Module Characterization

Energy Prediction Adjustment for Local Spectrum

Purpose

This document describes the means, methods, and data requirements necessary to compute spectral correction factors for First Solar modules for the purpose of deriving inputs for energy predictions.

Results

First Solar 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 First Solar 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:

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/m^2

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, AM_a 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].

AM_a is a function of relative air mass (AM_r) 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]:

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

AM_r 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, and First Solar has transcribed the Grover solar position algorithm into an Excel tool, PD-5-423 EX, which may be used to assist in spectral calculations[8].

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 First Solar 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 b_0 through b_5 are dependent on the module series being modeled. As shown in Table 2 below, there is one set of coefficients for First Solar Series 4-2 modules and later (FS-4XXX-2, FS-4XXXA-2, FS-4XXX-3, FS-4XXXA-3, FS-6XXX, and FS-6XXXA) and another set of coefficients for Series 4-1 modules and earlier (FS-2XX, FS-3XX, FS-3XX-LV, FS-3MDXX, FS-3XXR, FS-3XXR-LV, FS-3XXA-Plus, FS-3XX-Plus, FS-4XXX, and FS-4XXXA). 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.

Using Spectral Corrections in Energy Simulation Tools

First Solar introduced PlantPredict, a cloud-based web application that allows users to develop solar energy estimates for utility scale PV applications[10]. PlantPredict has the spectral correction method proposed by Lee and Panchula[9] natively included. In PlantPredict, spectral corrections can be applied automatically from weather and site input data on an hourly basis or manually input on a monthly basis.

First Solar recognizes that some PV simulation applications, such as PVsyst, do not have spectral corrections natively included. Moreover, these applications often do not allow the user to calculate spectral corrections on their own and input hourly performance corrections. When this is the case, the effects of spectrum can be reasonably approximated using monthly corrections [11]. For use in PVsyst, hourly spectral correction values should be irradiance-weighted and averaged for each calendar month to yield aggregate monthly spectral correction factors. The resulting spectral correction factor shall be presented as a relative loss or gain with regard to nominal energy ($M = 100\%$). For each calendar month:

$$M_m = 1 - \frac{\sum(M_h \times GHI_h)}{\sum GHI_h}$$

where, M_m is the monthly spectral correction factor, M_h is the hourly spectral correction factor for the given month, and GHI_h is the hourly irradiance measurement for the given month. Following standard PVsyst loss notation, positive values of M_m represent a loss in energy due to spectrum while negative values represent an energy gain. Example annualized calculations for selected geographical regions are included in the Appendix.

A Convenient Method of Inputting Monthly Spectral Corrections into PVsyst

Once the spectral correction factor is computed and aggregated on a monthly basis, the factor is used to adjust modeled plant performance. As a matter of convenience, this loss factor is combined with the monthly soiling loss input in PVsyst. For example, if, for a given month, the soiling loss is 4% and the spectral loss is -1% (with respect to nominal energy), then a soiling loss of 3% is input into PVsyst. An additional example of combining the soiling and spectral inputs for each month of the year is given in Table 3.

Month	Soiling Loss	Spectral Loss	PVsyst Soiling Loss Input
Jan	4.00%	2.42%	6.42%
Feb	4.00%	2.17%	6.17%
Mar	4.00%	0.63%	4.63%
Apr	4.00%	-0.56%	3.44%
May	4.00%	-1.85%	2.15%
Jun	4.00%	-2.69%	1.31%
Jul	4.00%	-3.52%	0.48%
Aug	4.00%	-3.37%	0.63%
Sep	4.00%	-2.70%	1.30%
Oct	4.00%	-0.07%	3.93%
Nov	4.00%	1.38%	5.38%
Dec	4.00%	2.02%	6.02%

Table 3. Example of combining soiling and spectral losses for input into PVsyst.

Because PVsyst does not allow negative soiling loss inputs, a workaround is required in the case that the spectral gain exceeds the soiling loss in any given month. In such cases, we recommend in- creasing the soiling loss so that the most negative monthly combined spectral and soiling loss equals zero and offsetting this increase with a decrease in the module quality loss. For example, if soiling values in Table 3 were decreased to 1%, there would be several months in which a negative soiling loss input would occur, the most negative of which would have a desired input of -2.5%. For this case, we would recommend reducing the desired module quality loss by 2.5% and increasing the soiling loss by 2.5% which would result in a net zero change in loss factors and no negative soiling loss inputs. The rightmost column in Table 4 represents the final recommended soiling inputs with the adjusted module quality loss. PD-5-423 EX may be used to assist in spectral calculations.

	with Desired Module Quality Loss of 0.0%			with Adjusted Module Quality Loss of -2.5%		
Month	**Soiling Loss**	**Spectral Loss**	**PVSyst Soiling Loss Input**	**Adjusted Soiling Loss**	**Spectral Loss**	**PVSyst Soiling Loss Input**
Jan	1.0%	2.4%	3.4%	3.5%	2.4%	5.9%
Feb	1.0%	2.2%	3.2%	3.5%	2.2%	5.7%
Mar	1.0%	0.6%	1.6%	3.5%	0.6%	4.1%
Apr	1.0%	-0.6%	0.4%	3.5%	-0.6%	2.9%
May	1.0%	-1.8%	-0.8%	3.5%	-1.8%	1.7%
Jun	1.0%	-2.7%	-1.7%	3.5%	-2.7%	0.8%
Jul	1.0%	-3.5%	-2.5%	3.5%	-3.5%	0.0%
Aug	1.0%	-3.4%	-2.4%	3.5%	-3.4%	0.1%
Sep	1.0%	-2.7%	-1.7%	3.5%	-2.7%	0.8%
Oct	1.0%	-0.1%	0.9%	3.5%	-0.1%	3.4%
Nov	1.0%	1.4%	2.4%	3.5%	1.4%	4.9%
Dec	1.0%	2.0%	3.0%	3.5%	2.0%	5.5%

Table 4. Example of combining soiling and spectral losses for input into PVsyst with Module Quality loss adjustment.

References

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[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&asset-Key=AS%3A273593643012096%401442241215893

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[8] First Solar Application Notes PD-5-423 EX, “Module Characterization: Energy Prediction Adjustment Calculation Aid” 2016.

[9] Lee, M. and Panchula, A. "Spectral Correction for Photovoltaic Module Performance Based on Air Mass and Precipitable Water," *43rd IEEE Photovoltaic Specialists Conference*, Portland, 2016.

[10] "PlantPredict: Solar Performance Modeling Made Simple." https://plantpredict.com (2016)

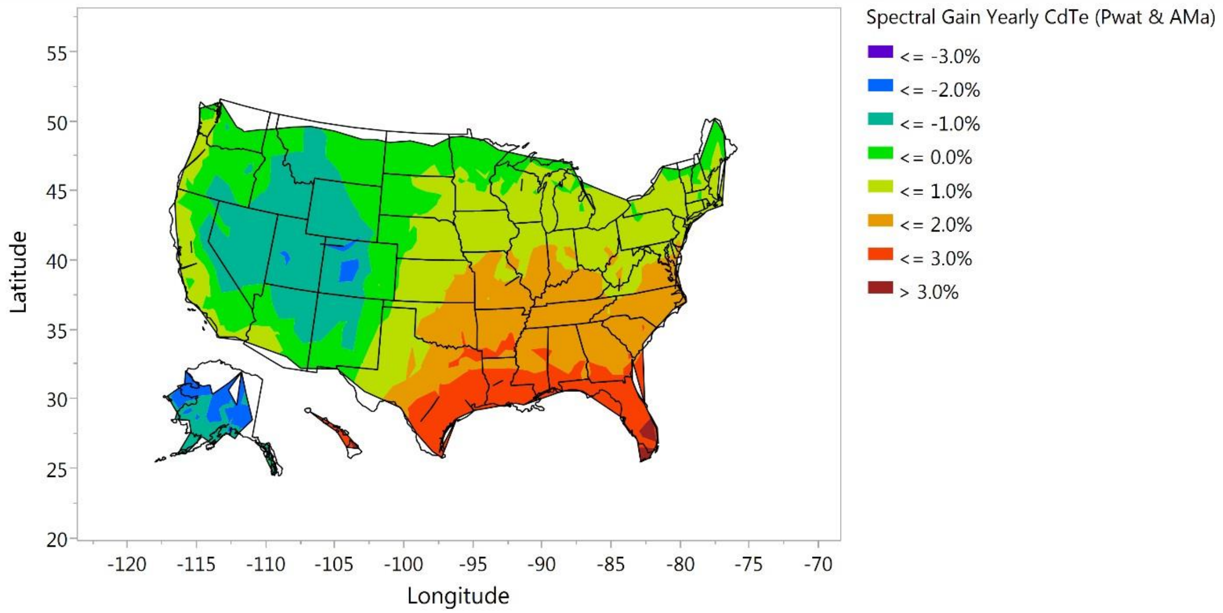
[11] Passow, K., Ngan, L., Littmann, B., Lee. M, and Panchula. A, "Accuracy of Energy Assessments in Utility Scale PV Power Plant using PlantPredict," *42nd IEEE Photovoltaic Specialists Conference*, New Orleans, 2015.

Appendix – Example Maps of Annual Spectral Gain

Graphs included below represent an expected percent annualized spectral gain. The calculation methods outlined above were used and averaged over the whole year, instead of determining monthly values.

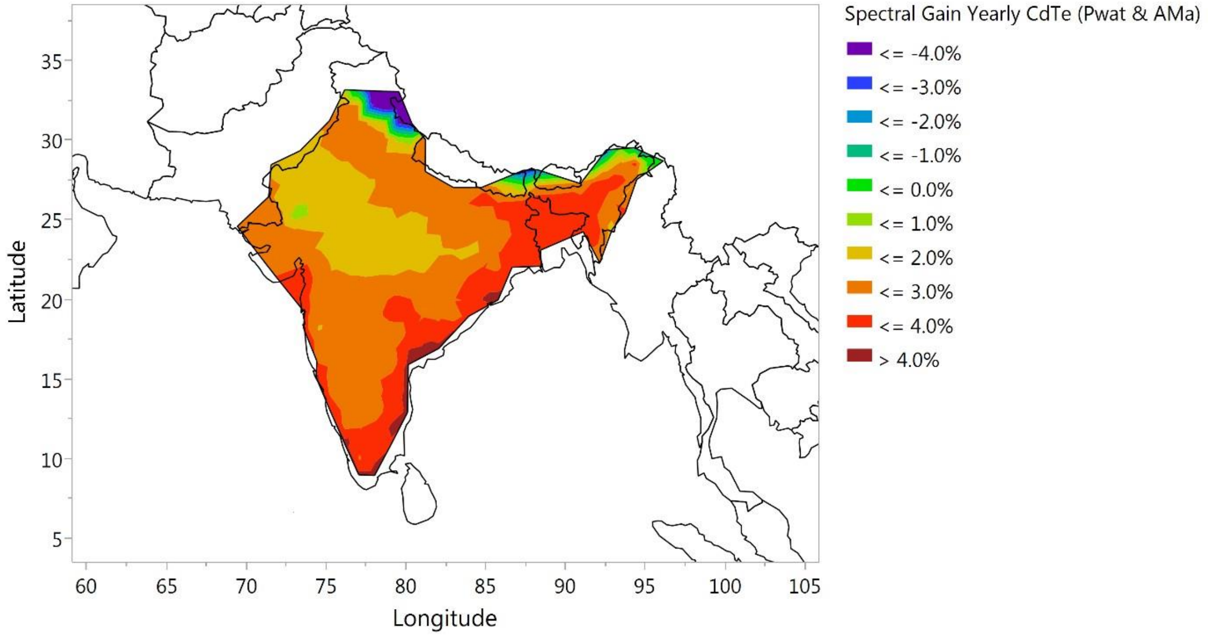
The average monthly spectral gain may not be the same as the annualized spectral gain due to the weighting with GHI. However, the annualized spectral gain indicated in the maps is the expected net gain due to spectral effects over a typical year.

Continental United States Spectral Correction Map for Series 4V2 and Later Modules



NOTE: Source environmental data taken from NREL TMY3 data sets.

India Spectral Correction Map for Series 4V2 and Later Modules



NOTE: Source of environmental data is from Meteonorm data sets.