

BEAM – TILTED CORRELATIONS

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ABSTRACT

A model is described and evaluated that calculates beam irradiance from tilted solar radiance. This model will then be used to estimate the performance of a photovoltaic system using only tilted data values and compared to results using measured direct normal beam values. The results and advantages of this model will then be discussed along with the limitations of this model.

1. INTRODUCTION

The number and variety of grid-tied photovoltaic (PV) systems being installed is stimulating interest in the performance of these systems and their components. Earlier efforts by groups such as PV USA and Sandia to evaluate system performance measured variables such as system AC output, DC current and voltage from the modules, module temperature, ambient temperature, wind speed, incident solar radiation and direct normal, global, and diffuse irradiance. Data gathered from these projects were used to develop models to estimate the performance of PV systems given manufacturer specification of module DC output under standardized operation conditions (25 Celsius and 1000 watts/meter² incident solar radiation). These models are now being used to estimate the system performance locations with meteorological and comprehensive solar radiation data. Specifically, these models were designed to use the National Solar Radiation Data Base that included direct normal, global, and diffuse irradiance values along with temperature, wind speed, and other meteorological variables and weather conditions.

With the variety of solar cell modules and balance of system components now available there is growing interest in how the new systems perform. Because of the expense of obtaining high quality solar radiation data, especially direct normal beam data, many of the systems being monitored

only install a pyranometer tilted in the plane of the array along with other meteorological sensors and watt transducers. The one draw back of this approach is that programs used to estimate system performance need direct normal beam irradiance values when calculating the transmittance of the solar radiation through the covering of the solar cell modules. Currently there are no models to estimate direct normal beam values from one tilted pyranometer.

This article will describe the development of a beam-tilted irradiance correlation model developed using solar radiation data gathered in Eugene, Oregon at the University of Oregon Solar Radiation Data Monitoring Laboratory (UO SRML). First the data will be discussed followed by the rationale of the model parameters finally selected. Next the beam-tilted irradiance model will be discussed and evaluated. This model will then be used to estimate the performance of a PV system and the errors introduced by the model will be evaluated.

2. THE DATA

Quality control, high quality instruments, consistent maintenance and calibration are helpful in ensuring the accuracy of the data used in any study. The data used in this study come from the main reference station of the UO SRML network in Eugene, Oregon. The tilted instruments are Eppley PSP pyranometers and the direct normal beam irradiance is measured using an Eppley Normal Incidence Pyrheliometer. Diffuse irradiance is measured with a Schenk Star pyranometer that is shaded by a shadeball on a Sci-Tek Automatic Tracker. The Schenk pyranometer is also mounted on a ventilator to help minimize the dust.

Recently studies have shown that thermopile pyranometers with black disks radiate to the sky and this re-radiation causes an offset by about 10 – 20 watts/meter². Black and

white thermopile pyranometers also radiate to the sky, but the black and white surfaces radiate almost an equal amount and the pyranometer works by measuring the temperature difference between the black and white areas. Hence the black and white pyranometers don't have this systematic error. At the UO SRML, the diffuse irradiance is measured by the Schenk Star pyranometer because it is a black and white pyranometer and has a minimum amount of error caused by the re-radiation to the sky.

The global irradiance on a horizontal surface is calculated by projecting the beam irradiance onto the horizontal surface by multiplying the beam irradiance by the cosine of the incident angle and adding the diffuse irradiance. These calculated global values provide a much more accurate estimate of global irradiance than the measured values and are the global horizontal values used in this study.

The tilted pyranometers also re-radiate. Since the instruments also see some of the surface as well as the sky, their re-radiation is somewhat less than that of a horizontal pyranometer. To help offset the effect of re-radiation, the UO SRML averages the re-radiation at night and adds it back in the daytime. This helps reduce the systematic offset by roughly 50%.

For this study, global values and tilted irradiance values at 30°, 45°, and 90° are utilized. These are all south facing pyranometers. The pyranometers at 30° and 90° have a shield that blocks some of the ground reflection while the pyranometer at 45° has no such shield.

The instruments are cleaned each workday and are calibrated annually. Data are collected in integrated 5-minute intervals using Campbell Scientific data loggers and the data are checked each workday to help insure completeness.

The absolute uncertainty of the beam values is about 2-3% and the uncertainty of the calculated global values is about the same. The uncertainty in the tilted values ranges from 3 to 5%.

The data used in this study are hourly averaged data collected in 2002.

3. DEVELOPING THE CORRELATION

The first step in developing the correlation was to divide the incident beam and tilted values by the equivalent extraterrestrial radiance. This is the standard method used in global-diffuse and beam-global correlations. This normalization helps eliminate some of the well-understood angle of incidence effects and the effects caused by the changes in the earth-sun distance over the year.

An example of the beam-global relationship is given in Fig. 1.

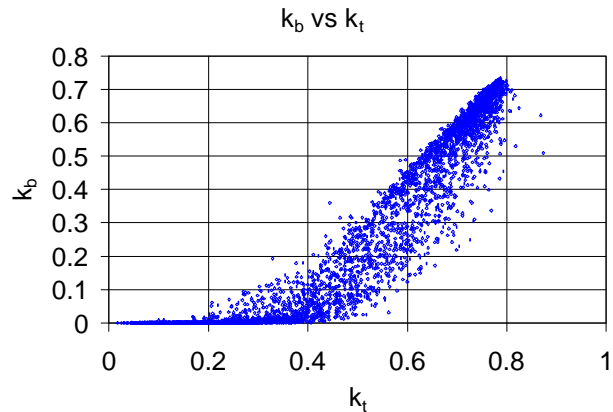
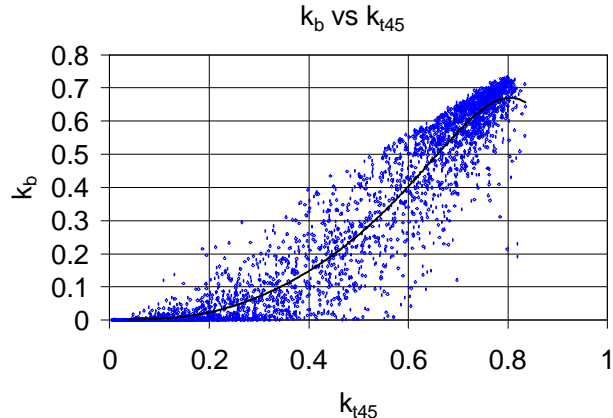


Fig. 1: Relationship between beam and global irradiance.

k_b is the beam irradiance divided by the extraterrestrial and k_t is the global irradiance divided by the extraterrestrial irradiance on a horizontal surface.

A similar relationship can be seen between k_b and k_{tTilt} , the irradiance on a surface tilted Tilt degrees divided by the extraterrestrial irradiance on a similarly tilted surface



(Fig.2).

Fig. 2: Relationship between beam and solar radiation on a 45° south facing tilted surface. Note the wider dispersion of data points than in the beam global irradiance in Fig. 1.

There are several differences between the Figs. 1 and 2. Besides the wider dispersion of data points, the mid values of k_{t45} yield higher values of k_b than the mid values of k_t . However, at high values of k_t and k_{t45} the corresponding values of k_b are similar. Also there are values of k_{t45} that are almost equal to k_b . These high values occur because the diffuse irradiance and ground reflectance can add considerably to the tilted irradiance values. There is no ground reflected irradiance on horizontal surfaces.

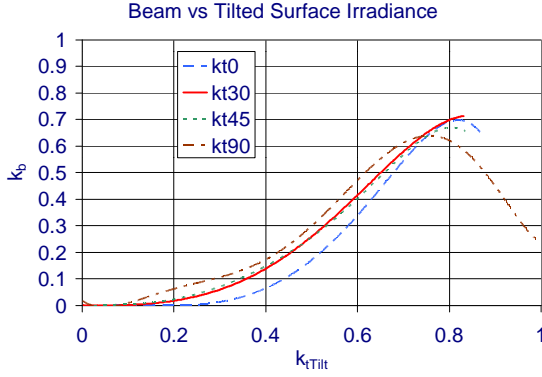


Fig. 3: Trend lines for the k_b versus normalized tilted irradiance k_{Tilt} . Note all trends cross at about $k_b = 0.65$

Trends seen in Figs. 1-2 are similar for other tilts as well. In Fig. 3, the trends of the relationships are plotted verse k_{t0} , k_{t30} , k_{t45} , and k_{t90} . At values of k_{Tilt} near 0.7, all trends correspond to similar values of beam irradiance. These values are typical of clear days where the diffuse irradiance is about 10%-20% of the beam irradiance.

3.1 Insights into variables.

In general, tilted irradiance can be broken down into three components.

$$\text{Tilted} = \text{Beam} \cdot \cos(Z_T) + \text{diffuse} + \text{ground reflected} \quad \text{Eqn. 1}$$

where Z_T is the angle of incidence on the surface tilted T degree. The diffuse (df_T) and ground reflected (gr_T) irradiance are dependent on the tilt of the \hat{e}_T .

Dividing the tilted irradiance by the equivalent extraterrestrial radiation, Eqn. 2, normalizes the tilted irradiance.

$$\text{ETR}_{Tilt} = I_o r \cdot \cos(Z_T) \quad \text{Eqn. 2}$$

Where I_o is the solar constant and r is the earth-sun distance factor.

Therefore,

$$k_{Tilt} = k_b + (df_T + gr_T) / I_o r \cos(Z_T) \quad \text{or} \\ k_b = k_{Tilt} - (df_T + gr_T) / I_o r \cos(Z_T) \quad \text{Eqn. 3}$$

where k_b is the beam irradiance divided by $I_o r$, the extraterrestrial beam irradiance.

Because the amount of beam irradiance varies considerably depending on the sky conditions, other beam-global correlation studies used the change in global irradiance from

TABLE 1 CORRELATION COEFFICIENTS AND THEIR STANDARD ERROR.

Variables	Coefficients	Standard Error
Intercept	-0.0881	32.0%
$\cos^2 \hat{e}_T$	-0.1485	-2.7%
k_{Tilt}	2.5785	10.8%
k_{Tilt}^2	-11.2055	-8.5%
k_{Tilt}^3	22.2090	6.0%
k_{Tilt}^4	-13.1394	-5.1%
$1/\cos Z_T$	-0.02906	-3.2%
$\cos^2 \hat{e}_T / \cos Z_T$	0.03131	3.9%
$\ddot{A}_{k_{Tilt}}$	-0.02499	17.0%

one hour to the next as a variable. This study will also use this variable, $\ddot{A}_{k_{Tilt}}$, where $\ddot{A}_{k_{Tilt}}$ is determined by subtracting the value of k_{Tilt} of the next hour from the value at the current hour.

In this correlation study k_b will be correlated against k_{Tilt} , $1/\cos(Z_T)$, $\cos(\hat{e}_T)$, and $\ddot{A}_{k_{Tilt}}$.

4. CORRELATION RESULT

The following is the result of a correlation study on four tilt, horizontal or 0° , 30° , 45° , and 90° . The data was screened to eliminate any hour when the average angle of incidence was greater than 85° . At angles great than 85° , there are larger uncertainties in measured values and the value k_{Tilt} can be greater than 1.

The correlation equation for the normalized hourly beam index is

$$k_b = a + b \cdot \cos^2 \hat{e}_T + c \cdot k_{Tilt} + d \cdot k_{Tilt}^2 + e \cdot k_{Tilt}^3 + f \cdot k_{Tilt}^4 + g / \cos Z_T + h \cdot \cos^2 \hat{e}_T / \cos Z_T + i \cdot \ddot{A}_{k_{Tilt}} \quad \text{Eqn. 4}$$

For some unknown reason the correlation gave a better fit for $\cos^2 \hat{e}_T$ than just $\cos \hat{e}_T$. The overall standard error for this correlation was 0.065 with an R^2 of .92. For comparison, the standard error (standard deviation) for just the beam-global correlation using the 2002 Eugene data is about 0.055. With the wider spread in the data shown in Fig. 2, the increase in standard error is expended.

For k_{Tilt} less than 0.15, $k_b = 0.05 \cdot k_{Tilt}$. Also, any values of k_b predicted to be less than zero were set to zero and any value of k_b greater than 0.75 were set equal to 0.75

4.1 Discussion of Correlation Results

Fig. 4 illustrates how well the correlation describes a relationship between beam and total tilted irradiance. The residuals (the difference between the data values and the predicted values) are plotted against k_{Tilt} .

While the trend line shows that the correlation accurately reproduces the mean k_b , there still is a fairly large scatter for values of k_{Tilt} in the mid range. This is to be expected because of the wide variety of cloudy conditions that yield the values of k_{Tilt} in this range. Clear periods, which yield high values of k_{Tilt} , have comparatively smaller variation in the diffuse values, resulting in better correlation with the beam values.

Very high values of k_{Tilt} can also be obtained and it is possible to get values higher than 1. For example, when the sun is behind the tilted surface, the extraterrestrial irradiance (ETR) on the tilted surface is zero but the diffuse and reflected irradiance can be significant. If this situation was allowed in this study, the calculated value of k_{Tilt} would be infinite. This situation is eliminated in this study because the angle of incidence was required to be greater than 85° . However, there are situations when the extraterrestrial beam irradiance can be smaller than the sum of the incident beam values plus the diffuse and ground reflected components. When using the correlation in this study, one has to take appropriate steps to ensure that extremely high beam values are not obtained. That is why k_b was limited to 0.75. For other areas with smaller turbidity values, especially at higher altitudes, the limit of k_b should be increased slightly.

Also this correlation should not be used to obtain beam values when the incident angle to the tilted surface is greater than 90° degrees.

5. PV SYSTEM EVALUATION

The reason this correlation model was developed was to determine the beam irradiance for use in modeling PV performance. The beam component is used to calculate how much incident solar radiation is transmitted through the glazing. Without an estimate of the beam irradiance, the calculation fails.

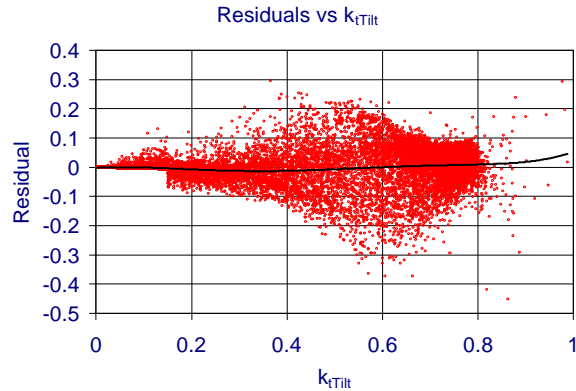


Fig. 4: Plot of residuals versus k_{Tilt} . Note the sharp increase in negative residuals at $k_{Tilt} = 0.15$. That is the result of changing to the more complex correlation.

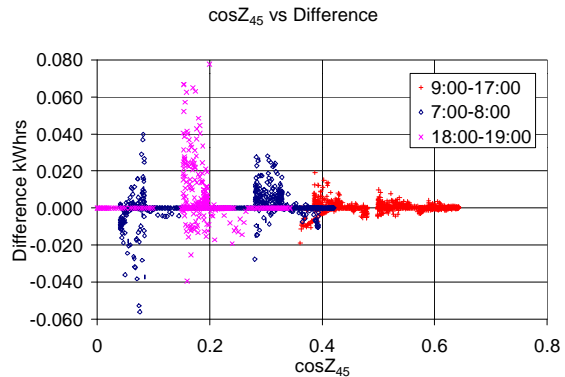


Fig. 5: The difference between estimated PV performance using measured and correlation derived beam values for the cosine of the angle of incidence greater than 50° . The differences are greatest in the early morning and late evening hours.

TABLE 2: COMPARISON OF SYSTEM PERFORMANCE WITH MEASURED AND CORRELATED BEAM IRRADIANCE (% DIFFERENCE)

comp	6:00	7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00
Jan	0	0	0	-1.5	0	0	0	0	0	0	-0.2	-7.9	0	0
Feb	0	0	-22.6	-0.7	0	0	0	0	0	0	0.0	-1.4	-71.0	0
Mar	0	0	-3.1	0.2	0	0	0	0	0	0	0.0	0.0	-0.7	0
Apr	0	62.7	2.8	0.3	0	0	0	0	0	0	0.1	0.9	14.9	0
May	0	6.1	5.1	0.5	0	0	0	0	0	0	0.2	1.8	32.6	0
Jun	0	-29.1	6.9	0.8	0	0	0	0	0	0	0.2	1.5	12.5	0
Jul	0	-72.0	4.7	0.6	0	0	0	0	0	0	0.1	1.0	9.0	0
Aug	0	-31.3	2.3	0.3	0	0	0	0	0	0	0.0	0.7	4.6	0
Sep	0	-74.4	-0.3	0.1	0	0	0	0	0	0	0.0	-0.6	-14.1	0
Oct	0	0	-2.9	-0.1	0	0	0	0	0	0	-0.1	-4.9	0	0
Nov	0	0	-5.2	-0.4	0	0	0	0	0	0	-0.6	-25.0	0	0
Dec	0	0	0	-2.5	0	0	0	0	0	0	-0.3	0.0	0	0

This study used a program based on PVWatts that can be found on the NREL web site at <http://rredc.nrel.gov/solar/>. The yearly kWhr output of a 1 kW AC array at a 45-degree tilt using the 2002 Eugene data is calculated to be 1415 kWhrs per year. With the beam irradiance determined by the correlation instead of the measured irradiance, the resulting kWhrs produced per year is estimated to be 1412 kWhrs or a difference of less than 1/2 of a percent. A small difference is expected because the only time the beam irradiance is used in the calculation is when the angle of incidence on the array is greater than 50°. But at least with the beam-tilted correlation, there is a way to estimate the system performance using only the tilted irradiance data.

Fig. 5 shows that the size of the errors decreases as the cosine of the incident angle increases. When there is little or no beam irradiance there is no difference in the calculations and that produces many of the data points showing zero difference.

Table 2 shows the typical errors in estimates of the PV system performance. This table shows the monthly average error for each hour of the month. Note that during the middle of the day, no error is introduced because the cosine of the angle of incidence is greater than 50° and the models predict the same values. Except for the early morning hours and late evening hours, there is an excellent match between the two calculations of PV system performance.

6. SUMMARY

With knowledge of the limitations, this model will enable evaluation of the performance of PV systems by enabling a comparison of system performance and estimated performance using tilted solar radiation and meteorological data. This work shows it is possible to develop a correlation model to calculate beam irradiance from tilted surface measurements as long as the incident angle on the tilted surface is such that the sun is in the pyranometer's field of view.

With that said, there are many cautions that need to be stated. The beam-tilted correlation should not be used in place of a beam-global correlation. There are already beam-global correlations that have been derived and tested at a variety of locations and fairly good estimates of the beam irradiance can be obtained from these existing models. While the global horizontal irradiance was used to help develop this model, a more precise beam-global correlation can be obtained by just using the beam and global data.

With the knowledge gained about improved diffuse measurements and the use of diffuse and beam data to get a better value for the global irradiance, new beam-global models are likely to appear in the future. With the better

starting data it might be possible to better understand and model the beam-global correlation.

Another limitation to this beam-tilted correlation is that it was developed for one location and a limited number of south facing tilts. To gain full confidence in the parameters of this model, it should be compared with quality data from other locations. Differences in albedo and atmospheric constituents may affect the correlation parameters.

It should be emphasized again that this correlation will not estimate the beam irradiance correctly when the incident angle is greater than 90°, when the sun is above the horizon but behind the pyranometer!

This model works best on clear sunny days, but it can produce significant errors in the beam irradiance, especially when the incident or zenith angle are near 90°. This can be seen in Fig. 5. On average, the correlation model does produce estimates comparable to those that use measured beam data.

This model provides for an important tool. PV system performance can now be compared with modeled estimates with just one tilted pyranometer and some meteorological data.

7. ACKNOWLEDGMENTS

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8. REFERENCES

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