



# PVWatts Version 1 Technical Reference

Aron P. Dobos

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## Abstract

The NREL PVWatts<sup>TM</sup> calculator is a web application developed by the National Renewable Energy Laboratory (NREL) that estimates the electricity production of a grid-connected photovoltaic system based on a few simple inputs. PVWatts combines a number of sub-models to predict overall system performance, and makes several hidden assumptions about performance parameters. This technical reference details the individual sub-models, documents assumptions and hidden parameters, and explains the sequence of calculations that yield the final system performance estimation.

**Keywords:** *photovoltaics, PVWatts, systems modeling, solar analysis*

## 1 Overview

This document summarizes the calculation methods used in the PVWatts<sup>TM</sup> photovoltaic system performance model. PVWatts is based on a number of individual sub-models, each of which has been independently documented and validated. This overview describes each sub-model in general and attempts to show how the pieces are connected together to go from solar irradiance input to AC power output. For a complete explanation of each sub-model, refer to the references cited throughout.

Several “versions” of PVWatts have existed in the past several years. The version documented here is the “standard” implementation of the hourly calculator that is available in the SAM Simulation Core (SSC) engine, denoted as module `pvwatts1`, and is used for the online PVWatts tool (<http://pvwatts.nrel.gov>), the NREL PVWatts V4 web service (<http://developer.nrel.gov>), and within the System Advisor Model (SAM) (<http://sam.nrel.gov>).

The reader may also be familiar with the former PVWatts version 2 online tool. PVWatts version 2 was a modified version of PVWatts that was tailored to work with a particular 40 km monthly gridded dataset in the United States. The calculations were first performed hourly using the algorithms described in this document for a nearby site, and then translated to the specific grid cell on a monthly timeframe by adjusting for the local irradiance and temperature. The details of the dataset and translation algorithm are given in [6].

## 2 Solar Resource

The PVWatts model is an hourly simulation program that requires hourly data for one year for two components of solar irradiance (beam and diffuse), as well as ambient dry bulb temperature and wind speed at 10 m. The PVWatts algorithms are indifferent to the source of such data; typical data sources are the hourly Typical Meteorological Year (TMY) version 2 or version 3

datasets [1, 2]. PVWatts also requires that each hour be timestamped with the year, month, day, and hour corresponding to the data line so that the sun position can be accurately calculated.

No adjustments are made for leap years or daylight savings time: hence, “hourly data” in this context implies 8,760 data points for one year. The required data are listed in Tables 1 and 2.

Table 1. Header Information

Field	Units
Latitude	degrees
Longitude	degrees
Time zone	hours offset from Greenwich Mean Time
Site elevation	meters above sea level

Table 2. Hourly Input Data Fields

Field	Units/Values
Year	1950-2050
Month	1-12
Day	1-31
Hour	0-23
Direct normal irradiance (DNI)	W/m <sup>2</sup>
Diffuse horizontal irradiance (DHI)	W/m <sup>2</sup>
Ambient dry bulb temperature	Celsius
Wind speed at 10 m	m/s
Snow cover ( <i>optional, typically in TMY2 files</i> )	cm
Albedo ( <i>optional, typically in TMY3 files</i> )	0..1

The standard implementation of PVWatts in SSC has the ability to read in 8,760 data files in the TMY version 2, TMY version 3, and Energy Plus Weather (EPW) data file formats.

### 3 Model Inputs

PVWatts requires a minimal set of PV system specifications as listed in Table 3. Other performance parameters such as module temperature coefficients are not available to the user.

Table 3. Input Parameters

Field	Units	Default Value
System size	kW (DC)	4
System derate	fraction	0.77
Array tracking mode	Fixed, 1-Axis, 2-Axis	Fixed
Tilt angle	degrees	Site Latitude
Azimuth angle	degrees	180

The specifications are used in the various submodels described in the next sections to estimate the energy generation of the system.

## 4 Sun Position

At each hour, PVWatts calculates the sun position using the algorithm described in [3]. The sun position is calculated at the midpoint of the hour: for example, from 5 p.m. to 6 p.m., the sun position is calculated at 5:30 p.m. to determine the solar zenith and azimuth angles. This is the case for normal daytime hours during which the sun is above the horizon for the whole hour.

For the sunrise hour, the midpoint between the sunrise time and the end of the timestep is used for the sun position calculation. Analogously, the midpoint between the beginning of the timestep and sunset time is used for the sunset hour.

## 5 Tracking

PVWatts performs angle of incidence (AOI) ( $\alpha$ ) calculations for fixed, one-axis, or two-axis tracking systems. Fixed systems implement standard geometrical calculations for the angle of incidence given surface tilt  $\beta$ , surface azimuth  $\gamma$ , solar azimuth  $\gamma_{sun}$ , and solar zenith  $\theta_{sun}$  angles, as listed in Eqn. 1.

$$\alpha_{fixed} = \cos^{-1} [\sin(\theta_{sun}) \cos(\gamma - \gamma_{sun}) \sin(\beta) + \cos(\theta_{sun}) \cos(\beta)] \quad (1)$$

For one axis trackers, the algorithm documented in [7] is used. It assumes ideal tracking and does not account for any shading. For one-axis trackers, a tracker rotation limit is adhered to, and it is hardcoded in PVWatts with a value of  $\pm 45$  degrees.

For two axis tracking systems, the PV surface tilt and azimuth are set equal to the sun zenith angle and the sun azimuth angle, respectively, and the incidence angle is zero.

## 6 Plane-of-Array Irradiance

The plane-of-array (POA) beam, sky diffuse, and ground-reflected diffuse irradiance components are calculated using the Perez 1990 algorithm [4]. The POA beam component  $I_b$  is simply the beam normal input multiplied by the cosine of the angle of incidence. The isotropic, circumsolar, and horizon brightening diffuse terms are calculated from the beam and diffuse input given two empirical functions F1 and F2 as defined and are summed to yield the total sky diffuse on the surface  $I_{d,sky}$ . A slight modification from the standard Perez model treats the diffuse irradiance as isotropic for zenith angles between 87.5 and 90 degrees. The ground reflected irradiance  $I_{d,ground}$  is treated as isotropic diffuse with a view factor calculated from the ground with respect to the tilted surface. The total POA incident on the module cover is the sum of the three components (Eqn. 2).

$$I_{poa} = I_b + I_{d,sky} + I_{d,ground} \quad (2)$$

The albedo, or ground reflectance, is by default fixed at 0.2. However, when using TMY2 files as input that have a valid snowfall (cm) data column, and the snowfall recorded is greater than zero, an albedo of 0.6 is chosen to account for increased ground reflected irradiance. Of course, this assumes that the photovoltaic panels are perfectly cleaned of any accumulated snow. When using TMY3 data as input, and valid data is found in the albedo column, the reported albedo from the data file is used.

## 7 Module Cover

Given the total POA irradiance incident on the module cover, PVWatts applies an AOI correction to adjust the direct beam irradiance for incidence angles greater than 50 degrees [8] to account for reflection losses. The correction uses the Sandia PV Array Performance Model polynomial correction, with coefficients for glass.

The incident POA  $I_{poa}$  is reduced using Eqns. 3 and 4, given angle of incidence  $\alpha$ , beam normal irradiance  $I_b$ , and the five polynomial coefficients for glass listed in Table 4.

$$f = b_0 + b_1\alpha + b_2\alpha^2 + b_3\alpha^3 + b_4\alpha^4 + b_5\alpha^5 \quad (3)$$

$$I_{tr} = I_{poa} - (1 - f) \cdot I_b \cos(\alpha) \quad (4)$$

Table 4. Module Cover Polynomial Coefficients

$b_0$	$b_1$	$b_2$	$b_3$	$b_4$	$b_5$
1.0	-2.438e-3	3.103e-4	-1.246e-5	2.112e-7	-1.359e-9

## 8 Thermal Model

PVWatts implements a thermal model to calculate the operating cell temperature  $T_{cell}$  using a first-principles heat transfer energy balance model developed by Fuentes [10]. The Fuentes model includes effects of the thermal capacitance of the module and performs a numerical integration between timesteps to account for the thermal lag transient behavior. The thermal model uses the total incident POA irradiance, wind speed, and dry bulb temperature to calculate the operating cell temperature. PVWatts assumes that the system is installed at a height of 5 m, and that the installed nominal operating cell temperature (INOCT) of the module is 45 °C.

The Fuentes paper discusses translation of the nominal operating cell temperature (NOCT) measured at standard conditions (800 W/m<sup>2</sup>, 20°C ambient) to INOCT based on mounting configuration, but this is not used in PVWatts in the current version. Future versions of PVWatts may include the NOCT to INOCT adjustment based on data for various mounting structures, as suggested in [10] and [11].

## 9 Module Model

The PVWatts module is an adaptation of a PVFORM version 3.3 model [12, 13] that uses the user-specified reference array power at 1,000 W/m<sup>2</sup>. The subroutine computes the DC power from the array with a specified nameplate DC rating of  $P_{dc0}$  given a computed cell temperature  $T_{cell}$  and transmitted POA irradiance  $I_{tr}$ . The array efficiency is assumed to decrease at a linear rate as a function of temperature rise.

$$P_{dc} = \frac{I_{tr}}{1000} P_{dc0} (1 + \gamma(T_{cell} - T_{ref})) \quad I_{tr} > 125 \text{ W/m}^2 \quad (5)$$

The temperature coefficient  $\gamma$  is fixed to -0.5 %/°C, which may be considered typical for crystalline silicon PV modules. The reference cell temperature  $T_{ref}$  is 25°C.

The code adjusts the array efficiency if the insolation is less than 125 W/m<sup>2</sup>. The adjustment arose from observations of plots of efficiency versus insolation at several Sandia PV field sites. When insolation is less than 125 W/m<sup>2</sup> the efficiency is adjusted down at a rate that is proportional to that that is observed in the measured field data. This algorithm assumes that the efficiency is zero at insolation of zero. This is not true but is a reasonable assumption for a performance model. The effect is to reduce the overall performance of a fixed-tilt system at low light levels.

$$P_{dc} = \frac{0.008 \cdot I_{tr}^2}{1000} P_{dc0} (1 + \gamma(T_{cell} - T_{ref})) \quad I_{tr} \leq 125 \text{ W/m}^2 \quad (6)$$

## 10 System Derates

The overall system derate  $\xi_{sys}$  provided by the user as a fraction between zero and one represents losses in the system due to nameplate direct current (DC) ratings, inverter efficiency at maximum power, mismatch, diodes and connections, DC wiring, alternating current (AC) wiring, soiling, system availability, shading, tracking error, and aging. The default derate on power is given as a factor of 0.77, as discussed in [9].

The system losses applied to the DC output of the system include all losses except the inverter efficiency at maximum power  $\eta_{inv}$ . Therefore, the derated DC power output is given by

$$P'_{dc} = P_{dc} \cdot \frac{\xi_{sys}}{\eta_{inv}} \quad (7)$$

The derated DC power  $P'_{dc}$  is passed to the inverter model.

## 11 Inverter Model

The inverter model in PVWatts is an adaptation of the PVFORM version 3.3 subroutine that computes AC power from the inverter system. It uses a model developed by Leeman and Menicucci of Sandia based on efficiency changes of typical power conversion unit systems as a function of the load on the system. These efficiency changes were determined through numerous measurements made at Sandia, and the model is determined by fitting a curve through a set of inverter efficiency measurements ranging from inputs of 10% of full power to 100% of full power. The efficiency equation is a third order polynomial. Between 0% and 10% a linear change is assumed.

PVWatts assumes a nameplate DC-to-AC ratio of 1, so the inverter AC nameplate rating  $P_{ac0}$  is equal to the DC rating  $P_{dc0}$  of the system. An effective inverter DC input power rating  $P_{inv,dc0}$  is calculated from the full-load inverter efficiency and the AC nameplate rating  $P_{ac0}$ . The part-load operation fraction  $f$  is defined by the ratio of derated DC power  $P'_{dc}$  to the inverter DC rating  $P_{inv,dc0}$ .

$$P_{inv,dc0} = P_{ac0}/\eta_{inv} \quad f = P'_{dc}/P_{inv,dc0} \quad (8)$$

The inverter conversion efficiency at operating conditions  $\eta_{op}$  is given by Eqn. 9 whose coefficients arise from measurements of typical inverter performance [12, 13].

$$\eta_{op} = 0.774 + 0.663f - 0.952f^2 + 0.426f^3 \quad \text{for} \quad 0.1 \leq f \leq 1 \quad (9)$$

$$\eta_{op} = -0.015 + 8.46f \quad \text{for} \quad 0 < f < 0.1 \quad (10)$$

For either condition,  $\eta_{op}$  is constrained between 0 and 0.925, and no night time standby losses are calculated.

As noted in the previous section, the overall system derate includes the nameplate inverter efficiency. The nominal maximum power inverter efficiency  $\eta_{inv}$  is assumed to be 0.92. The ratio of the specified inverter efficiency at full load  $\eta_{inv}$  and a fixed reference efficiency of 0.91 at full load is used in addition to compute the effective inverter efficiency at the operating conditions. The fixed reference conversion efficiency of 0.91 corresponds to the data at which the part-load efficiency curve described above was determined. Therefore, the final AC power output is given by

$$P_{ac} = P'_{dc} \cdot \eta_{op} \cdot \frac{\eta_{inv}}{0.91} \quad (11)$$

For  $f > 1$ , the power output is clipped to the maximum AC power rating  $P_{ac0}$ .

## 12 Model Outputs

PVWatts calculates several hourly outputs based on the system specifications and hourly irradiance, temperature, and wind speed data. They are summarized in Table 5.

Table 5. Hourly Calculated Outputs

Field	Units
Incident POA irradiance	W/m <sup>2</sup>
Transmitted POA irradiance	W/m <sup>2</sup>
DC power	W
AC power	W

In addition, the average incident POA irradiance per day in each month is reported to the user. For each month  $m$ , the average POA in (kW/m<sup>2</sup>/day) is given by Eqn. 12.

$$POA_m = \frac{0.001 \cdot \sum_m POA_h}{\text{number of days in month } m} \quad (12)$$

The hourly outputs DC and AC power are aggregated into monthly and annual energy totals that are reported to the user.

## 13 Conclusion

This document provides a detailed outline of the modeling steps undertaken by the PVWatts model. The integrated system model requires a minimal set of user-specified system specifications and makes numerous assumptions about various performance parameters intended to yield typical results for “common” PV system configurations and types. The small number of user inputs makes it possible for novices to use the model and have acceptable confidence in obtaining reasonable results.

## 14 Future Work

The world-wide PV industry has progressed significantly since the inception of PVWatts. As PVWatts remains a popular tool across a variety of stakeholders and in many cases remains the calculation basis for incentive and rebate amounts in various localities, it is important to ensure that PVWatts results reflect current technologies that are being deployed. For example, inverters in 2013 are notably more efficient than the 92 % efficiency assumed. The list below indicates potential future areas of investigation by the PVWatts development team.

- Update to the overall 0.77 derate default value based on analysis of large datasets of current PV system performance
- Update to the inverter part-load efficiency curve based on analysis of over 1000 inverter performance datasets
- Inclusion of mounting configuration specific adjustments to the INOCT in the thermal model
- Ability for the user to select “premium” versus “standard” modules; this choice will affect the module temperature coefficient  $\gamma$  and possibly the incidence angle modifier polynomial coefficients  $b_i$ .

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