates unwanted parallel paths for the negative currents and the fault currents will also flow through the DC bonding connection.



A typical GFPD has a overcurrent device installed in the DC bonding connection. When the DC ground-fault currents exceed the current rating of the device, it opens. By opening, the overcurrent device interrupts the ground-fault current. When a fuse is used, an additional electronic monitoring circuit in the inverter provides an indication that there has been a ground-fault..

The GFPD detects and interrupts ground faults **anywhere** in the DC wiring and the GFPD may be **located anywhere** in the DC system. GFPDs installed in the utility-interactive inverters or installed in DC power centers on stand-alone systems are the most logical places for these devices. Installing them at the modules would significantly increase the length of the DC grounding electrode conductor and complicate the routing of that conductor.

During a ground fault, the DC bonding connection is opened, and if the ground fault cures itself for some reason, the DC system remains ungrounded until the system is reset. A positive-to-ground fault may allow the negative conductor (now ungrounded) to go to the open-circuit voltage with respect to ground. This is addressed by the marking requirements. A very high value resistance is usually built into the GFPD and this resistance bleeds off static electric charges and keeps the PV system loosely referenced to ground (but not solidly grounded) during ground-fault actions. The resistance is selected so that any fault currents still flowing are only a few milliamps, far too low to be a fire hazard.

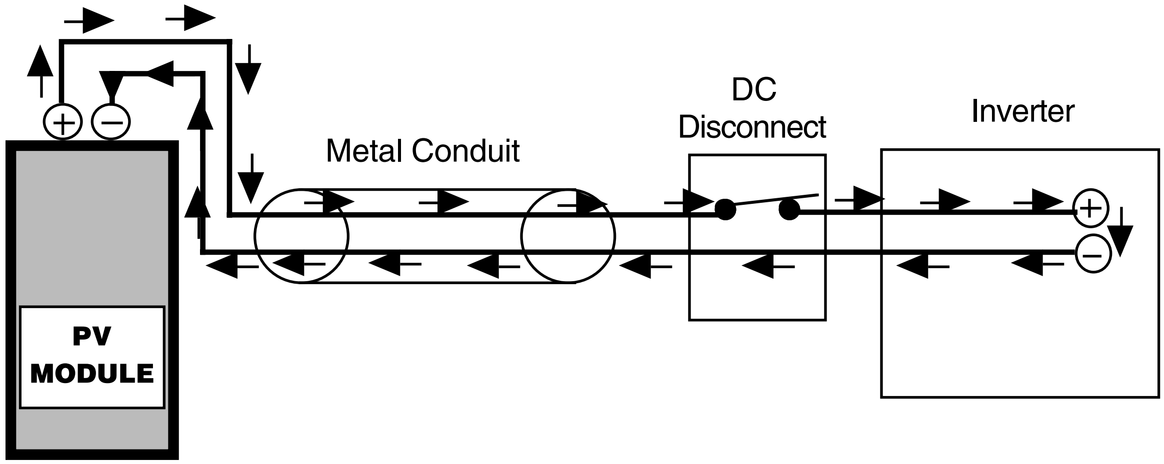
The purpose of the ground-fault protection device is to reduce the possibility of fire from an arcing fault to ground.

Many residential PV systems (6kW and below) have all of the PV equipment, both AC and DC, grounded by a single equipment grounding conductor connected from the modules to the grounding bus bar in the residential AC load center. The module frames, the PV array mounting rack, the DC disconnect, the inverter, and one or more AC disconnects are all grounded by the **single equipment grounding conductor** routed to the AC load center. The equipment grounding conductor from the PV system inverter connects to the AC load center grounding bus bar and the AC load center connects to ground (earth).

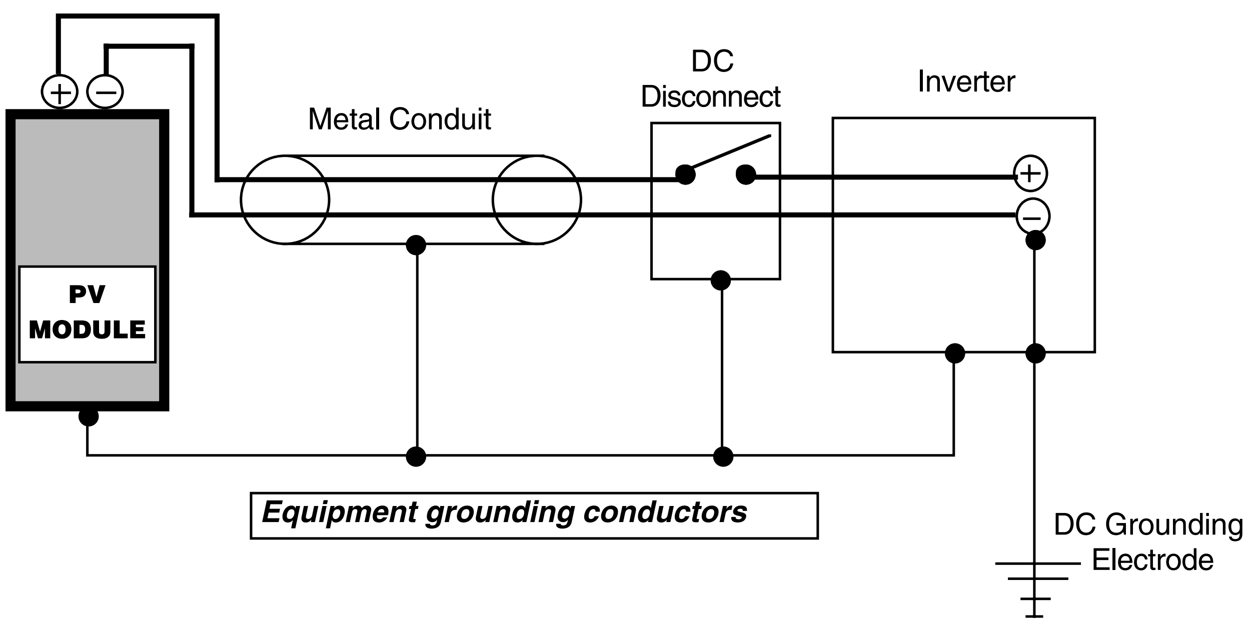
The common AC ground-fault circuit interrupters (GFCI) are NOT designed to be backfed. The output of a utility-interactive inverter connected to the load terminals and backfeeding a receptacle or breaker GFCI, a 30-milliamp equipment protection ground-fault breaker, or even a 600-1200 amp main breaker with ground-fault elements may damage that device with no external indication of a problem. Anytime a utility-interactive PV system is installed, the entire AC premises wiring system should be examined all the way from the PV inverter output to the service entrance to ensure that there are NO ground-fault devices in that circuit that may be subject to backfeeding. Some of the newest ground-fault breakers in the 1000 amp and larger sizes are listed as suitable for backfeeding, but that information must be obtained on any AC ground-fault device that could be subject to backfeeding.

Arc-fault circuit interrupters (AFCI) are, in some ways, similar to GFCIs and should NOT be backfed by PV inverters unless listed and identified for backfeeding. They are being required in many locations thereby increasing the safety of electrical systems here in the U.S., DC arc-fault interrupters are not currently available.

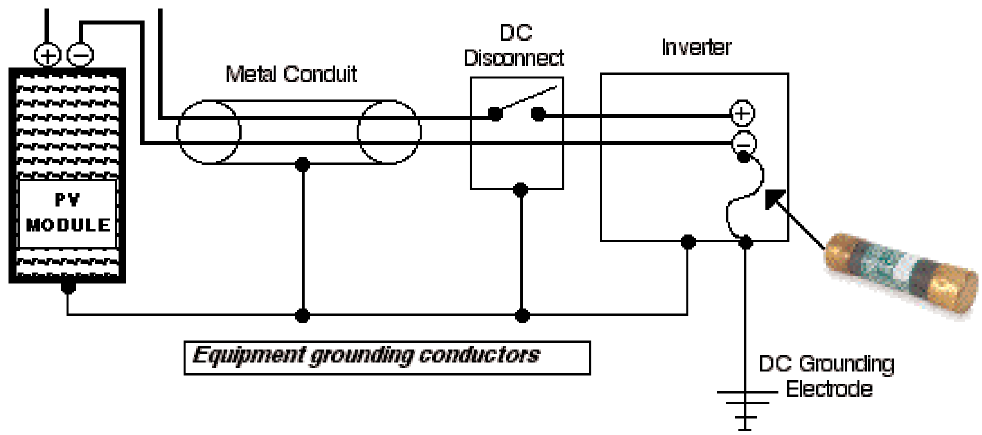
The complete DC circuit



All metal must be connected by an equipment grounding conductor



Now a fuse or circuit breaker is connected in the DC system-bonding conductor



All ground-fault currents must flow through this DC bonding connection on their way from the ground fault back to the source, the module. When the current flowing through this bonding connection exceeds the rated 0.5 or 1 amp, the overcurrent device opens.

It is extremely important to make the grounding and bonding connections properly to ensure electrical continuity and the capacity to conduct safely any fault current likely to be imposed.

Conductor connections affect circuit resistance, grounding and bonding circuits should be checked for loose or corroded terminals. Tightening or reterminating the connections reduces circuit resistance.