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Evaluation of irradiation measurements on tilted planes at PV systems in the Netherlands

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ABSTRACT: Monitoring data of Dutch PV systems in the field show lower values for the measured global irradiation in the array plane than expected from model calculatations. Since the locations of the PV systems contain obstacles, we expect that shielding of diffuse irradiation may cause the difference. For the Netherlands, the Perez model is the recommended model for calculating the diffuse array plane irradiation. We developed a correction to the Perez model to account for shielding of diffuse irradiation. We tested this model using 5 years of measured data of the PBB system in Utrecht. With the correction model, we could reduce the overestimation of the annual array plane irradiation from 9% to 2%. Both the Perez model and the correction model use an idealized description of the sky dome As a consequence, the correction model may overestimate the impact of the obstacles on the array plane irradation
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1. INTRODUCTION

Design and performance evaluation of PV systems usually involve an estimation of the irradiation incident on the PV module plane. For design purposes usually only global horizontal irradiation is available, published by meteorological institutes. Using irradiation models, one can calculate the gain in irradiation on the tilted plane with respect to the horizontal irradiation.

Monitoring data from a number of Dutch PV systems in the field, where both the horizontal and the array plane irradiation were measured, indicate a smaller array plane irradiation than expected from model calculations (see for example [1]). Alarmed by these data, we performed a study to investigate the cause of the discrepancy. All PV systems are located in a build environment. Therefore, we expected that shielding of irradiation by obstacles may contribute to the discrepency. To study the impact of shielding of irradiation we made a simple model of this phenomenon.

For the study, we used data sets from six PV systems in the Netherlands, with a length of two to five years. At all systems, the horizontal global irradiation has been measured with a pyranometer and the array plane irradiation with a reference cell. At one system, the PBB system at Utrecht University, the horizontal diffuse irradiation and the array plane irradiation with a pyranometer have been measured in addition.

The final report of the study contains the model evaluations for all six PV systems. In this paper we focus on the most complex of the model calculation, viz. the conversion of the diffuse irradiation from the horizontal to the array plane. We use five years of measured data of the PBB system, viz. the horizontal global, horizontal diffuse and global array plane irradiation, all measured with a pyranometer. We evaluate the model calculations by comparing calculated and measured array plane irradiation, both without and with the shielding correction.

2. THEORY

2.1 Calculation of Irradiation on a Tilted Plane

The calculation of the global irradiation on a tilted plane from the horizontal global irradiation can be split up in six steps:

1) Separation of the global horizontal irradiation in a direct and diffuse part. This can be done either by separate measurement of global (or direct) and diffuse irradiation, or by means of a model. The Orgill and Hollands model [2], has been recommended for the Netherlands [3].
2) Conversion of the direct horizontal irradiation to the tilted plane. This is a straightforward calculation on the basis of geometry.
3) Conversion of the diffuse horizontal irradiation to the tilted plane. The Perez model [4] has been recommended for the Netherlands [3].
4) Determination of the ground reflected irradiation, either by measurement or calculation. The impact of ground-reflected irradiaton is usually calculated by means of the albedo.
5) Corrections for reflection and spectrum if the measuring instrument in the tilted plane is a reference cell.
6) Adding the contributrion of the direct, diffuse and reflected irradiation in the array plane.

In the Perez model, it is asssumed that the area surrounding the measuring equipment is free from obstacles that block diffuse light. Since this is not the case for the analyzed data sets, we expand the Perez model in order to incorporate shielding of irradiation by obstacles. The expansion of the Perez model uses the approach of the Perez model. Therefore, we first discuss the Perez model and then our expansion of the Perez model to take into shielding.

2.2 The Perez model

The Perez model is made up of three elements. The first element is a geometrical description of the sky dome consisting of an isotropic background, a circumsolar region and an infinitely small horizon band. In this geometry the diffuse irradiation on a plane with tilt angle β is given by:

$$G_{di} = G_{dh}\left[0.5\left(1-\cos\beta\right)\left(1-F_1'\right)+F_1'\left(\frac{a}{c}\right)+F_2'\sin\beta\right]$$

with G_{di} = diffuse array plane irradiation
G_{dh} = diffuse horizontal irradiation
F_1', F_2' = brightness coefficients
a, c = solid angles occupied by circumsolar region, for array and horizontal plane

The second element is a parameterization of the insolation conditions by means of the parameters the sky clearness parameter ε, the sky brightness parameter Δ and the sun azimuth angle Z.
The third element of the Perez model is an empirical relationship between the first two elements:

$$F_i' = F_{i1}'(\varepsilon) + F_{i2}'(\varepsilon)\Delta + F_{i3}'(\varepsilon)Z$$

where i can be 1 or 2.

The Perez model contains a table of values for $F_{ij}'(\varepsilon)$. Negative values of $F_{2j}'(\varepsilon)$ correspond to meteorological conditions where the top of the sky dome emits more radiation than the horizon band.

2.3 Perez Model with Shielding Correction

We developed a simple correction to the Perez model to incorporate the shielding of diffuse light originating from the isotropic background and the horizon band by an object with a simple geometry. We used the geometry of the sky dome of the Perez model.

We assume that the object has an angle height ξ and that the left and right corner are at LC and RC respectively (LC and RC are expressed as the angle relative to the surface azimuth angle of the tilted plane). The object is assumed to be completely black.

To be able to use the Perez model we should calculate the amount of horizontal diffuse irradiation that is blocked by the shielding object. In the Perez model the horizon band does not contribute to the irradiation on a horizontal plane. Therefore, we can obtain a correction factor for the horizontal diffuse irradiation by integrating the isotropic irradiation over the area of the sky dome that is shielded by the object. This results in:

$$G_{dh}^{ideal} = G_{dh}^{meas} + \frac{(1-F_1')}{8} \bullet (RC - LC) \bullet (1-\cos(2\xi))$$

where the superscript ideal denotes irradiation in the absence of the shielding object.

G_{dh}^{ideal} can now be used as in input to the Perez model to calculate the diffuse irradiation on the tilted plane if no shielding object were present. The resulting value can than be corrected for the presence of the shielding object:

$$\begin{aligned} G_{di} = \; & G_{di}^{ideal} \\ & - \frac{(1-F_1'')}{2\pi} \bullet \xi \sin(\xi') \bullet \left[\sin(RC) - \sin(LC)\right] \\ & - \frac{1}{2} F_2'' \sin(\beta) \bullet \left[\sin(RC) - \sin(LC)\right] \end{aligned}$$

The first correction term in this formula is the correction for the shielding of the isotropic diffuse light. The geometry of the shielding object is similar to the geometry of the horizon band in a previous version of the Perez model [5]. Therefore, we used the same approximations as Perez in the previous version of his model. F_1'' is the same as F_1' except that we set negative values to zero, because an obstacle does not emit irradiation.

The second correction term is the correction for the shielding of light from the horizon band. F_2'' is calculated in a similar way as F_2' with the difference that negative values of F_{2j} are set to zero. Negative values of F_{2j} correspond to the presence of a bright region at the top of the sky dome, rather than to the horizon band absorbing irradiation [6].

3. VALIDATION METHOD

The annual tilt ratio, defined as the ratio of the annual array plane irradiation and the annual horizontal irradiation, is often used to estimate the impact of the tilt of the array plane on the energy output of a PV system. We use this quantity to compare the calculated and measured values of the array plane irradiation.

4. MEASUREMENTS

4.1 The measuring equipment

The PBB (Photovoltaic/Battery/ Backup generator) system at Utrecht University has been built to study the performance of hybrid autonomous systems [1]. The system has been equiped with an extensive data monitoring system, including sensors for measuring irradiation (see Table 1) and temperature. The measuring sensors have a reported accuracy of 2% on a daily basis [7]. Data are sampled with a time step of one second and stored as one minute averaged value. Continous monitoring takes place since 1991. The measuring sensors have been cleaned regularly.

Table I: Irradiation sensors at the PBB system, relevant to this study.

Measured Quantity	Measurement equipment
Horizontal global irradiation	Kipp & Zonen CM11 pyranometer
Horizontal diffuse irradiation	Kipp & Zonen CM11 pyranometer with CM121 shadowring
Array plane irradiation	Kipp & Zonen CM11 pyranometer Orientation: 179^0 Tilt: 52^0 (1991-1994) 45^0 (1995-present)

The PBB system is located at University of Utrecht, the Netherlands (52.1° N, 5.2° E). It is situated on a meadow surrounded by buildings on the south and west. These buildings block the view of the measuring instruments from 135^0 (SE) to 270^0 (W) at an estimated average height of 7^0.

4.2 Screening of the Data Set

Unrealistic values and known irregularities during measurement were removed from the data. Negative pyranometer data were set to zero.

In September, October, and November 1994, the shadow ring of the pyranometer for measuring the diffuse irradiation was adjusted incorrectly. In January 1995, the pyranometers were removed for calibration. For calculations of the annual tilt ratio, we replaced data from these five months by data of the same month in the next or previous year.

5. RESULTS

5.1 Results the Perez Model without Shielding Correction

We calculated the global array plane irradiation from the global irradiation measured with a pyranometer and the diffuse irradiation as measured with a pyranometer with shadow band. This is the value as would be measured by a pyranometer.

Figure 1 shows the values of the monthly tilt ratio in the period 1991-1996. At the latitude of the PBB system tilting the array plane causes a loss in irradiation in May, June, and July and a gain in the rest of the year. The figure also shows that the monthly tilt ratio can vary up to twenty percent from year to year.

The measured and calculated annual tilt ratios for the PBB system are given in Table II. These results show that the calculated value is on average 0.09 higher than de meausred value. This is different from the study by van den Brink [3] who found a difference of less than 0.5% for south oriented planes with tilt 45^0 and 67^0.

Table II: Annual tilt ratios for the PBB system

Year	Tilt (^{0})	Measured tilt ratio	calculated tilt ratio
1992	52	1.05	1.14
1993	52	1.05	1.14
1994*	52	1.05	1.15
1995*	45	1.13	1.21
1996	45	1.11	1.20

It appears that there is a seasonal variation in the ratio of the monthly calculated and measured array plane irradiation (see Figure 2a). The results of the model calculation are better in summer than in winter.

The differences between summer and winter months are illustrated in Figures 3a and 3b. These figures show calculated values as a function of the measured values for the one minute irradation data. In the winter months the spread is much larger than in the summer. Figure 3b also contains days for which the calculation performs extremely poor. Days of this type occur in December, January, and February. We could not correlate the occurrence to irregularities in the measurements, to the presence of snow or to the shading of direct sunlight. Removal of these days from the data set reduced the difference between the calculated and the measured annual tilt ratios by less than 0.01. Since we could not find an explanation for these deviating days, we did not exclude them from the calculations.

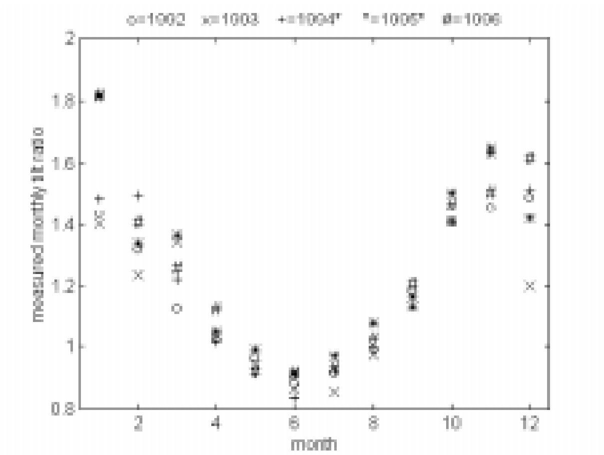


Figure 1: Monthly tilt ratios for the PBB system

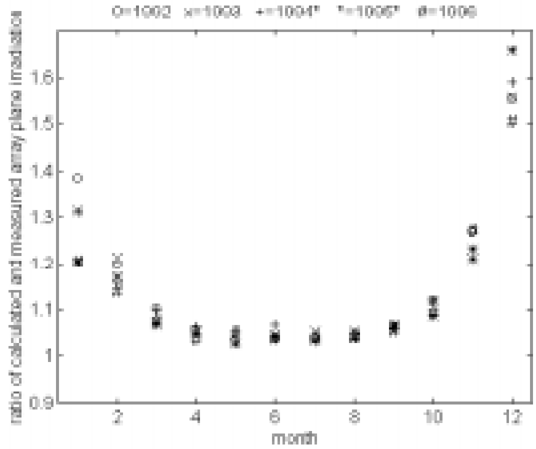


Figure 2a: Performance of the model calculation for the Perez model

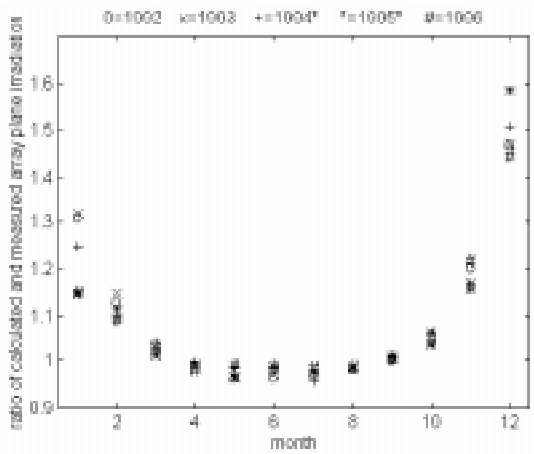
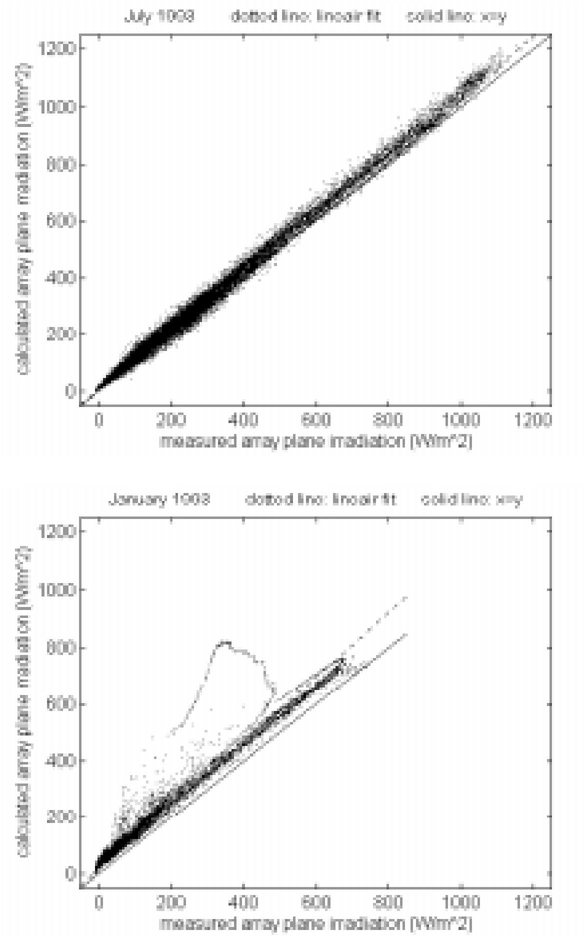


Figure 2b: Performance of the model calculation for the Perez with shielding correction



Figures 3a and 3b: Performance of the Perez model for (a) a typical summer month (b) a typical winter month

5. 2 Results of the Perez Model with Shielding Correction

Table III shows that application of the Perez model with the expansion described in Paragraph 2.3 improves the result of the calculation considerably: the average overestimation in the annual tilt ratio is reduced from 0.09 to 0.02. However, comparison of the Figures 2a and 2b shows that the pattern in the seasonal dependence does not change.

Table III: Calculated divided by measured annual array plane irradiation for model calculations using the original Perez model and the Perez model with shielding correction.

year	Tilt (^{0})	Perez model	Perez model with shielding correction
1992	52	1.09	1.02
1993	52	1.09	1.02
1994*	52	1.09	1.03
1995*	45	1.08	1.02
1996	45	1.08	1.02

NB: The values in the first column can also be derived from Table II.

6. DISCUSSION

In the development of the shielding correction to the Perez model we assumed that the Perez model gives a realistic description of the sky dome. This assumption is not entirely correct. In the model the horizon band has an infinitely small height, while in reality the irradiation from the horizon has a continuous distribution over a finite height of the sky dome. Thus, in the model we neglect the contribution of the horizon band that rises above the obstacle. As a result, we may underestimate the array plane irradation.

7. CONCLUSIONS

We used the Perez model to calculate the annual tilt ratio for the PBB system in Utrecht from the measurements of global and diffuse horizontal irradiation. The results showed an overestimation of the calculation compared to measurements by 9%.

We developed a simple correction to the Perez model to incorporate the shielding of diffuse light by buildings surrounding the measuring site. Using this correction we could reduce the difference between calculation and measurement to 2%.

The Perez and also the correction model use an idealized description of the sky dome As a consequence, the correction model may overestimate the impact of the obstacles on the array plane irradation

The results discussed in this paper are part of a larger study to evaluate the performance of tilt conversion models under field conditions. Results of this study will be published in the final report.

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