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CHARACTERIZATION OF BIPV(T) APPLICATIONS IN RESEARCH FACILITY ‘SOLARBEAT’

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ABSTRACT: The SolarBEAT facility is an outdoor Research & Development infrastructure for innovation on BIPV(T). The facility is a cooperation between SEAC and the Technical University Eindhoven and is located in the Netherlands. It has been founded early 2014 and has grown rapidly to its full capacity at the moment: a total of 6 projects are testing 8 different BIPV prototypes on one full year performance in realistic outdoor conditions. Performance (Ratio) is measured according to the norms and best practices. The secondary standard Solar Measurement Station is checked continuosly with the measurements of the nearby official Dutch meteorological institute (KNMI). Data is coming in flawless from more than 500 sensors. The daily data stream sums up to more than one million data points which are imported by a central relational (SQL-based) server. Much care is taken that every data point is synchronized with atomic time within 5 seconds, which makes a comparison between different projects possible. Moreover, at SolarBEAT, reliability issues can be checked by using professional equipment a.o. Infrared Thermography (IRT), and in-house developed outdoor Electroluminescence (EL).

1 INTRODUCTION

A largely diversified BIPV market is picking up the last couple of years in many European countries. Especially in the Netherlands, PV is growing fast due to net metering. Moreover stricter regulations in the field of Energy Performance Coefficients (EPC) are enforced by the European EPDB directive. From the 1st of January 2015 newly built houses in the Netherlands onwards have an EPC constraint of 0.4. Experts in the building industry expect that about 10 m^2 of PV will be used to obtain this EPC 0.4 in a cost-effective way. Architects are trying to get this PV area/modules integrated in the houses in the best possible way. This is often realized by BIPV, because of the improved aesthetics and the multi-functional application of BIPV in the building skin. Moreover, in the Netherlands, the integration of BIPV in the building code has been formalized by a BIPV-norm [1].

Figure 1: Picture of SolarBEAT taken in front of the Solar Measurement Station (SMS).

The SolarBEAT facility, see figure 1, is an outdoor Research & Development infrastructure for innovation on BIPV(T). The facility is a cooperation between SEAC and the Technical University Eindhoven and is located on a large south oriented roof with a clean horizon. The roof is equipped in order to investigate all key topics of BIPV(T) research in a realistic outdoor setting. It was first presented to the solar community in the previous 29th PVSEC conference (Amsterdam 2014) [2]. Since then, a lot of progress has been made which we like to present in this paper.

The most important deliverable for nearly all BIPV(T) prototypes is the performance. Or more precisely, how all the various parameters are influencing the performance of the BIPV-product. For all projects, we define a “performance model”, which describes the electricity yield (and hot water/air heating yield in case of solar thermal products) as a function of input parameters such as solar irradiation and weather conditions. Other topics of research involve:

- Building integration aspects of BIPV in roofs and facades (water tightness, ventilation, condensation);
- Partial shading effects;
- Architectural customization of BIPV (colour, size, shape, patterns);
- Operation and Maintenance aspects (pollution, repair & replace);

Figure 2: Sketch-up model of the complete research facility shows the various project names. The model is also used for shading analysis.

The various research projects (see figure 2) are executed in cooperation with universities and knowledge institutes, BIPV(T)- product developers and construction companies. The SolarBEAT research facility was set up/developed in order to be able to address the above-mentioned research topics. Six dummy building structures are made from wood and are thermally insulated in such a way that they represent a typical Dutch residential or utility building (see figure 3).

Figure 3: Picture of SolarBEAT taken from a drone in June 2015.

2 INFRASTRUCTURE INCLUDING THE SOLAR MEASUREMENT STATION

A fully equipped weather and solar station of ISO-secondary standard is measuring on a one minute timescale since May 2014. Moreover, the extension of the infrastructure of SolarBEAT in the last year has given a lot of challenges and results. For this article, three major aspects related to the infrastructure are presented: data handling & time synchronization, hemisphere blockage (due to obstacles at the horizon), and correspondence of irradiance measurements with official Dutch meteorological institute (KNMI).

2.1 Data handling & Time synchronization

At the moment (mid 2015), there are in total 6 projects testing 8 different BIPV prototypes. This is done with a total of about 10 dataloggers and various other measurement equipment. In total 683 sensors are sampled every minute. Data storage is done locally for one full day. Between 23:00 and 01:00 all equipment is uploading the data of the past day to a central FTP-server. This server runs pre-processing scripts and imports the data into a central relational database (SQL-based). At 05:00 next morning, the data is available to specific user and password combinations. Apart of some small bugs and hiccups (which are common for a big project like this) the complete data stream is running flawless. More than 10 different users are monitoring and analysing their own data regularly. Various Matlab- and Python-based data analysis tools have been written for automated determination of properties like Performance Ratio (PR), effective module temperature and weather type. At the moment, the SQL-server is adding about 1.1 million data points per day for all projects at SolarBEAT.

To be able to compare data between different projects, dataloggers, and sensors, it is important that every equipment has the exact same time. That might sound trivial, but it actually involves a lot of work. The time server of the NTP-project [3] is used by all of our equipment. On regular intervals, the site coordinator is checking if all equipment is still running on atomic time. A critical check can be done by plotting both active power P [W] and irradiance G_{POA} [W/m^2] as a function of time. The clock of the power measurement is running on a completely different system as the clock of the pyranometer. Nevertheless a first look at figure 4 shows that time synchronization is quite good for 20 minutes on an arbitrary day.

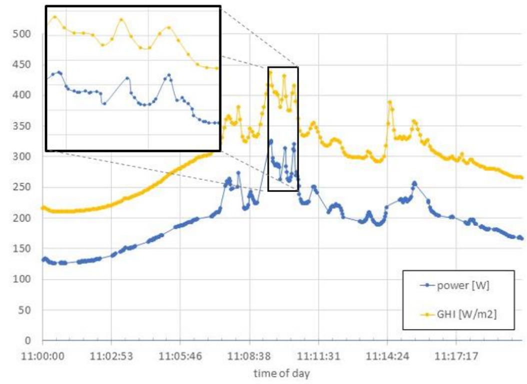

Figure 4: Active power (blue markers and line) and GHI (yellow markers and line) between 11:00:00 and 11:20:00 AM on an arbitrary day with many small clouds passing. The zoomed inset shows just 1.5 minutes of data between 11:09:30 and 11:11:00 with a time interval of 5 seconds.

Zooming in is done in the box in figure 4, where 18 regular GHI measurements with a 5 seconds interval are shown (hence just 1.5 minutes). Power measurements are a bit more irregular but as frequent as the GHI-irradiance measurements. Now, one has to realize that the RC-time of the pyranometer is about 5 seconds, hence it will only make sense to compare power and irradiance on a time scale that is equal or larger than 5 seconds. Looking at the zoomed box of figure 4, one can see that even on this time scale, the power of a PV-panel is following the irradiance perfectly. Even the smallest disturbance (in this example: 3 small clouds within 1.5 minutes) is causing an effect on power and irradiance on the very same moment.

2.2 Comparison irradiance on SolarBEAT and on official Dutch meteorological institute (KNMI)

At SolarBEAT the Global Horizontal Irradiance (GHI), the Diffuse Horizontal Irradiance (DHI) and the Direct Normal Irradiance (DNI) are measured by the SMS. If we add the DNI*cos(solar elevation) to DHI, that addition should be exactly equal to GHI. In figure 5, one can see that the stacking of the yellow and grey bars are indeed very close to the blue bar.

But there is a significant difference comparing the blue bar with the green stars. These stars represent the GHI measurement of the of the official Dutch meteorological institute (KNMI) at Eindhoven Airport. The KNMI data is significantly higher than the SolarBEAT data, although that meteorological station is installed at a distance of only 4 km as the crows flies.

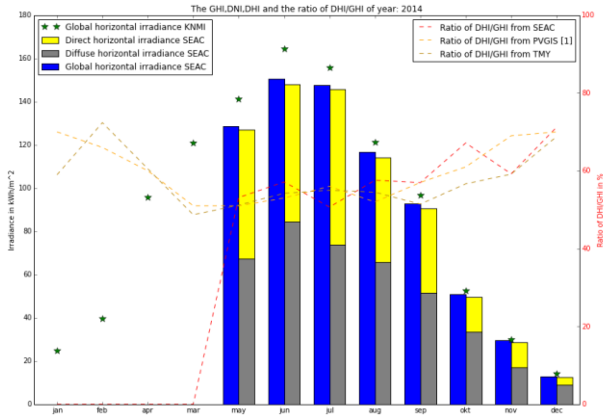

Figure 5: Colored bars are monthly sums of Global Horizontal Irradiance (GHI), cos(solar elevation)-component of Direct Normal Irradiance (DNI), and Diffuse Horizontal Irradiance (DHI) since operation May 2014. Green points are the GHI measured at the KNMI meteo-site.

2.3 Hemisphere blockage

For an official GHI measurement according to the WMO-standards [4], the horizon needs to be completely clean. Whereas our research facility is installed in the built environment with a fairly, but not perfectly, clean horizon. A fish-eye picture taken at the position of the SMS GHI-pyranometer (see figure 6) shows that the close-by high rise building blocks a significant part of the horizon. A pixel count on figure 6 yields a blockage of 15% of the sky.

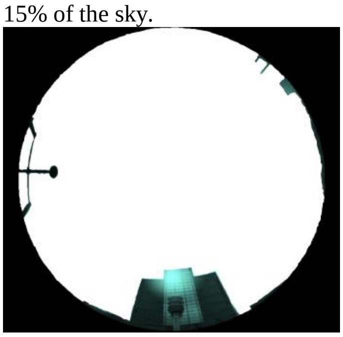

Figure 6: Fish-eye camera picture taken at the position of the pyranometer clearly shows obstacles at the horizon.

The DHI-measurement can be corrected for this 'lacking' irradiance from the sky. This is done in figure 7 by creating an additional 'artificial' irradiance component (dark grey bars) that has a contribution of 15% of the DHI (light grey bars). Now the stack of these three irradiance components are much closer to the KNMI-measurement (green bar) as the uncorrected graph. After July 2014, the difference seems to be systematically higher, which could be caused by additional irradiance from reflections from the high rise building. However, further research is needed, before a solid quantitative conclusion can be drawn on that part of the comparison.

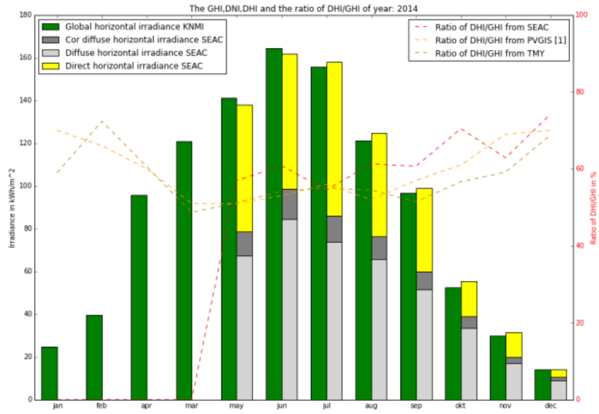

Figure 7: GHI at KNMI (green). And cos(solar elevation)-component of DNI (yellow), DHI (light grey), and corrected hemisphere blockage DHI component (dark grey) at SolarBEAT.

3 PERFORMANCE RESULTS

Every project at SolarBEAT measures performance in its own specific way, because the research questions for every project are different. Four specific results are presented in this chapter.

3.1 Two dimensional histograms of GHI and yield

Some project developers claim enhanced performance under low solar elevation; a condition which is often the case in the Netherlands. To back-up this observation, we made a two-dimensional histogram showing the number of 15-minute intervals in our test facility with a specific solar azimuth (on the x-axis) and a specific solar elevation (on the y-axis) for the second half of 2014.

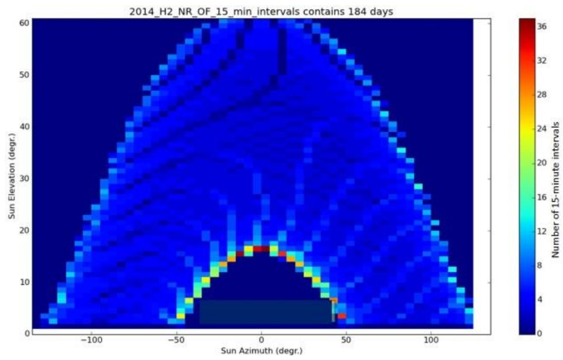

Figure 8: Two-dimensional histogram showing the number of 15-minute intervals with a specific solar azimuth (on the x-axis) and a specific solar elevation (on the y-axis) for the second half of 2014.

This histogram, see figure 8, indeed shows high values for the lower solar elevations. However, one could ask how much solar irradiance is present in those moments/minutes of low solar elevation? To answer that research question, the same histogram is weighted with the actual measured Global Horizontal Irradiance (GHI). The result is a new histogram in which the colors represent the kWh/m^2. For an arbitrary month (April 2015) this is shown in figure 9 below.

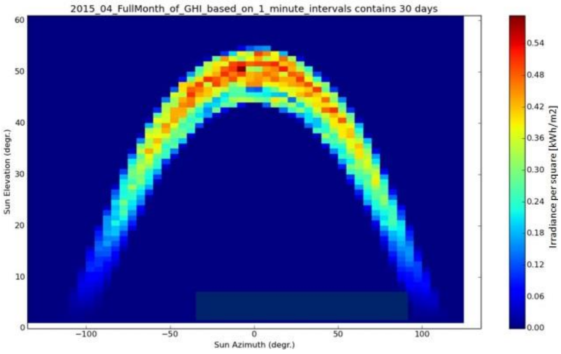

Figure 9: Two-dimensional weighted histogram showing the actual GHI in kWh/m^2 for a specific solar azimuth (on the x-axis) and a specific solar elevation (on the y-axis) for April 2015.

It can be seen that the graph is not perfect smooth because of the fluctuating weather. On the other hand, the chosen period of one month does have enough averaging effect to draw general conclusions. It can be concluded that in April 2015 in the Netherlands indeed low solar elevations are present, but the contribution to the total amount of solar irradiation is low. In addition to this monthly histogram, also versions of a complete season and even a complete year can be made. Moreover, the actual produced kWh of that very moment/minute of the SolarBEAT reference setup have been plotted. An element wise division of both plots gives a 2D Performance Ratio histogram, which is implemented at the moment. We are convinced that those 2D colored histograms can be very powerful for product developers to analyse their product under the various solar angles. Moreover, it makes it easier to understand how the performance of their products will be at other locations on earth were the solar trajectory in the sky is completely different than in the Netherlands.

3.2 Performance of reference BIPV system

One system in SolarBEAT is the reference system. It is a BIPV solar tile of the company Stafier [5], which has already been on the market for a couple of years. This reference setup is split into two fields: one has all PV-panels attached to a classical string inverter, and one has micro-inverters.

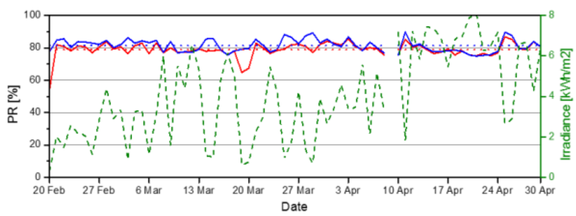

Figure 10: Daily performance ratio of string inverter (blue line) and micro-inverter (red line). Green line with values on the secondary y-axis shows the amount of daily irradiation measured [kWh/m^2/day] in the same plane as the panels.

The difference in daily performance ratio (PR) between the string inverter and micro-inverter is very low in general as seen in figure 10. The main reason for this is that the SolarBEAT site is 98% of the time without shade. Therefore the advantage of a micro-inverter in shade situation [6] will not become visible in this SolarBEAT reference system. The difference between the string- and micro-inverter becomes a bit larger on very low irradiance days. On those days the efficiency of the string inverter is a bit higher than the micro-inverter. However, one should realize that the absolute power production on those days is also low. So in the monthly PR, the effect is small as can be seen in fgure 11 for 2015.

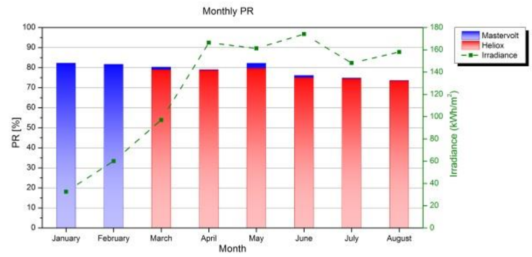

Figure 11: Monthly PR for the field with the string inverter (blue bars) and the micro-inverters (red bars). Green line with values on the secondary y-axis shows the amount of daily irradiation measured [kWh/m^2/month] in the same plane as the panels.

Data from the reference system has been recorded since early 2015. Therefore, we are able to generate Performance Ratio (PR) reports which are in compliance with the norm IEC 61724:1998 [7]. Moreover, project specific, additional graphs are generated according to the recently published 'Analytical Monitoring of Grid-connected Photovoltaic Systems, Good Practices for Monitoring and Performance Analysis' of IEA PVPS Task 13 [8]. These 'PR+Task13-reports' are a powerfull tool for product developers to maximize the yield of their BIPV prototypes.

3.3 PVT

The performance of PVT and solar thermal systems can also be measured on SolarBEAT. To this end, a thermal loop was designed to set the input temperature and flow rate. The input temperature for the systems can be set between 7 and 80°C. Several uncovered PVT systems are currently installed. The PVT panels are electrically connected to power optimizers and an inverter, therefore, the electrical and thermal performance of the PVT modules is measured at maximum power point.

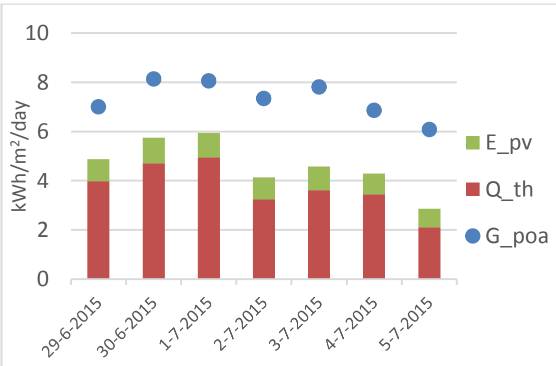

Figure 12: Daily global in-plane irradiation (G_poa) and thermal (Q_th) and electrical (E_pv) yields [kWh/m^2] of a uncovered PVT system on Solar BEAT.

Figure 12 shows the daily in-plane irradiation and the daily thermal and electrical yield for one of the systems. The thermal yield depends largely on the difference of the fluid temperature to ambient temperature. This explains the large difference in efficiency between 1st and 2nd July 2015. In general, one can see that the thermal yield is much higher than the electrical yield, which is well known in the research field of solar energy.

3.4 Combined outdoor EL and IRT

Electroluminescence (EL) and Infrared Thermography (IRT) are widely used. EL is normally performed indoors, because it is hampered by surrounding light. At SolarBEAT we developed an outdoor version of EL [9] by using four different measures: long shutter times, shielding tent, measurement at dusk, and a matched filter on the camera. The most interesting result is shown in figure 13, at which one can see the dramatic degradation of the major part of a CdTe-panel that has been under open voltage for about half a year.

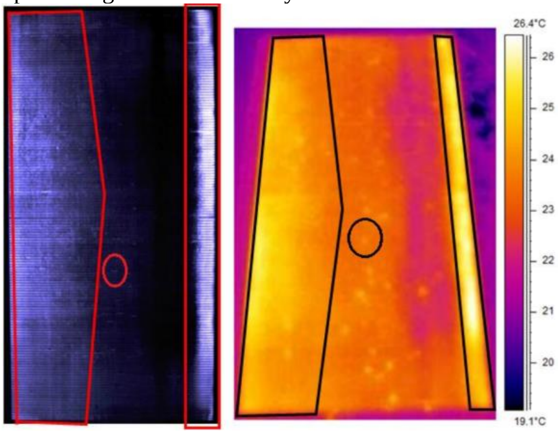

Figure 13: EL-image (left picture) and IRT-image (right picture) of the same CdTe-panel that has been under open voltage for about half a year. Only the the shaded right side of the panel is not degraded (see text for more details).

In figure 13, it can be seen clearly that the brighter areas in the EL image of the module are corresponding to the hotter areas in the IRT image, and the darker areas in the EL look cooler in the IRT. There are some dark spots in the EL image that are present in the IRT image as hotspots. One example is circled in both images. The brighter/hotter area on the right side of the module corresponds to an area that was shaded during operation. It was installed in such a way that the right few cm's of the module were shaded by the roof ridge nearly the full day. As this area was not under normal illumination conditions at all, Light Induced Degradation was not present. Therefore, this part is not degraded as the rest of the module. Also individual hot-spots can be pin-pointed convincingly when the combination of EL and IRT imaging technique is applied.

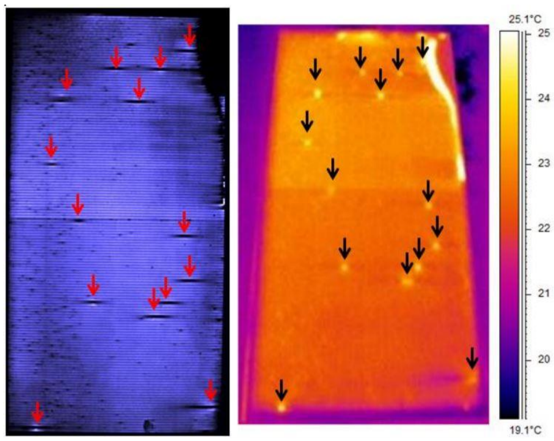

Figure 14: EL-image (left picture) and IRT-image (right picture) of the same CdTe-panel.

Figure 14 shows more clearly how the shunt resistances (seen in the EL-image) will result in hotter spots in the IRT-image. Every shunt resistance present in the EL (indicated with red arrows) corresponds to one hotspot in the IRT image (indicated with black arrows). The broken section of the module at the top right corner shows how the temperature rises in the edge of the broken section.

4 CONCLUSIONS

In conclusion, we experience a large interest in outdoor research on BIPV(T). Project partners are coming with diversified BIPV(T) prototypes designed and developed for a specific market segment of the ever growing solar energy application market in the built environment. Dedicated sensors, data acquisition systems, a central SQL-database and advanced data processing routines have been developed to answer the R&D questions that arise during BIPV(T) product development.

5 REFERENCES

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[4] page 173 in https://www.wmo.int/pages/prog/gcos/documents/gruanmanuals/CIMO/CIMO_Guide-7th_Edition-2008.pdf states ‘If practicable, the site should be chosen so that no obstruction, in particular within the azimuth range of sunrise and sunset over the year, should have an elevation exceeding 5°’.
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6 ACKNOWLEDGEMENT

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