Module Characterization
Energy Prediction Adjustment for Local Spectrum

Purpose

This document describes the means, methods, and data requirements necessary to compute spectral correction factors using the First Solar method.

Results

PV modules are rated under Standard Test Conditions (STC) assuming a spectral distribution as defined by ASTM G173 with an Air Mass of 1.5. Much like temperature and total irradiance, site-specific spectral irradiance will deviate from STC, resulting in varying performance compared to module nameplate. The following procedure presents a method to account for this difference by defining a new variable called the spectral correction factor (***M***) which can be used as an input for energy predictions. Spectral corrections for PV modules are primarily driven by two factors: atmospheric precipitable water (P_{wat}) and absolute air mass (AM_a).

Precipitable water, also known as the integrated water vapor, is the depth of water in a column of the atmosphere if all of the water in that column were condensed into a container on the earth's surface. Absolute air mass, also known as elevation adjusted air mass, is a measurement of how much atmosphere irradiance must pass through before it reaches the earth's surface. An AM_a of 1 corresponds to the sun being directly overhead (90° from the horizon) when at sea-level, AM_a 1.5 corresponds to a solar position 60° from the horizon, and AM_a 10 corresponds to the sun being roughly 5° above the horizon.

Consequently, to use this spectral correction method, both precipitable water and absolute air mass data are needed in order to run an energy prediction. If precipitable water is not available, either relative humidity and ambient temperature or dew point and ambient temperatures can be used to approximate it. Absolute air mass is a function of solar geometry and surface level atmospheric pressure. If atmospheric pressure is not available, it can be estimated using surface altitude. The following measurement variables are used in the calculation of the spectral correction factor:

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Variable Name	Description	Units
M	Spectral Correction	%
P_{wat}	Precipitable Water	cm
T_{amb}	Ambient Temperature	°C
RH	Relative Humidity	%
T_{dp}	Dew Point Temperature	°C
AM_a	Absolute Air Mass	Unitless
AM_r	Relative Air Mass	Unitless
SLP	Surface Level Pressure	mbar
Z	Apparent Zenith Angle	°
GHI	Global Horizontal Irradiance	W/m²

Table 1. Key variables used in calculating the spectral correction factor.

Methods of Estimating Precipitable Water

If precipitable water is not available in the meteorological data source, either ambient temperature and relative humidity or ambient temperature and dew point temperature can be used to approximate P_{wat}.

Using Ambient Temperature and Relative Humidity to Estimate Precipitable Water

If the available weather file does not include precipitable water but does include ambient temperature and relative humidity, the following calculations should be performed. Ambient temperature should first be converted from degrees Celsius to degrees Kelvin:

$$T_{amb,K} = T_{amb} + 273.15$$

Next, precipitable water is estimated from ambient temperature and relative humidity on an hourly basis[2]:

$$P_{wat} = 0.1\left(0.4976 + 1.526\frac{T_{amb,K}}{273.15} + e^{13.6897\frac{T_{amb,K}}{273.15} - 14.9188\left(\frac{T_{amb,K}}{273.15}\right)^3}\right)\left(216.7\frac{RH}{100T_{amb,K}}e^{22.33-49.14\frac{100}{T_{amb,K}} - 10.922\left(\frac{100}{T_{amb,K}}\right)^2 - 0.39015\frac{T_{amb,K}}{100}}\right)$$

For example, if RH = 70% and Tamb = 30°C, P_{wat} is estimated at by the above equation to be 4.7 cm. The expected range of precipitable water is 0.1 cm to 8.0 cm.

Using Ambient Temperature and Dew Point Temperature to Estimate Precipitable Water

If the available weather file does not include precipitable water or relative humidity but does include ambient and dew point temperatures, the following calculations should be performed. Relative humidity should first be estimated from ambient and dew point temperatures[3]:

$$\boldsymbol{RH = 100\left(e^{\frac{17.1T_{dp}}{234.2+T_{dp}}} \Big/ e^{\frac{17.1T_{amb}}{234.2+T_{amb}}}\right)}$$

For example, if dew point temperature is 15°C and ambient temperature is 20°C, *RH* is estimated to be 72.6%. Once *RH* is estimated, the equation in the previous section for estimating P_{wat} from *RH* and T_{amb} should be used.

If precipitable water is available in the meteorological data source, the above calculations need not be performed.

Methods of Estimating Absolute Air Mass

Absolute air mass is not commonly available in meteorological data sets and cannot be measured directly. Fortunately, *AMa* is primarily a function of sun-earth geometry, and it can therefore be easily estimated for any location on earth at any moment in time. All of the functions used to estimate absolute air mass are contained within PV_LIB, a set of well documented functions for simulating the performance of photovoltaic energy systems that was developed by Sandia National Laboratories[4].

AMa is a function of relative air mass (AMr) and surface level atmospheric pressure:

$$AM_a = AM_r \cdot \frac{SLP}{1013.25\, mbar}$$

If pressure is not available, it can be estimated from surface altitude (*ATL*), where *ALT* is in meters[5]:

$$SLP = \left(\frac{44331.514 - ATL}{11880.516}\right)^{(1/0.1902632)}$$

AMr is a function of apparent zenith angle. It can be estimated using the methodology proposed by Kasten and Young[6]:

$$AM_r = \frac{1}{\cos(Z) + 0.50572 \times (6.07995 + (90 - Z)^{-1.6364})}$$

Apparent zenith angle can be calculated using a wide array of solar position model models. Grover Hughes of Sandia National Laboratories proposed a solar position model that has been validated using other sun-pointing algorithms and by other astronomical and satellite tracking tests[7]. This full solar position algorithm is also available in PV_LIB.

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Calculating Spectral Correction Factor from Precipitable Water and Absolute Air Mass

The spectral correction factor is estimated for each prediction time interval (commonly 1 hour) from precipitable water (cm) and absolute air mass (unitless) using the algorithm below[9]. The spectral correction is of a simple functional form so that it can be computed with relative ease. The following equation should be used to compute the spectral correction factor for all PV modules:

$$M = b_0 + b_1 \cdot AM_a + b_2 \cdot p_{wat} + b_3 \cdot \sqrt{AM_a} + b_4 \cdot \sqrt{p_{wat}} + b_5 \cdot \frac{AM_a}{\sqrt{p_{wat}}}$$

The values of coefficients b0 through b5 are dependent on the module technology being modeled. As shown in Table 2 below, there is one set of coefficients for First Solar Series 4-2 modules and later and another set of coefficients for Series 4-1 modules and earlier. The spectral correction model can also be applied to crystalline silicon type PV modules. Representative coefficients for mono-crystalline silicon (Mono-Si) and poly-crystalline silicon (Poly-Si) PV modules are also contained in Table 2. The coefficients for Mono-Si and Poly-Si modules are intended as representative examples. While research suggests that the provided coefficients are reasonable approximations, First Solar has not confirmed that the provided coefficients are applicable to all modules of each respective technology type.

Module	b_0	b_1	b_2	b_3	b_4	b_5
FS4-2 and Later	0.86273	-0.038948	-0.0125060	0.098871	0.084658	-0.0042948
FS4-1 and Earlier	0.79418	-0.049883	-0.0134020	0.167660	0.083377	-0.0044007
Mono-Si	0.85914	-0.020880	-0.0058853	0.120290	0.026814	-0.0017810
Poly-Si	0.84090	-0.027539	-0.0079224	0.135700	0.038024	-0.0021218

The spectral correction is applicable to precipitable water values between 0.1 cm and 8 cm. P_{wat} values outside of this range are uncommon, and should be double checked to ensure data quality. If deemed accurate, P_{wat} values below 0.1 cm must be replaced with 0.1 cm or filtered from the dataset in order to ensure model stability. P_{wat} values above 8.0 cm will not cause the model to destabilize, but should be treated as suspect.

Similarly, the spectral correlation is applicable to absolute air mass conditions between 0.58 and 10. AM_a conditions below 0.58 only occur at elevations higher than permanent human settlements and should be treated as highly suspect. AM_a values greater than 10 occur near sunset and sunrise when overall irradiance conditions are low. To ensure model stability, AM_a values greater than 10 must be set equal to 10 or excluded.

References

[1] First Solar Application Notes PD-5-423/PD-5-423 EX, "Module Characterization: Energy Prediction Adjustment for Local Spectrum" 2015.

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[3] Meteonorm Global Meteorological Database. Version 7. "Handbook part II: Theory." September 2014. Page 50. http://meteonorm.com/images/uploads/downloads/mn71_theory.pdf.

[4] Sandia Corporation, "PV Performance Modeling Collaborative: PV_Lib Toolbox," 2014. https://pvpmc.sandia.gov/applications/pv_lib-toolbox/

[5] Portland State Aerospace Society, "A Quick Derivation Relating Altitude to Air Pressure" https://www.researchgate.net/file.PostFileLoader.html?id=5409cac4d5a3f2e81f8b4568&assetKey=AS%3A273593643012096%401442241215893

[6] Kasten, F., Young, A., 1989. "Revised Optical Air Mass Tables and Approximation Formula", Applied Optics vol. 28(22), pp. 4735–4738. https://www.osapublishing.org/ao/abstract.cfm?uri=ao-28-22-4735

[7] Zimmerman, John C. "Sun-Pointing Programs and Their Accuracy." Sandia National Laboratories, SAND81-0761, May 1981. http://www.osti.gov/scitech/servlets/purl/6377969