Towards simulation-assisted performance monitoring of BIPV systems considering shading effects

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***Abstract* -- Nowadays, the application of BIPV systems is growing very fast and among this type of technology, application of BIPV façade systems is becoming more common. A main question in this field is how we can ensure the intended performance of such systems considering different involved parameters over the system's life-time. To do so, we need to be able to predict normal behavior of BIPV systems in urban environments, considering the effect of shading from neighboring obstructions. This research investigates a combination of real-time shading simulation using Rhino and Grasshopper with BIPV performance monitoring to detect abnormal system operation. The application of this approach is demonstrated for a 12 m^2 vertical BIPV system in the SolarBEAT test facility in Eindhoven, the Netherlands. We have conducted an experiment to better understand the impact of different partial shading scenarios on the I-V curve of a vertical CIGS BIPV panel. The results show that the simulation-assisted approach, coupled with data visualization and a decision tree can be a powerful tool for guaranteeing robust BIPV system output.**

***Index Terms* -- BIPV façade systems, performance monitoring, shading effect.**

I. Introduction

Solar energy is becoming more and more important in modern society and gradually it is one of the main sources of energy production in the future. Considering the need for zero-energy buildings and districts, the application of PV panels in the built environment is becoming increasingly common. In recent years, PV is not only applied on existing rooftops, but there is also attention for the integration of PV in building envelope components; to maximize the number of PV modules installed and hence the electrical power generated, other facades of the building envelope are sometimes utilized [1].

In all applications of BIPV in the built environment, there is always a need to track the performance of the setup over time. Among the many influencing factors, shading is one of the most important ones, because it has a significant direct effect on the final energy yield of the system. Due to their vertical installation, the performance of façade-integrated PV is more influenced by its adjacent surroundings compared to rooftop applications. Hence, getting a profound understanding of the time-varying effects of partial shading is of high importance to support design and operation of façade-integrated BIPV.

II. Problem Description

PV panels need to receive direct or diffuse sunlight to produce energy. In situations when there is partial shadow on the PV modules, depending on the position of the shade and architecture of the circuits, there would be a sudden drop in the final energy yield of the PV module that is disproportional to the shade area (Figure 1). Low energy output can also be caused by overcast sky conditions or defects of the PV system.

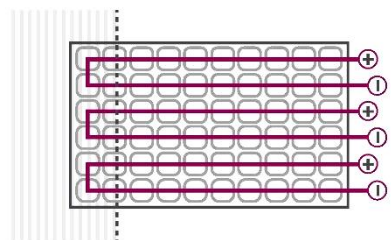


Fig. 1.The situation that shading is covering parts of the PV circuit and also will affect the output energy yield.

When monitoring the output of a BIPV system, a main problem is to distinguish between the previously mentioned three situations. A systematic approach is necessary to detect whether low PV output of a specific module in the PV installation is due to normal system operation, or whether there is a defect that causes the anomaly. This is a challenging task, because it is not straightforward to predict whether partial shading would be expected during real-time operation. The goal of this paper is to introduce a novel methodology, based on the integration of simulations with structured data analysis of monitored PV output, to identify normal and abnormal PV system behavior in an automated way.

III. Research Methodology

In this research, the whole process of monitoring has a logic behind to ensure that the result is trustable; this logic and its scenario is defined in Figure 2.

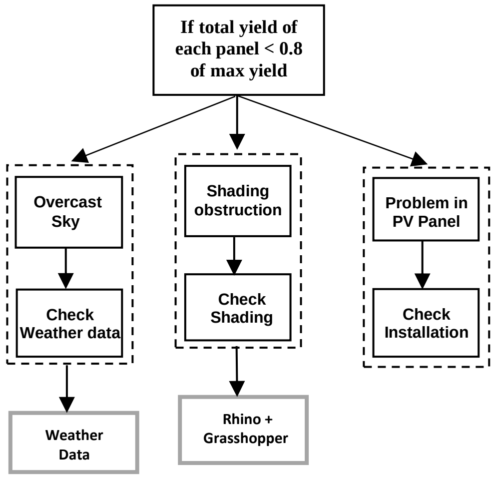


Fig. 2.Fault detection logic for installed PV

According to this logic, the methodology of this research is defined in a way that facilitates fault detection and reduces the amount of time that the system operator needs to understand and certify acceptability of the data. To achieve this goal, and with the help of the proposed logic, the whole methodology and inference mechanism is shown in Figure 3.

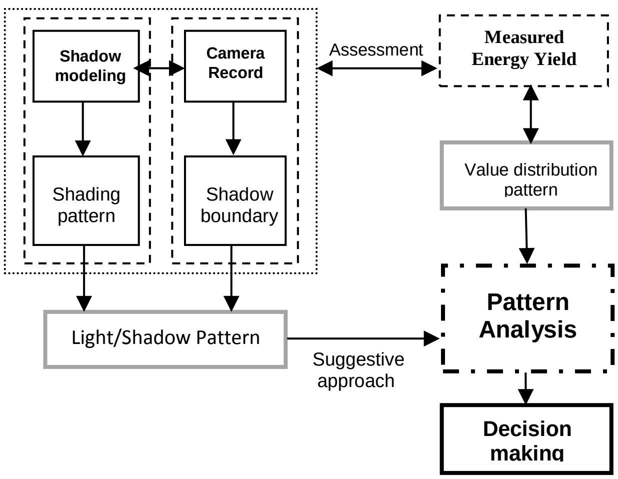


Fig. 3.Research method and inference mechanism

So the final outcome of this research would be a systematic approach to ease fault detection and decision making. In this process we will use data with weighted color to simplify fault detection.

Therefore, the main objectives of this research are as follows:

- Quantify and visualize the effect of shading on energy yield of vertical BIPV systems.
- Validate this approach with the help of data obtained from a full-scale BIPV outdoor test facility.

The automated fault detection approach is demonstrated with results from an experimental BIPV test facility, SolarBEAT in Eindhoven, the Netherlands. The real-time shading simulations are carried out with Rhino and Grasshopper.

A. *Experimental setup in SolarBEAT*

The SolarBEAT BIPV test facility was initiated by the Solar Energy Application Center (SEAC) at the Eindhoven University of Technology campus in the Netherlands. The test site provides facilities to perform research regarding new BIPV product prototypes, using full-scale building–integrated prototypes, exposed to real outdoor conditions.

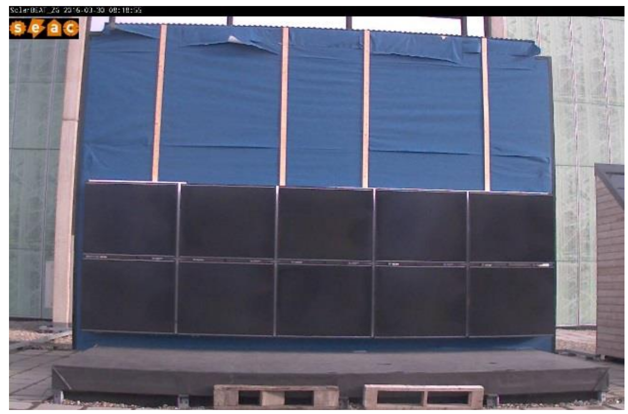


Fig. 4.CIGS installation in Solar BEAT

The goal is to investigate the performance but also the whole system design of innovative BIPV components.

For this research, we use the monitoring results of 10 CIGS Solar PV panels which are vertically installed in the façade of a dummy house in SolarBEAT.

Every module is connected with a high voltage power optimizer. A string inverter is then used to convert DC to AC power and inject it at the electricity grid. While power optimizers can supply power and energy generation data, a dedicated monitoring system has been set up. Shunt resistances and voltage transducers have been utilized to simultaneously record module current and voltage output.

Figure 4 shows the 10 uniform CIGS panels that are installed in the south-facing test façade. The characteristics of the installed CIGS PV panels are provided in Table 1.

TABLE I
INSTALLED CIGS PV PANELS' CHARACTERISTIC

PV	power optimizer	Pmax	Ipm	Vpm	Isc	Voc
1	2028BEBD - C3	164.9	1.92	85.8	2.163	112
2	2028BC1B - 1F	164.8	1.91	86.2	2.142	111.9
3	2028BDAB - B0	163.2	1.95	83.3	2.161	110.7
4	20288088 - C0	163	1.9	85.4	2.101	110.1
5	2028BC57 - 5B	163	1.89	85.9	2.113	109.7
6	2028C059 - 61	160.8	1.94	82.8	2.144	109.3
7	2028BE43- 49	161.8	1.88	86	2.111	110.3
8	2028BEEE - F4	162.4	1.88	86.1	2.092	110.1
9	2028BDFC - 01	161.5	1.94	83	2.138	109.7
10	2028BFF8- FF	163.6	1.96	83.2	2.172	109.4

B. Shading simulation and validation of the model

Shading patterns of neighboring obstructions are simulated with the help of parametric design tools Rhinoceros and Grasshopper [5,6]. First, the geometry of all SolarBEAT constructions and other important adjacent obstructions were modeled in the 3D modeling platform Rhinoceros (Figure 5).

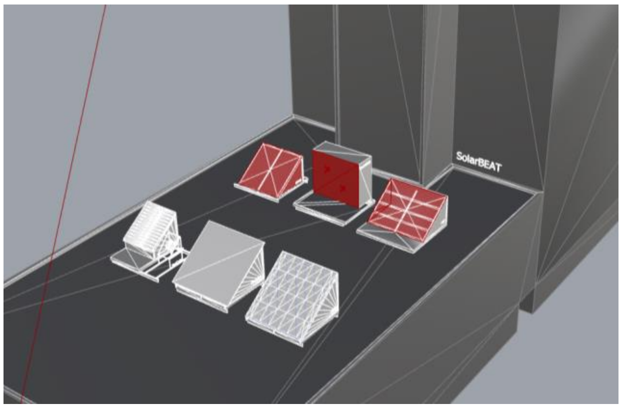


Fig. 5. Geometric representation of the SolarBEAT test set-up. The CIGS panels are located in the construction in the middle row with the red vertical façade.

This 3D model is then coupled the Grasshopper environment. Grasshopper uses sun position and shading mask algorithms following the equations described in Duffie and Beckman's Solar Engineering of Thermal Processes [7]. To gain confidence that the model is able to predict shading patterns at different times of the day with sufficient accuracy, Grasshopper visualizations were compared with camera recordings during a day with clear sky conditions (10th of March 2016). The results of this validation activity are reported in Table 2.

It is clear from the nearly identical match in the reported results that the simulation model is able to accurately predict the shadow patterns throughout the day. Since the model makes use equations that are widely used in solar engineering, we expect that it will also be able to predict this kind of direct shading effects in more complex urban configurations.

C. Shading Experiment

Following the simulation, in a sunny day we ran a simple experiment to find out the real effect of different type of shading on the power and I-V curve of PV panel.

To do so, we have chosen one of our CIGS panels that normally has shadings from neighbors and we have recorded the whole I-V curve for four different situations as described below. It should be considered that the shadow area on the panels is around 10 percent of the whole PV panel.

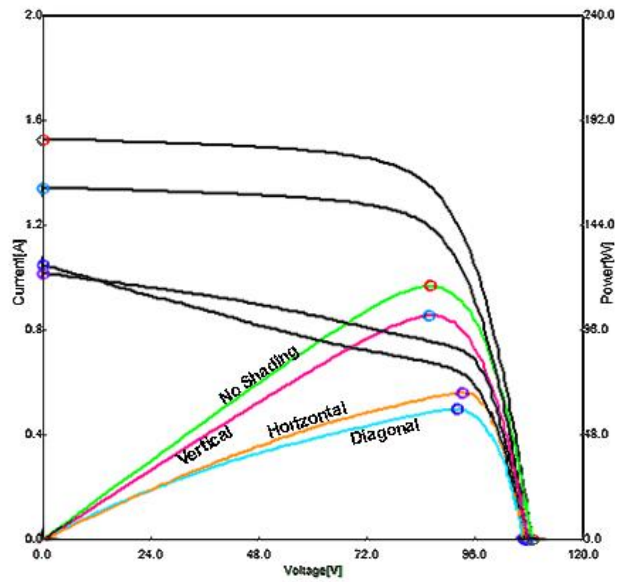


Fig. 6.Maximum power point and I-V curve for all different situations

The first situation is captured from the panel considering direct uniform sunlight without shading. This situation, as shown in green color in the graphs, acts as reference for further comparisons.

The second record is for partial vertical shading which is presented by pink color in the graphs. The third record is

TABLE 2

VALIDATION OF SHADING SIMULATION WITH THE HELP OF CAMERA RECORDS FROM FIELD INSTALLATION.

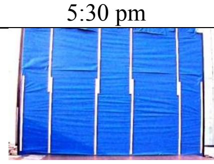
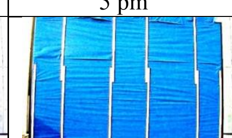
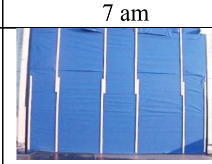
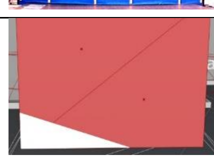
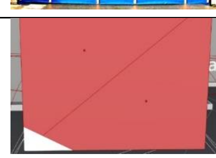
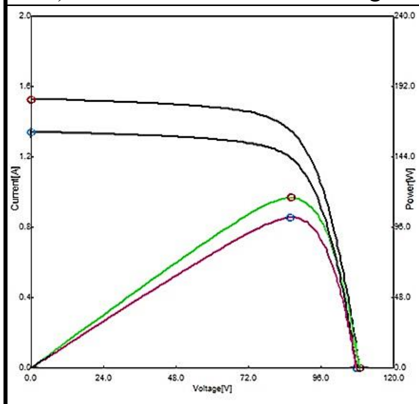
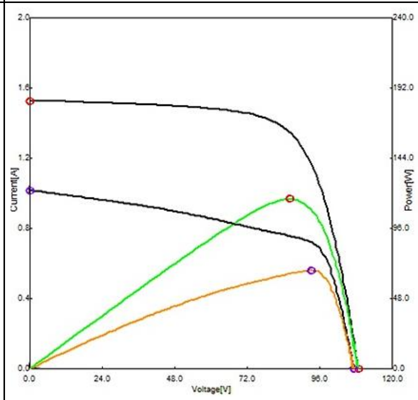
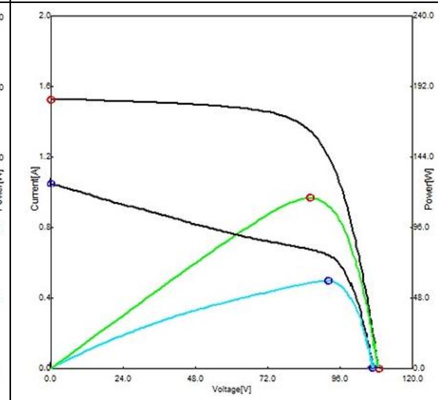
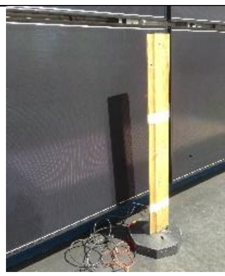
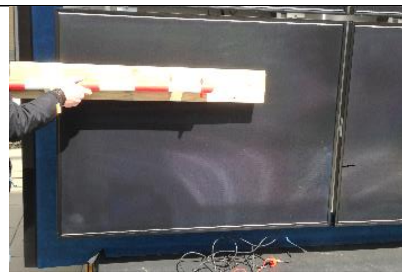
	5:30 pm	5 pm	7:30 am	7 am
Camera records from prottype				
Simulation snap shots				

TABLE 3
I-V CURVE AND MPP RESULT FROM EXPERIMENT WITH DIFFERENT SHADING SITUATION

1) Panel with vertical shading	2) Panel with horizontal shading	3) Panel with diagonal shading
		
		

from the horizontal shading experiment, as shown by orange color. And finally the fourth situation is a combination of vertical and horizontal shading which we call diagonal shading.

According to the experiment, the worst situation affecting the performance of the PV is when we have combination of shading obstruction in both vertical and horizontal direction. As it is clear in the above figure, there is decrease in power point peak by changing the type of shading pattern; Moreover, the type of shading has a direct effect on the current that is coming from the PV panel.

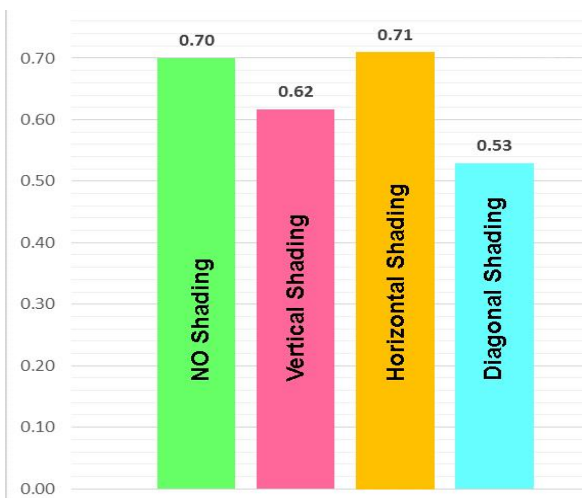


Fig. 7.Fill Factor for I-V curve of different shading situation

Figure 7 presents the Fill Factor of the I-V curve for the different shading situations. We there is no shading, the Fill Factor has the highest proportion and when shading is present the best Fill Factor is for horizontal shading records.

IV. Future Perspectives

Future work will combine the results of the previously shown numerical and experimental shading analysis into one overall BIPV performance monitoring framework. Initially, the goal of this framework is to aid the analysis of experimental data obtained in the CIGS SolarBEAT set-up. Eventually, however, we also foresee the use of this approach for systematic performance monitoring of actual BIPV systems in the field.

To illustrate the concept, Figure 8 shows the measured PV output of the CIGS installation at a certain moment in April 2016. Based on just this information, it is not immediately clear whether the low output from panel 1.1.10 is caused by a fault in the system, or whether this behavior is expected due to partial shading.

By making use of the Rhino/Grasshopper simulation results, the system operator can quickly check whether hading due to neighboring obstructions was to be expected for the given circumstances. In a similar way, a "clean window" can be extracted for the analysis. During this period, it is assured that irregular behavior cannot be caused by partial shading effects, and therefore must be due to some other influencing factor.

Once this whole process gets automated, also the shaded fraction (%) and directionality of shading (angle) can be computed for each PV module. By multiplying this information with the I-V correlations obtained from the shading experiments, and combining this with real-time meteorological data, it is possible to obtain time series of the typically expected output range for each of the panels. Comparing this expected range to the actual measured output provides a systematic framework with potential for effective monitoring and anomaly detection of BIPV systems.

The parametric nature of the Rhino/Grasshopper environment provides ample flexibility to extend and apply the computational shading analysis towards more complex urban areas. Especially when geographic information system (GIS) data is available, the geometry of neighboring obstructions can be modeled at a high level of detail with little manual effort.

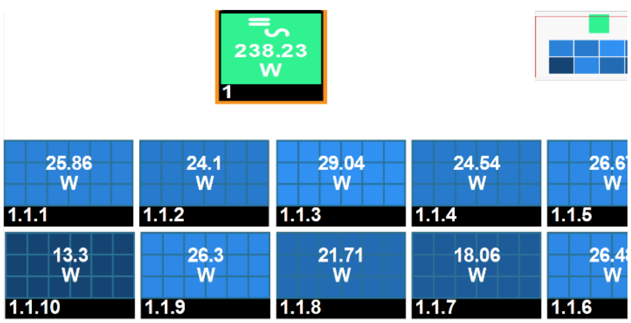


Fig. 8.Measured CIGS energy yield for clear sky conditions in SolarBEAT

V. Analysis And Discussion

To be able to analyze the monitoring results, and apply our systematic approach, we produced a sample set of data to show an example of output (Figure 9), Illustrating five groups of data for different hours for the installed PV system.

Although the first four sets of data contain unpredictable variations, in the last set of presented data, it is clear that the variation of 10 PV panels are in a way that by using the proposed simulation approach, it could be easily recognized whether as overcast sky situation or shading obstruction. And furthermore with the real-time shading simulation using Grasshopper, the system can automatically decide whether shading, or a system defect is the reason for the anomaly.

The correlation of shading coverage and power output of a solar module and system depends on many factors such as the cell and system layout and size, by-pass diodes and diffuse to direct ratio of the irradiance. Results suggest that the partial shading orientation affects power output in different ways. When partial shading is applied horizontally power reduction is at its minimum due to the coverage of less solar cells in the solar module. However when the same shading obstruction under the same irradiation conditions is applied vertically, power output suffers disproportionally. The absence of by-pass diodes in the specific modules under test affect the current of the whole module resulting in lower fill factor and thus reduced power output.

Further development of this approach has the capability to recognize the main feature of some irregular variation in a set of PV panel outputs. For the predicted result of this study it is obvious that there would be some of those variation as well. So our estimation is that this model at this stage would answer better to this problem where there is a normal pattern of data.

1	79.75	85	76	77.5	78.75
	77	81.5	80	73	75
2	110.5	100	101.25	104.75	102
	104.5	112.25	107	107.5	102
3	96.5	92.75	99.75	99	92
	98.25	95.25	91.5	96	99
4	93.75	101.75	87.75	93.5	89.25
	95.25	99.5	95.5	95.75	101
5	12	20	25	20	20
	8	20	20	20	20

Fig. 9.Sample of predicted result per set of installed PV panel

References

[1] Li, Danny HW, Liu Yang, and Joseph C. Lam. "Zero energy buildings and sustainable development implications–a review." Energy 54 (2013): 1-10.

[2] Zhao, Ye, et al. "Graph-based semi-supervised learning for fault detection and classification in solar photovoltaic arrays." Power Electronics, IEEE Transactions on 30.5 (2015): 2848-2858.

[3] Zhao, Ye, et al. "Outlier detection rules for fault detection in solar photovoltaic arrays." Applied Power Electronics Conference and Exposition (APEC), 2013 Twenty-Eighth Annual IEEE. IEEE, 2013.
[4] Platon, Radu, et al. "Online Fault Detection in PV Systems." Sustainable Energy, IEEE Transactions on 6.4 (2015): 1200-1207.
[5] Rhinoceros 3D modeling tool. https://www.rhino3d.com/
[6] Grasshopper Algorithmic modeling for Rhino. http://www.grasshopper3d.com/
[7] Duffie, J.A., and Beckman, W.A. (2013) Solar engineering of thermal processes. Vol. 4. New York: Wiley.
[8] Silvestre, Santiago, et al. "Analysis of current and voltage indicators in grid connected PV (photovoltaic) systems working in faulty and partial shading conditions." Energy 86
[9] Silvestre, Santiago, et al. "New procedure for fault detection in grid connected PV systems based on the evaluation of current and voltage indicators." Energy Conversion and Management 86 (2014): 241-249.
[10] Zomer, Clarissa, et al. "Shading analysis for rooftop BIPV embedded in a high-density environment: A case study in Singapore." Energy and Buildings 121 (2016): 159-164.
[11] Eke, Rustu, and Cihan Demircan. "Shading effect on the energy rating of two identical PV systems on a building façade." Solar Energy 122 (2015): 48-57.
[12] Valckenborg, R. M. E., et al. "Characterization of BIPV (T) applications in research facility ‘SOLARBEAT’." (2015).
[13] Sinapis, Kostas, et al. "Outdoor characterization and comparison of string and MLPE under clear and partially shaded conditions." Energy Science & Engineering 3.6 (2015): 510-519.
[14] Schoen, Tony JN. "Building-integrated PV installations in the Netherlands: examples and operational experiences." Solar energy 70.6 (2001): 467-477.
[15] Lai, Chi-Ming, and Shuichi Hokoi. "Solar façades: A review." Building and Environment 91 (2015): 152-165.