Solar PV panels–power output ratings

Douglas A. Kerr

Issue 1
December 24, 2023

ABSTRACT

An important "rating" of a solar photovoltaic (PV) panel is its maximum electrical output power under some stated solar radiation incidence (irradiance). This property may be determined under three common sets of standardized test conditions, and is usually stated by the manufacturer as determined under one or more of those sets of conditions.

The common sets of test conditions are called STC ("standard test conditions"), NCOT ("normal cell operating temperature", and PTC ("PVUSA test conditions"). This article concisely describes these, and discuses some ramifications of each. Background is given in the important underlying technical concepts.

1 BACKGROUND

1.1 General

A solar photovoltaic (PV) panel is a (usually flat) panel that, when exposed to solar irradiation, generates electrical power.

1.2 Quantifying arriving solar radiation

The "potency" of the arriving solar radiation as it reaches a certain point is quantified by the property *flux density*, which is denominated in the SI unit watt per square meter (W/m^2).

The "impact" the solar radiation as it lands on a surface with a certain orientation, at that point, is quantified by the property *flux density*, which is also denominated in the SI unit watt per square meter (W/m^2).

1.3 Output power

When receiving a certain non-zero irradiance, the solar PV panel will deliver an electrical output. The voltage of that output is determined by the current being drawn: the greater the current, the less the voltage. The decline in voltage with increasing current, however, is not linear.

Figure 1 shows a typical current vs. voltage curve for a hypothetical panel exposed to an irradiance of 1000 W/m^2.

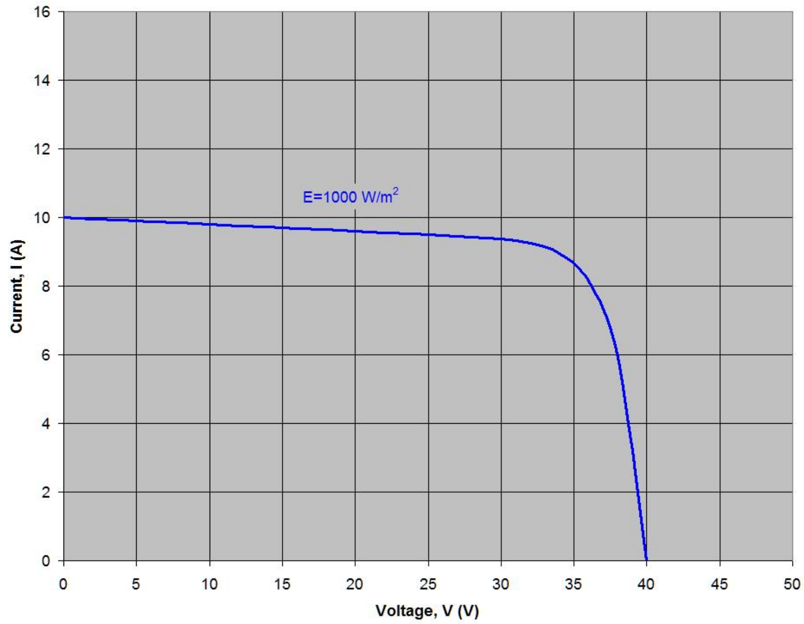

Figure 1. Hypothetical solar PV panel— current vs. voltage

Note that I described the relationship as the voltage being dependent on the current, which suggests that we should plot the relationship with current as the horizontal axis. However, it is the custom to plot it with voltage as the horizontal axis, so I follow that here.

To put this in perspective, note that the irradiance a solar panel can receive, at an ideal location and an ideal time of year, and at an ideal hour of the day, with clear skies, and with the panel at an ideal orientation, is on the order of 1000 W/m^2. Thus that irradiance value is often used as the "reference value" of irradiance for the measurement and description of the output properties of a panel. (In fact, that level of irradiance is sometimes, not very officially, called "one sun" of irradiance.)

For operation at a certain irradiance and at any given current (and thus the corresponding voltage), the output power is the product of that current and that voltage. On Figure 2 we also see that output power *vs*. voltage relationship for this same hypothetical panel.

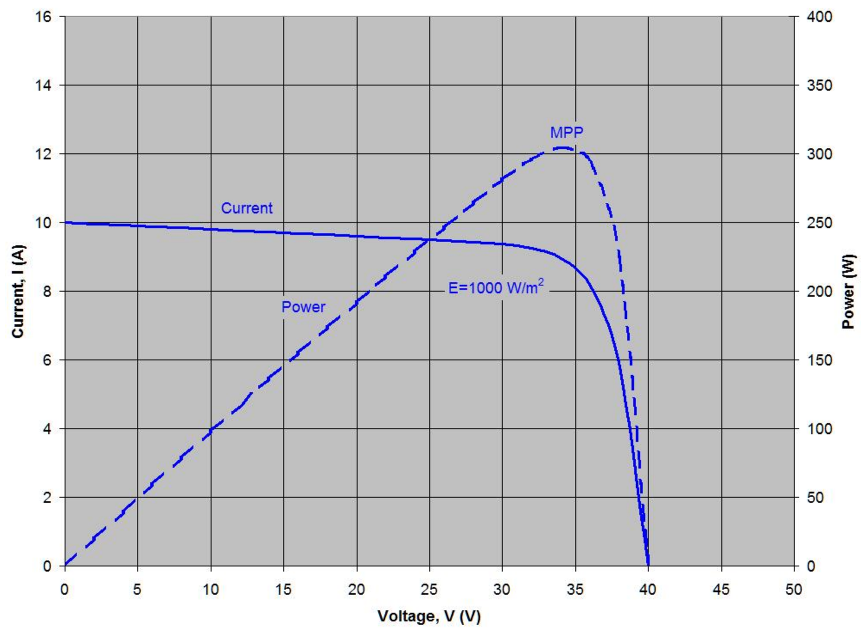

Figure 2. Hypothetical solar PV panel—output power vs. voltage

We see that for this panel, receiving this irradiance, there is an "operating point" (a certain voltage and the associated current) at which the output power is a maximum (this operating point called the "maximum power point", or MPP).

In typical modern solar energy systems, the power will be taken from the panel by a module (called a "power optimizer") that determines the MPP for the panel at any given time and extracts the power from the panel at the that leads to that voltage, so as to extract the maximum amount of power that panel can deliver at the present irradiance. This approach is sometimes called "maximum power point tracking" (MPPT).

At a lower irradiance, of course the current vs. voltage curve is different, and as a result, the output power vs. voltage curve will be different, as we see in Figure 3.

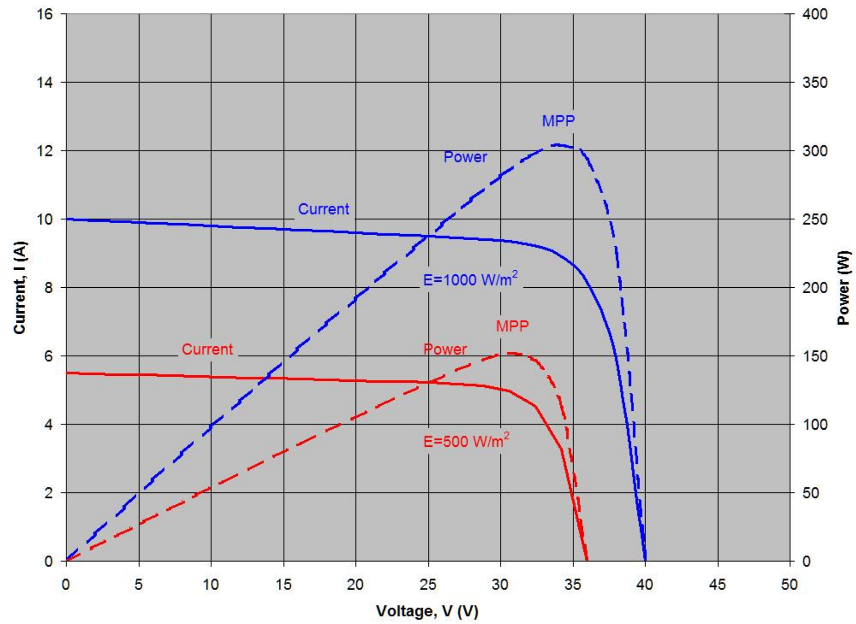

Figure 3. Curves for two different irradiance values

In this set of curves for our hypothetical panel, the maximum power is proportional to the irradiance, E, on the panel. In reality, the relationship is not linear. Increases in irradiance lead to a greater than proportional increase in maximum power output.

1.4 Cell temperature

It is important to note that, almost invariably, the temperature of the photovoltaic cells in a panel affects, for any given irradiance, the maximum available power, that normally being less as the cell temperature increases. We will see shortly how that fits into the matter of test conditions for determining a panel's "rated power output".

2 SOLAR PANEL OUTPUT POWER RATINGS

2.1 Introduction

It is of course important in planning a solar electric energy system to know what (maximum) output power can be expected from a particular type of solar panel under various values of solar irradiance.

A simplistic description of the panel's capabilities is its "rated output power". This is done at some standardized irradiance value, and stated conditions regarding the cell temperature. Three different "sets of test conditions" (I sometimes call them "protocols") are in use for this. Normally the panel manufacturer, stating an output power rating, will cite which of these pertains, and may even state the value under two or all three of these.

Each of these contain many subtle prescriptions. I will only identify the items that are key to understanding the difference between them

2.2 Standard Test Conditions (STC)

This includes the following key prescriptions:

- The irradiance on the panel is 1000 W/m^2.
- The temperature of the photovoltaic cells is 25°C (77°F).
- Air mass = 1.5 (see Appendix A)

This is often the set of test conditions used to determine the stated "power output rating" of a solar panel—the number that, for example, identifies this particular model at the top of its specification sheet (and may even be built into the panel's "model number").

A disadvantage of this set of test conditions is that the stated temperature of the photovoltaic cells (25°C) is overoptimistically low under most operation at a high irradiance. And from a practical viewpoint, for testing a completed panel it may be inconvenient to precisely measure the temperature of the cells.

This problem is "solved" (albeit in an odd way) by the next set of test conditions.

2.3 Cell temperature

But first, let me talk a bit about the temperature of the actual photovoltaic cells that make up a PV panel.

First we note that, even in the higher-efficiency PV panels available today, only perhaps 21% of the power in the arriving solar irradiation is turned into electrical power. The rest is turned into—yes, heat. This of course escapes into the surrounding atmosphere, or by radiation or through the support fittings into the building on which the panel is mounted, but in the course of that it raises the temperature of the whole thing (prominently including the cells) above the ambient air temperature.

Additionally, part of the electrical power developed by the cells is lost to so-called I^2R heating: heating of the interconnecting conductors, and the cells themselves, by the flow of the current drawn from the cell array. This also serves to increase the cell temperature.

2.4 Normal Operating Cell Temperature (NOCT)

This is sometimes spoken of as the Normal Module Operating Temperature (NMOT) protocol.

Formally, this does not mean that this is a set of test conditions for measuring output power done with the cells at their "normal operating temperature".

Rather, formally, it is an algorithm for determining what the cell temperature would probably be under certain conditions, to wit:

- Irradiance on the panel of 800 W/m^2.)
- Outside air temperature of 20°C (68°F).
- No load on the cells (panel output open-circuited)
- Air movement at 1 m/s.
- Air mass = 1.5 (see Appendix A)

But these values (other than the "open circuit" condition) have come to be used as a set of test conditions under which the maximum power output of a panel is determined (and are then identified as the "NOCT" test conditions).

And then the name can in fact be interpreted as meaning "testing at (presumed) normal cell operating temperature" (however that comes about from the ambient air temperature and irradiance specified).

In any case, for the ambient air temperature of 20°C (68°F) (not very hot, at least for us in southern New Mexico), the predicted cell temperature is usually in the range of 40-45°C, quite a bit higher than the 25°C upon which the STC test conditions are predicated.

Recall that this is actually not intended to be a set of test conditions for determining a "power rating" for a panel, although it is pressed into that use. Its use for that, given that it prescribes a test irradiance of only 800 W/m^2, will lead to produce a value that cannot fairly be compared with the STC power rating (or even the PCT power rating to be discussed subsequently).

2.5 PVUSA test conditions (PTC)

2.5.1 *Introduction*

The Photovoltaics for Utility-Scale Applications (PVUSA) research site was established in 1986. It did research in various areas related to the emerging field of solar electric power generation.[1]

One result of this research was a set of standard test conditions (named for the organization) for determining the power rating of a solar panel, although in a rather complicated way.

[1] Later known as Photovoltaics for Utility System Applications This organization no longer exists, but its work on testing protocols has been taken on by another organization.

2.5.2 *Simplistically*

Simplistically, these test conditions are:

- Irradiance on the panel of 1000 W/m^2.
- Outside air temperature of 20°C (68°F).
- Air movement at 1 m/s.
- Air mass = 1.5 (see Appendix A)

So, as to these basic parameters, we see that this protocol takes the general approach of the NOCT "protocol", but at the irradiance of the SPT protocol.

2.5.3 *More precisely*

To be precise, the PVUSA test protocol seeks to determine, by regression analysis of data from multiple tests, the constants a, b, c, and d of this equation:

$$P = E(\mathrm{a} + \mathrm{b}E + \mathrm{c}W + \mathrm{d}T) \tag{1}$$

where *P* is the available power output (at the MPP), *E* is the irradiance on the panel, *W* is the wind velocity, and *T* is the ambient air temperature. (I think this is to be done for test conditions in the region around $E = 1000$ W/M^2, $W = 1$ m/s, and $T = 20°$ C.)

The rated power of the panel is then obtained by plugging into that equation (with the constants determined as mentioned above), the values $E = 1000$ W/M^2, $W = 1$ m/s, and $T = 20°$ C.

This approach avoids the need to, for example, establish an irradiance of essentially exactly 1000 W/m^2, an ambient air temperature of essentially exactly 20° C, and so forth (which is not that easy to do).

Instead, what we must do is to establish stable conditions near those values (which is fairly easily done) and then very accurately measure the values (which is fairly easily done). Then we proceed as described just above: using regression analysis to ascertain the most likely values of the parameters of Equation 1. The resulting power value is said (a bit inaccurately) to be as determined under "PTC test conditions"

2.6 Acceptance

Many authorities believe that testing under the PTC test conditions gives the "most meaningful" result of all of the three protocols I discuss here.

It is common for formal agreements for solar power systems have the system “maximum output capacity” stated in terms of the STC test conditions. But in other cases, it is the PTC test conditions value that must be used. Probably for the reason I discussed at the end of section 2.4, the NOCT power rating is rarely prescribed for such purposes.

2.7 Caveat

Remember that in any case the “power output rating” of a PV panel is that which would be expected under an arbitrary irradiance dictated by the test conditions. and is useful for “getting the measure” of a solar panel. The actual power that the panel can deliver at any instant is of course dependent on the irradiance it receives at that instance.

2.8 Present specification practice

2.8.1 *General*

At this writing (Fall, 2023), many manufacturers of solar PV panels commonly publish output power ratings under STC, NOCT, and PTC test conditions.

2.8.2 *Specific examples*

The Jinko “Eagle” JKM385M-6RL3-B panel is called the “385 W” panel within that product family (note those same digits in the model number). Its maximum output power rating under STC conditions is stated as 385 W (well, we have seen those digits before), and under NOCT conditions as 286 W (the NOCT temperature is stated as 45°C). The output power under PTC conditions is stated as 356 W.

The Trina TSM-385DE09C.07 panel, said to be the “385 W” panel in that series (again note those same digits in the model number), has a stated power rating under STC conditions of 385 W (fancy that!) and under NOCT conditions of 290 W. The NOCT temperature is stated as being 43°C. The power rating under PTC conditions is stated as 359 W.

The Canadian Solar CS3N385MS panel has an output power under STC conditions stated as 385 W, and an output power under NMOT conditions (Normal Module Operating Temperature, for all practical purposes the same as the NCOT conditions) stated as 288 W. The NMOT cell temperature is stated as 42°C. The power rating under PTC conditions is stated as 363 W.

The JA Solar JAM72S09-385/PR panel has an output power under STC conditions stated as 385 W, and under NOCT conditions, 285 W (with an NOCT temperature of 45°C). The power rating under PTC conditions is stated as 357 W.

Appendix A
The "air mass" parameter

A.1 INTRODUCTION

You will have noted that in the list of pivotal parameters of the three output power measurement "protocols" discussed above was a parameter called "air mass", which has the value 1.5 for all three protocols. This appendix tells what that is all about.

A.2 SPECTRAL DISTRIBUTION

The Sun's radiation is of course not equal at every imaginable wavelength.

In describing such radiometric properties as *irradiance*, the total power in the radiation is considered, without any concern for how it may be made up of components of differing potency at different wavelengths.

But that aspect of the situation can be important. It is reflected by a "spectral plot" of the radiation. We see that (among other things) on Figure 4. Note the shaded area, which represents what is normally considered the range of the "visible spectrum" (about 0.4-0.7 μm, or 400-700 nm).

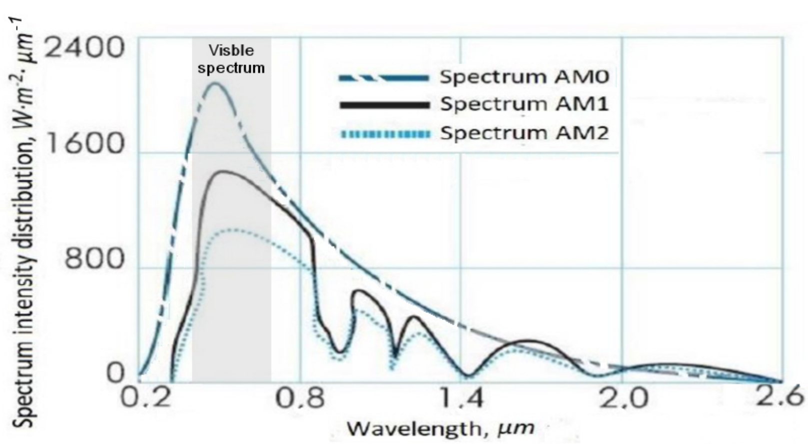

Figure 4. Solar radiation spectrums

The spectrum of the radiation as it just arrives at the earth's atmosphere is the curve labeled "AM0" (we'll see what that notation means shortly).

A.3 SOLAR PANEL RESPONSE

A solar panel cell also differs as to its efficiency in converting solar radiation power into electrical power with the wavelength involved.

We see the spectral response plot for one type of solar cell in figure 5. The actual spectral response various quite a bit over the different types of PV cell. This is just to give you a general idea.

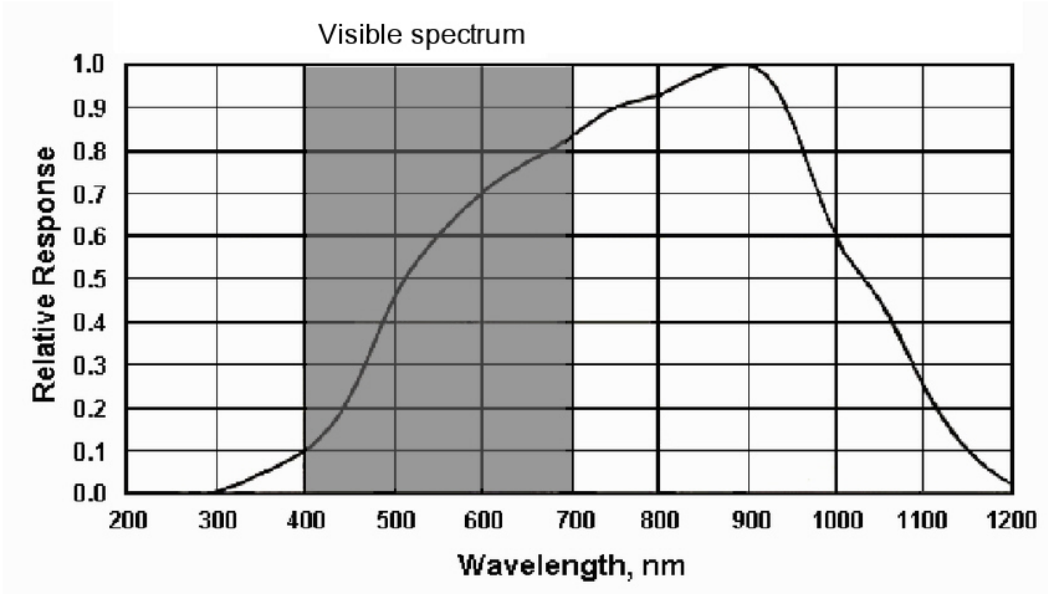

Figure 5. Typical solar PV cell spectral response

Again the shaded area reminds us of the wavelength range for human vision. We note that for this type of PV cell, the peak response is outside the range of human vision, in what we sometimes call the "near infrared".

A.4 THE TRIP THROUGH THE ATMOSPHERE

As the solar radiation first encounters the Earth's atmosphere, it has a certain spectral distribution (seen as the "AM0" curve in figure 4). But different wavelengths suffer different degrees of attenuation as the radiation passes through the atmosphere on its way to the Earth's surface.

However, the path for the radiation to reach our solar panel encounters different distances through the atmosphere depending on the angle at which the sun's rays, heading toward our site, make with a line from the sun to the center of the earth. This angle, in turn, varies with the latitude of our site and the time of year. It is the least when the sun is directly overhead (which, by the way, never actually happens for larger latitudes)

And as that distance varies, so varies the spectral distribution of the solar radiation when it reaches our site, reaches our panel.

As a result, so varies the ratio between the incident irradiance (based on all components at different wavelengths having equal weight) and the response of our panel (because of it dealing differently with different wavelengths.

The "distance of travel through the atmosphere" is defined in terms of a property with the not-too-sensible name, *air mass*. This is the ratio of (a) the distance the solar radiation has to travel though the atmosphere in the case of interest to (b) the shortest distance it might ever have to travel through the atmosphere (which would be if and when the sun was directly overhead the site of interest.

Going back to Figure 4, the notation "AM0" ("air mass = 0") designates the spectrum of radiation traveling zero distance through the atmosphere (and thus is the spectrum as the solar radiation just reaches the outer limit of the atmosphere).

"AM1" means "air mass = 1", and designates the spectrum as the solar radiation would travel the shortest possible distance through the atmosphere to the Earth's surface (when the sun is directly overhead).

"AM2" means "air mass = 2", and designates the spectrum when the solar radiation has to travel twice that distance to reach the site (as when the sun is a bit lower in elevation). This occurs when the sun is about 60° from directly overhead.

Those spectrum curves are "absolute", and so we see that for a greater distance traveled through the atmosphere, not only is the spectral distribution different but (not surprisingly) the overall power in the radiation is less.

But this latter does not figure into the matter of testing with the various sets of test conditions. They are predicated on the actual irradiance on the panel under test (as might be measured **at the panel**).

2.9 The air mass value 1.5 in the test condition specifications

The consistent value of 1.5 for the "air mass" in the three testing condition specifications says that testing should be done with a source whose spectral distribution is what solar radiation would have upon arrival at a site where the distance traveled through the atmosphere was 1.5 times the distance traveled in the case where the sun was directly overhead.

This is sort of an "average" of what the air mass ratio might be over all actual situations. It corresponds specifically to the sun being about 48° from directly overhead.

-#-