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Calculating Actual PV System Output

A typical photovoltaic (PV) system consists of a solar array, its mounting structure, DC wiring, a battery bank (in battery-equipped systems), and an inverter. All of these components must be designed, sized, and installed correctly to work in unison to properly generate power from the sun.

Installation issues such as amount of insolation (the amount and quality of the light that reaches the array), correct array orientation, tilt, and partial shading considerations play a crucial role in the overall output of a solar system. An array that is exposed to less than the 1000 W/ m^2, positioned a few degrees off correct orientation, or exposed to partial shading from nearby tree limbs, power lines, or chimneys will certainly output less power than it can, but that same array is also impacted by a host of environmental conditions. The purpose of this paper is to illustrate some of the factors involved in estimating the output of a solar array.

The DC rated output of each solar module is provided by the PV manufacturer in the form of values taken under Standard Test Conditions (STC). These conditions create a specific solar environment by indicating:

- Solar Cell Temperature = 25 °C (the temperature of each cell in a module)
- Solar Irradiance = 1000 W/m^2 (the amount of light that shines on a module)
- ASTM Standard Spectrum (the type of light that shines on a module)

Since each module manufacturer rates the module output at STC, the system designer has the ability to compare various manufacturer's modules and choose an array based on an "apples to apples" comparison of watts STC (for module A) vs. watts STC (for module B). What is important to remember, is that, while STC conditions are convenient for measuring module output in a laboratory, the actual cell temperature is much lower in the laboratory than will typically be seen in the field. Since the PV output decreases with increasing temperature, this STC rating must be de-rated to arrive at a "real world" array output.

Production Tolerance – Manufacturers often assign an allowable output tolerance to the module's rating. For example, if this tolerance is +/- 5% of the rating, a 100 watt module could actually yield 95 watts to 105 watts under STC, yet still be sold as a 100 watt device.

Temperature – The cell temperatures of a solar array will vary drastically due to ambient conditions such as sun intensity, air temperature, wind speed, and other factors. Module construction and how the array is mounted can also impact module's cell temperature. Roof-mounted arrays typically yield peak cell temperatures in the range of 50 °C to 75 °C – two to three times higher than specified by STC. To account for the higher cell temperature, a de-rating factor of 0.89 for crystalline modules has been recommended by the California Energy Commission. Thus, taking a conservative approach, a 100 watt module, factoring in production tolerances and temperature de-ratings, would essentially output only 85 watts: 100 watts (rating) x 0.95 (tolerance) x 0.89 (de-rating) = 85 watts.

Dirt and dust – Arrays mounted in real world conditions eventually become covered with a fine layer of dirt and dust, decreasing the amount of light reaching each cell. The amount power loss due to soiling depends on variables such as the location, the type of dust, and the length of time since the last rainfall. Tests performed at PVUSA in Davis, CA showed a reduced output by a factor of 0.93 while other locations have suggested as much as a 2 to 4 percent reduction. Factoring in production tolerances, temperature de-ratings, and adding a value for soiling further reduces the 100 watt module's output to 79 watts: 100 watts (rating) x 0.95 (tolerance) x 0.89 (de-rating) x 0.93 (soiling) = 79 watts.

Mismatch and wiring losses – The sum of the whole is always less than the sum of the parts, so an array made of many modules that differ, even slightly, must be de-rated by a factor of 0.98. Furthermore, DC wiring also accounts for power losses due to the resistance of the wiring in a system. Even in a well-designed and installed system, DC wiring losses can account for an additional de-rating factor of 0.97. Thus, the output of the 100 watt module is now down to 75 watts: 100 watts (rating) x 0.95 (tolerance) x 0.89 (de-rating) x 0.93 (soiling) x 0.98 (mismatch) x 0.97 (wiring losses) = 75 watts.

DC to AC conversion losses – We have now accounted for losses leading from a well-installed and positioned array down to the inverter. Since there are two types of grid tie inverters (without batteries and with batteries), these components must be factored into the equation as well.

> A system **without batteries** has a conversion loss (DC to AC) that is based on the inverter efficiency. On average, over a day, this efficiency is about 90% - resulting in a de-rating factor of 0.90 for the system without batteries.
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> For a system **with batteries**, battery losses and conversion efficiency must be factored in. A battery-based system must maintain the battery at float voltage incurring additional losses. With its related components, the system with batteries has losses of about 10%. Inverter efficiency is slightly less than the system without batteries (above), averaging about 86% - resulting in a total de-rating factor of 0.77 for a system with batteries.

Environmental and equipment dynamics can have a drastic impact the output of a typical solar electric system. If the installation accounts for correct array orientation, tilt, partial shading considerations, etc., then, when calculating the output yield for a 1000 watt array, the following de-rating factors must be included:

Environmental Condition	**without Batteries**	**with Batteries**
Module production tolerance	0.95	0.95
Temperature	0.89	0.89
Dirt and dust	0.93	0.93
Module mismatch	0.98	0.98
Wiring losses	0.97	0.97
Battery system losses	N/A	0.9
Conversion losses	0.9	0.86
Total de-rating factor	*0.67*	*0.58*

The result, for a typical 1000 watt system, is an average 670 watts output for a system without batteries and an average 580 watts for a system with batteries – assuming a perfectly sunny day and a properly designed and installed system. This calculation accounts for environmental and equipment factors that impact system performance for demonstrative purposes only.

These concepts and additional factors that impact solar electric system performance are discussed in greater detail in the “A Guide to Photovoltaic System Installation and Design” prepared by Endecon Engineering for the California Energy Commission (CEC).

P/N 970-0054-01-01 Rev. A