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# ENERGY LOSS DUE TO SHADING IN A BIPV APPLICATION

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# ENERGY LOSS DUE TO SHADING IN A BIPV APPLICATION

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## ABSTRACT

Building integrated PV systems are often subject to shading. This results in the loss of available irradiation and, in case of partial shading, it may result in the so-called mismatch loss. Monitoring data of a BIPV system were used to quantify these effects. The simulation tool PVSYST has been used to model the same effects. Comparison of the measured and modelled results show that the in-plane irradiation can be calculated from the irradiation on the horizontal plane accurately, even in presence of shading elements. The calculated mismatch loss due to the partial shading of strings seems to be over-estimated in case of the chosen PV system.

## 1. INTRODUCTION

Building integrated PV systems (BIPV) are very often subject to shading. As a consequence these systems may produce less energy than optimally situated systems due to the loss of available irradiation caused by shading and due to the so-called mismatch loss caused by partial shading. Also the use of different orientations within the PV array may lead to mismatch losses. These losses are hard to quantify in general terms since measured data on a certain BIPV application cannot easily be translated to other situations. For this reason validated simulation models have to be used for the prediction or assessment of the energy performance of complicated BIPV applications.

One of ECN's buildings is equipped with sunshade devices made of PV modules. Detailed monitoring of these systems resulted in experimental data on the shading effects. The experimental data were used to validate the simulation model PVSYST V3.21 (ref. [1]). The results of this validation are given in this paper.

## 2. PV SYSTEMS

The building with PV systems is shown in figure 1. In this paper the PV modules on the roof are not addressed. The PV modules of the awning and of the lamellas are grouped into 13 vertical sections, with one inverter per section. One PV system consists of 7 lamella strings and 2 awning strings, each string having 6 modules. The lamellas have a tilt angle of 38° and the awning has a tilt angle of 18°. The façade is almost south oriented (173°).


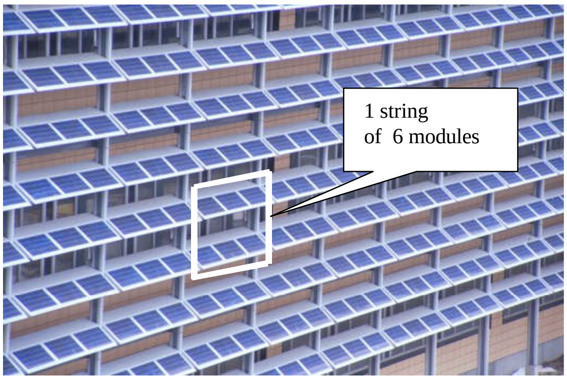


*Photo: Marcel van Kerckhoven. Copyrights: BEAR Architecten,*
**Fig. 1** ECN building 31 with its PV systems.

## 3. MONITORING SYSTEM

The PV systems are monitored extensively (see ref. [1]). The sensors relevant for this paper are given below.

- Pyranometer on the roof (horizontally, unshaded)
- Reference cell on the awning (in-plane, unshaded)
- Reference cell and temperature sensor on the third lamella from above (in-plane, shaded by the upper lamellas). This reference cell is one of the cells of one of the modules, withdrawn from the power system.
- DC-power of the PV system in the central section

The data are measured once per second and condensed into averaged values of 10 minutes. The averaged values are stored for off line data reduction into hourly values, needed for the validation.

The data collection started in august 2001 and is still ongoing. The data used for this paper cover the period from august 2001 till august 2002.

## 4. VALIDATION PVSYST V3.21

### 4.1 Irradiation without shading

An important step of simulation models is the calculation of the in-plane irradiation from the available irradiation on the horizontal plane. The validation of this model was performed using the measured hourly data from the pyranometer on the roof (horizontally mounted) for the calculation of the hourly in-plane irradiation on the awning. This calculated irradiation was then compared with the irradiation on the awning as measured with the in-plane reference cell.

The simulation is performed in two steps:

- The calculation of the diffuse component of the measured hourly irradiation on the horizontal plane. This was done using the model of Liu & Jordan.
- The transposition of the diffuse and of the direct irradiation on the horizontal plane to the in-plane orientation, defined by azimuth angle and tilt angle. This was done using the Hay model.

Since the measured in-plane irradiation was obtained with a reference cell, also the reflection model of PVSYST was included in the simulation (ASHRAE model; bo = 0.05). The measured and simulated hourly data were summed into monthly irradiation values. The results are given in figure 2.

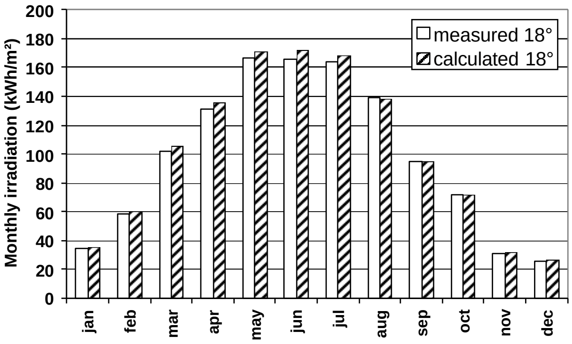


**Fig. 2** Measured and simulated irradiation on the awning

Figure 2 shows that the calculated irradiation, expressed as monthly values, corresponds well with the measured data. The annual data show a difference of 2%.

### 4.2 Irradiation with shading

The lamellas are sometimes shaded by the facade and by the upper lamellas, depending on the time and date. The irradiation on the third lamella from above was calculated using PVSYST in a similar way as described in paragraph 4.1. This resulted in the calculated irradiation for the imaginary situation that the lamella was unshaded. The same calculation was performed including the shading calculation of PVSYST ("Near Shading Option"). This resulted in the calculated irradiation for the real situation that the lamella was shaded. The results, presented in figure 3, show that the loss of potential irradiation in the summer is significant. Over the complete year this loss equals 20%.

For the validation of the used shading model the irradiation was used as measured with the reference cell in the lamella. This irradiation is also presented in figure 3. The figure shows that the calculated irradiation, expressed as monthly values, correspond well with the measured data. The annual data show a difference of 1%.

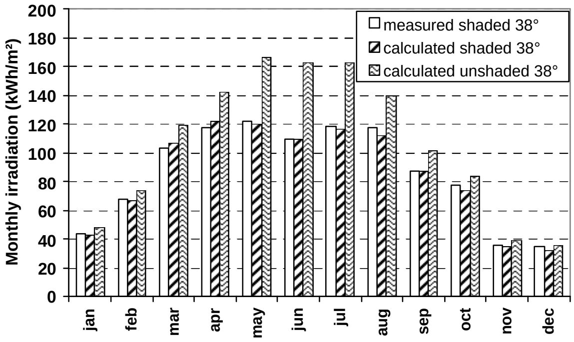


**Fig. 3** Measured and simulated irradiation on the lamella

### 4.3 Mismatch model

#### 4.3.1 Heterogeneous orientation

The PV system consists of 2 strings on the awning (tilt angle of 18°) and of 7 strings on the lamellas (tilt angle of 38°). Due to the differences in the orientation of the awning strings and the lamella strings the irradiations and module temperatures are different. Since the voltages are forced to be equal due to the parallel connection of the strings the various strings cannot be operated in their own MPP (maximum power point). This mismatch causes a loss in the overall performance.

PVSYST allows splitting the total PV array in two parts with different orientations. The PV modules within a string should all have the same orientation since the electrical behaviour of modules connected in series and at the same time having different orientations is very complex. PVSYST was used to calculate the system performance for the imaginary situation that all strings have a tilt angle of 38° and also for the real situation that 2 strings have a tilt angle of 18° and 7 strings have a tilt angle of 38°. The shading was not taken into account. Both situations obviously result in different energy production values since the available irradiation differs and because of the mismatch effect. To isolate the mismatch effect the array efficiencies were compared, not the energy productions. On annual basis the modelled array efficiency is only a factor 0.992 lower than that of the imaginary situation of all strings having the same orientation. This means that the calculated mismatch loss due to the different tilt angles of the various strings is very small. Unfortunately the experimental data give no possibility to validate the calculation model.

#### 4.3.2 Partial shading

Partial shading of a string of modules causes an over-proportional loss of performance due to the mismatch of the currents of the various modules. The modules of the PV system are subject to partial shading during certain periods, depending on the date and time, when the lamellas cast a shadow over the edge of the lower lamellas. PVSYST offers the possibility of ignoring this effect (by calculating the averaged irradiation over the strings) and it also offers the possibility to account for the mismatch effect. The applied model for the mismatch effect is based on the approximation that the complete string is shaded during the period that any part of the string is shaded. With both options the effective irradiation was calculated on the lamellas of the PV system.

The complete PV system consists of 7 lamella strings and 2 unshaded awning strings, each string having 6 modules. The total irradiation on the PV array was calculated by adding the irradiation on the awning modules, calculated by PVSYST, to the effective irradiation on the lamella modules. This resulted in an effective irradiation on the total PV array for the two options: with and without accounting for the mismatch effect of the lamella strings. The ratio of the effective irradiation on the total PV array as determined by these two options is the calculated mismatch factor caused by the partial shading. The mismatch factor is given in figure 4 per month and over the complete year (0.83).

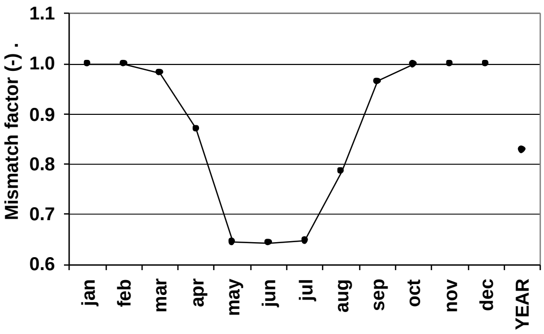


**Fig. 4** Modelled mismatch factor for the total PV system

For the validation of this calculation method the measurement data of March were used to estimate the annual energy production of the PV system without partial shading. This month has been chosen because it has a wide irradiance coverage (up to 1000 W/m²) and it has no partial shading conditions. The array efficiency of March was combined with the annual irradiation distribution to calculate the annual energy production without partial shading. In a similar way the array efficiency of the complete year was combined with the annual irradiation distribution to calculate the annual energy production with partial shading. The array efficiencies were calculated from the measured DC-power, corrected for the difference between the measured module temperature and the reference temperature of 25°C, and the total irradiance on the PV array. The total irradiance was calculated by summing the irradiance on the awning modules, measured with the reference cell on the awning, and the irradiance on the lamella modules, measured with the reference cell on the lamella 3. The resulting array efficiencies, defined for the net cell area, are given in figure 5 for March and for the complete year.

Combining the array efficiencies of figure 5 with the measured frequency distribution of the annual irradiation on the PV array resulted in the annual energy production of the PV system in the real situation and in the virtual situation without any partial shading. The ratio of these two energy productions is 0.94. This means that the experimentally determined annual mismatch factor of the PV system is 0.94, in contrast to the modelled mismatch factor of 0.83.

The used model for the mismatch calculation of PVSYST turns out to result in an over-estimation of the mismatch loss. This is caused by the simplification, made by PVSYST, that a string is completely shaded when it is partly shaded. In the case of the described PV system this approximation has strong consequences because the modules are often shaded at the very edge only.

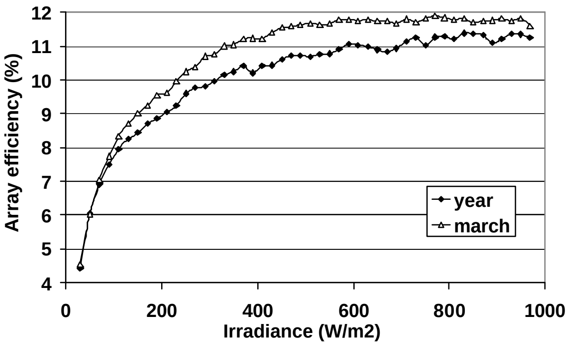


**Fig. 5** Array efficiency (net cell area, module temp. °C)

## 5. CONCLUSIONS

Building integration of PV may result in sub-optimal orientations of (part of) the PV array and it may result in energy losses by shading. The various effects can be accounted for using simulation models. Comparison of the simulation results obtained by PVSYST with measurement data on the described PV system leads to the following conclusions.

- The transposition of the irradiation data on the horizontal plane to the plane of the PV array is very accurate.
- The calculation of the loss of potential irradiation due to shading is very accurate.
- The mismatch effect due to the application of strings with different orientations can be modelled. No experimental data were available to validate the model.
- The mismatch effect due to partial shading of strings is over-estimated by the model.

## 6. REFERENCES

[1] PVSYST V3.2; A. Mermoud, University of Geneva, Centre of Energy CUEPE. http://www.unige.ch/cuepe/pvsyst/pvsyst/index.htm

[2] N.J.C.M. van der Borg, M.J. Jansen: "Performance of the PV systems of ECN building 31"; ECN-C-02-030; Petten, september 2002. http://www.ecn.nl/library/reports/2002e/c02030.html