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3-D curved composite façade elements with PV: Results of a pilot project

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ABSTRACT

This paper describes the design, manufacturing, installation and monitoring of a BIPV system that consists of coloured 3D structured façade elements, mounted on an existing office building at the High Tech Campus in Eindhoven. The façade elements contain thin film CIGS modules, which adopt the curved structure of the elements. The encapsulation of the PV modules into the façade elements, the colouration and the curvature led to a relative loss of about 10 % of the efficiency. The PV façade consists of 48 elements with a STC capacity of 5.8 kWp. Each element was equipped with a power optimizer, enabling individual monitoring of each façade element. The elements have been installed at the east and south façade of the building. The monitoring presented in this paper comprised a period of 5 months: the summer and autumn of 2023. The DC performance ratio during that period was 75 % for the elements on the East façade and 80 % for the elements on the South façade; which is in accordance with simplified model predictions. The result is a visual attractive retrofitted PV façade contributing to zero emission strategy of the Eindhoven High Tech Campus.

1. Introduction

The transition to natural gas-free neighbourhoods and buildings necessitates the implementation of localized sustainable electrical energy generation methods to satisfy the heat demand, for example with heat pumps. For office and other utility buildings, it is therefore desirable that the façades can also be used to generate solar power. Recent studies have shown the potential of and the need for Building Integrated PV (BIPV) to obtain buildings and districts with a high level of self-suppliance with renewable energy [1–3].

However, integration of solar panels in façades is still too little applied nowadays due to the limitations in design options. Façade PV elements that are now commercially available can be varied in colour and size but still have a flat surface [4,5]. To increase the aesthetic value of new and retrofitted buildings, the option of 3-dimensional facade elements is often desired. The project that is described in this paper was aiming at this purpose. The goal of the project was to develop a manufacturing process of 3-dimensional PV façade elements, based on composites. It had to be a generic manufacturing process that could be used to create elements with an infinite number of colours and designs.

2. Methods & design specifications

2.1. Design

The starting point of the design was to retrofit an existing office building, HTC5, at the High Tech Campus in Eindhoven (the Netherlands). The façades of this building are made of gravel concrete and had to remain intact. The PV façade elements had to be addons to this (Fig. 1).

For the pilot project, the east and the south facade of the stair tower were available. Due to safety regulations [6] the PV façade elements had to be positioned higher than 2.5 m and below 13 m from the ground, leaving a space of about 60 m^2 on the east façade and 40 m^2 on the south façade for the pilot.

The design work started with the definition of a plan of requirements. This plan contained some hard constraints with respect to timing, safety, annual yield and maintenance but also some soft constraints like the visual quality. This latter was important to obtain an environmental permit from the municipality of Eindhoven.

Several designs were made by the project partner INBO and discussed within the consortium and finally a design was selected that represented a stylized ivy plant. The design consists of triangles of which the legs are curved parallelograms. Each parallelogram has a width of

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Fig. 1. Office building HTC 5 prior to the installation of the PV façade elements.

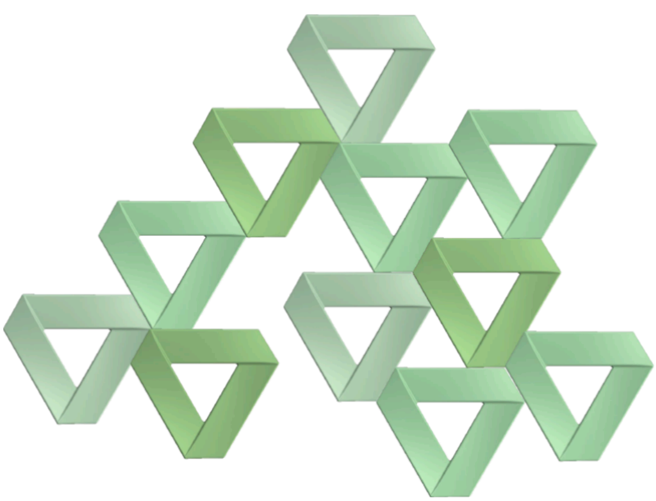

Fig. 2. Selected design of the façade elements.

400 mm and a length of 1475 mm. To increase the visual quality of the full arrangement, the façade elements would obtain different colour tints varying from light green to dark green (greyish) (Fig. 2).

The final arrangement of the façade elements in shown in the graph below. The arrangement consists of 48 elements. Of these 48 elements four are without PV: one element 'winded around the corner': half on the south side and the other half on the east side; a second and a third element are positioned partly above the height limit of 13 m and a fourth element is (partly) positioned at a height below 2.5 m (Fig. 3).

The façade elements are equipped with thin film CIGS solar cells on steel foil from MiaSolé [7] with a nominal efficiency of 17 %. The cells can be cut in different formats and were series connected to modules with a length of 1040 mm and a width of 400 mm. The three modules in each triangle were series connected as shown in the picture below. The nominal power output of the series connected modules in each element, prior to integration was about 145 Wp (Fig. 4).

Each façade element is equipped with a power optimizer (SolarEdge S440) and the system is divided into two strings: one string of 15 elements on the south façade and one string of 29 elements on the east façade. The strings are series-connected to a SolarEdge SE5k inverter.

2.2. Fabrication and testing of PV laminates

Prior to the fabrication of the façade elements, extensive tests were carried out to ensure the longevity of the PV laminates. The composite material of the façade elements does not protect the PV laminates against moisture, and therefore it is crucial that the PV laminates themselves contain well-functioning moisture barriers. Further, it should be noted that the PV laminates in the façade elements are not positioned flat but follow the curvature of the front surface of the elements. The moisture barrier therefore also has to follow this curvature, which is putting an additional challenge on the functionality of the that barrier.

We have tested two types of barrier foils in Damp Heat (DH) and Thermal Cycling (TC) tests according to IEC 61215 with PV laminates in flat and in bent position. The laminates varied also in the presence of a bypass diode behind the solar cells and were integrated into the composite material to evaluate the effect of the stresses during and resulting from the integration process into the composite elements.

The results of all these configurations are shown in the graph below and point out that the PV performance loss is less than 10 % after 500 hrs of testing. The losses can be attributed to the full extent to the ageing/ yellowing and delamination of the composite material; not to PV degradation due to barrier damage resulting in moisture ingress (Fig. 5).

The overall conclusion is that both barrier foils offer sufficient protection to the PV laminates for this application. The ageing of the composite material is due to the extreme conditions in the prescribed accelerated test for PV products, which do not represent standard accelerated test conditions for facade elements.

B1 barrier foil was selected for the fabrication of the full-scale façade elements. To test the effects of the scaling up of the processing of the elements, one full size element was subjected to damp heat testing. The three individual PV laminates in the element were measured on performance before and after damp heat testing.

A similar result was obtained as for the test on the individual PV

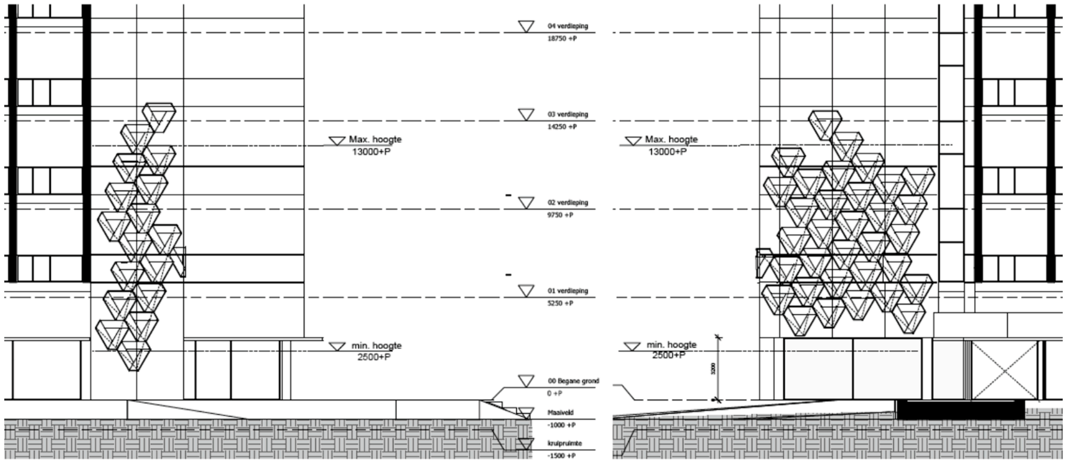

Fig. 3. Final arrangement of the façade elements on the south side (left) and the east side (right).

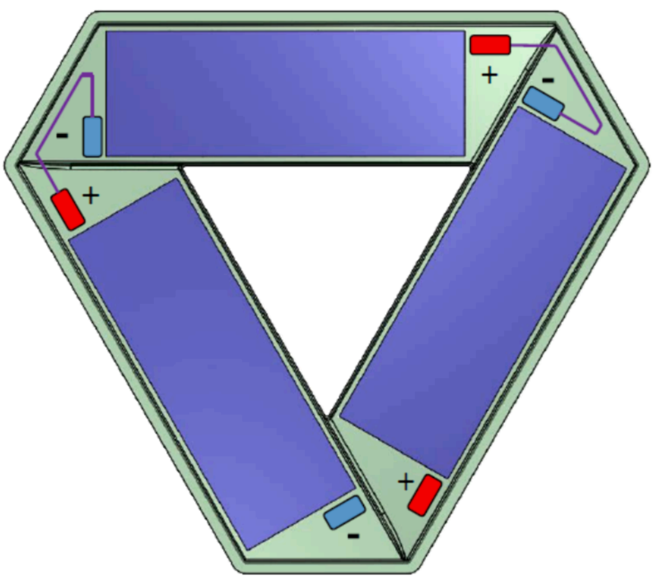

Fig. 4. Schematic drawing of the series connected PV modules in each façade element.

laminates. After 500 h of damp heat testing, a power conversion loss of about 13 % was observed, mainly caused by a decrease in generated current.

2.3. Fabrication and installation of the façade elements

The fabrication of the elements took place in two steps. The first step was the fabrication of the PV laminates by TNO. As mentioned before these laminates were made of CIGS cells on steel foil. Front and rear side of the laminates were protected with a moisture barrier foil (WVTR=10–4 g/m^2 day 38C/90 %RH). The PV performance of each laminate was measured with a solar simulator before they were sent to Flexipol for further processing.

The fabrication of façade elements at Flexipol is a batch process. The elements are built up by placing various layers of composite material in a mould. In between these layers, the PV laminates are placed, so they are fully encapsuled. The used mould was especially designed for this project to achieve the 3D curved structures according to the design. The composite material itself is highly transparent and is coloured by adding a dye. In this project Flexipol had to use a new, experimental dye product, which unfortunately resulted in less strong colours than expected. After drying and hardening of the composites, the façade element is released from the mould and is subjected to a finishing process to obtain clean edges and surfaces.

Thereafter, the façade elements were sent to TNO, where the mounting of the junction boxes, the connector cables and the power optimizers took place. Subsequently, the PV performance of all elements was measured with a flash tester under STC conditions.

All PV elements were functional, and the average power was 131 Wp with a standard deviation of 3.8 Wp. The encapsulation of the PV laminates into the coloured façade elements thus leads to an average performance reduction from 145 Wp to 131 Wp, that is 10 %. The power reduction is partly due to light absorption by the composite material itself and partly by the dye. The average powers per colour are very near

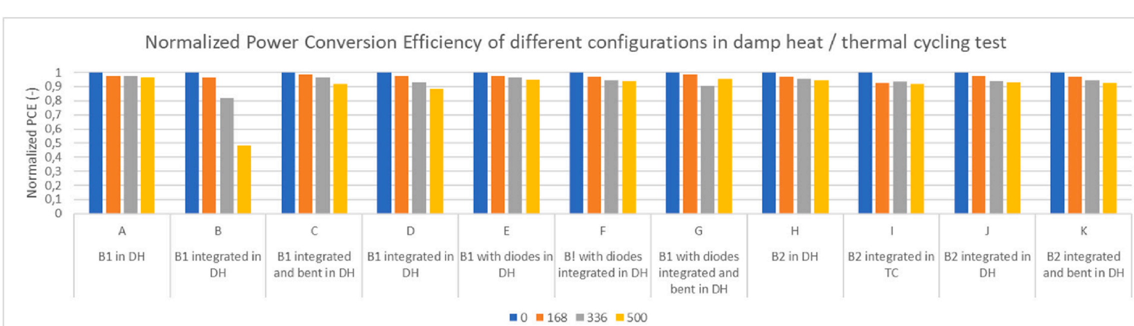

Fig 5. Normalized power conversion efficiency of the PV laminates in different configurations with barrier foils B1 and B2 in DH and TC tests after 168, 336 and 500 h.

Fig. 6. First facade element with PV.

Fig. 7. Facade elements with PV after installation. South façade on the left with 15 elements; East façade on the right with 29 elements.

to each other, but it should be noted that the colour variation is not that large either (Fig. 6).

2.4. Installation

Installation of the façade elements was carried out with a crane vehicle (cherry picker) and was conducted in a few days. The elements were fixed to the façade with screws; the inverter was installed inside the building, close to the façade (Figs. 7 and 8).

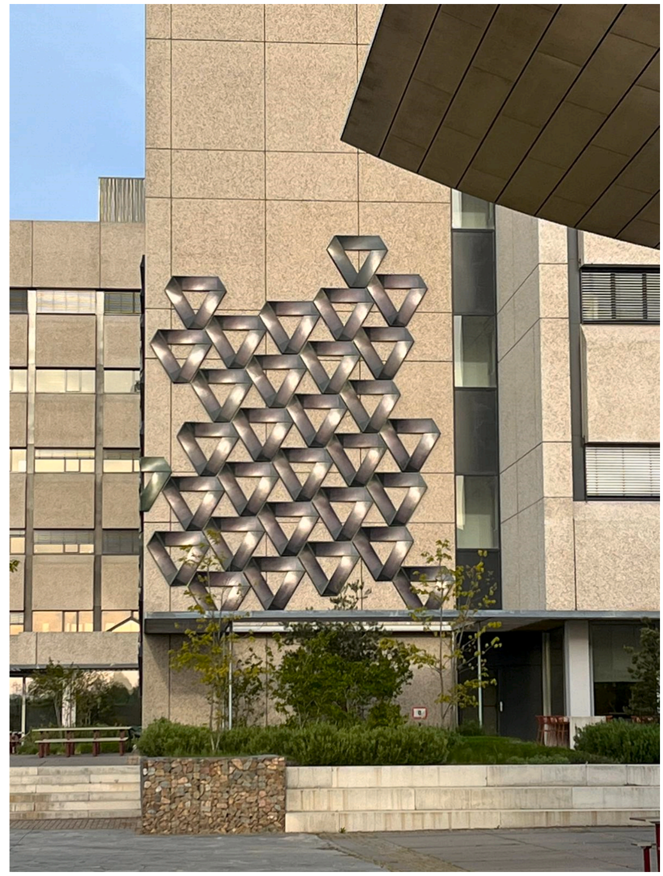

Fig. 8. East side of the building in the morning light, showing special visual effects due to the curvature of the elements.

3. Results and performance analysis of system

Precise labelling of all components was very important in this project, because it allowed for full traceability completely back to the original components and materials used. All modules have first been checked visually, with Electroluminescence (EL) and an IV-curve at STC. Thereafter the complete element was checked again with an IV-flash after it had been assembled. Then, each element was labelled with a unique code (see Fig. 9) and a unique Power Optimizer (PO).

The study and the measurement period spanned from 1st June 2023 till 27th October 2023, hence nearly 5 full months. The uptime of the irradiance measurements was about 99 %, for which no correction was done because extrapolations are always prone to misjudgement. The uptime of all the electrical measurements from the SolarEdge monitoring portal was 100 %. Because we have downloaded all individual PO-data, we could also calculate the specific yield per element, by using the rated power in Wp from the indoor measurement as discussed in chapter 4.

The total AC-yield of the complete system with both facades in the monitoring period has been measured to be 1630 kWh. The rated power of the complete system is 5756 Wp. Hence the AC specific yield of the full system is 283 kWh/kWp. For the irradiance we calculated the 'façade weighted irradiance' which is 29 times the irradiance on the East façade added with 15 times the irradiance on the South façade; and that sum divided by the factor $29 + 15 = 44$. This results in 392 kWh/m^2 for the measurement period. Finally, the performance ratio (PR) is by definition the fraction between specific yield and irradiance: PR_AC =

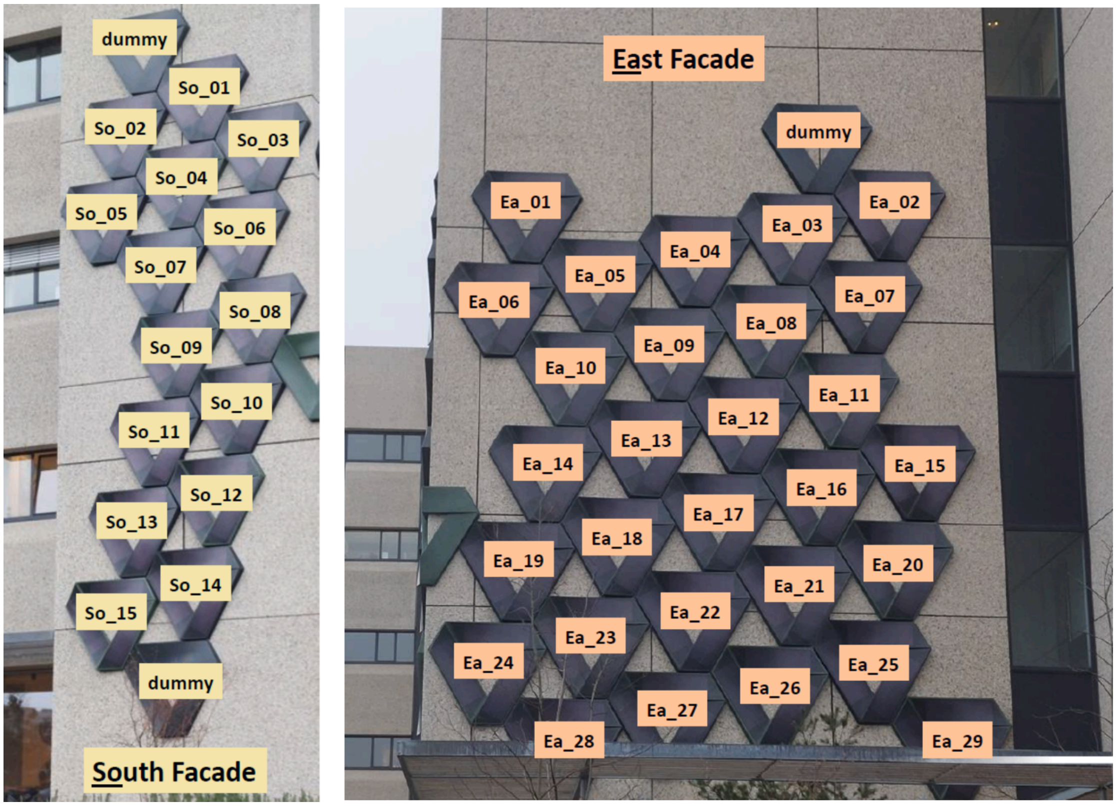

Fig. 9. Unique labelling of all elements is needed for full traceability from SolarEdge Power Optimizer down to individual components (like PV-cells) used in the modules.

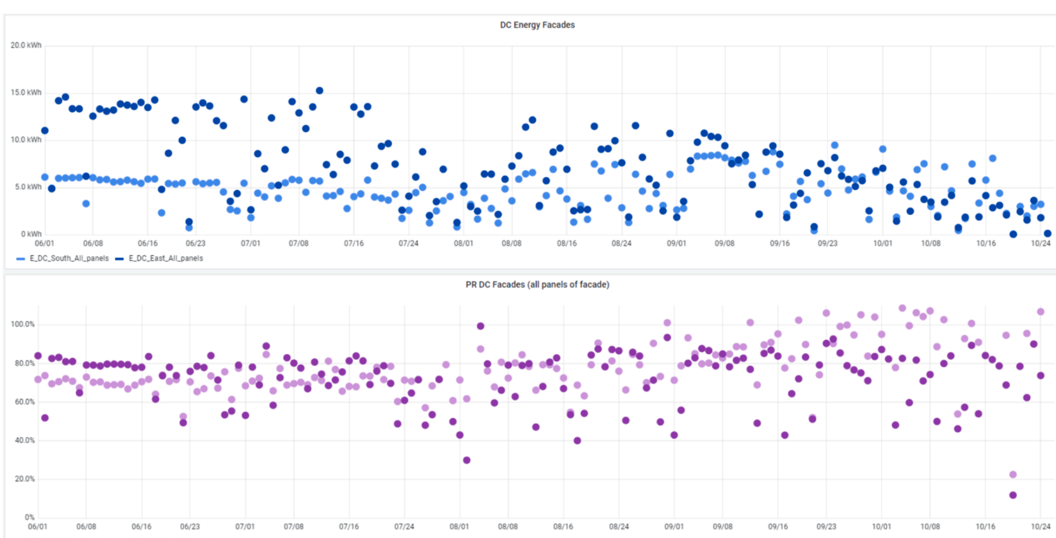

Fig. 10. Upper graph: DC energy of all elements in South facade (light blue) and East Facade (dark blue) per day. Lower graph: PR_DC of South facade (light pink) and East façade (dark pink). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

72 %.

It is expected that both facades behave differently during the seasons. To investigate the PR of each façade we have added the DC data of the individual elements. In Fig. 10 one can see the DC energy yield per day of the full façade in the upper graph and the PR_DC of the full façade in the lower graph. In the first spring period the amount of irradiance on the south and east façade are quite comparable (figure not depicted here). Therefore, the upper graph of Fig. 10 can be understood easily: there are roughly two times more elements in the East façade (dark blue marker) when compared to the South façade (light blue marker). In the lower graph this effect is cancelled out by looking to the PR_DC.

To investigate a potential seasonal effect, the same data are summed per month; see Fig. 11.

Now, it can be observed that in spring the East façade performs better (dark pink marker) when compared to South façade (light purple marker), whereas the effect gets reversed in autumn. In summer the PR of both facades are comparable. The explanation can be found in either an effect of the PO’s or the temperatures of the elements. We will

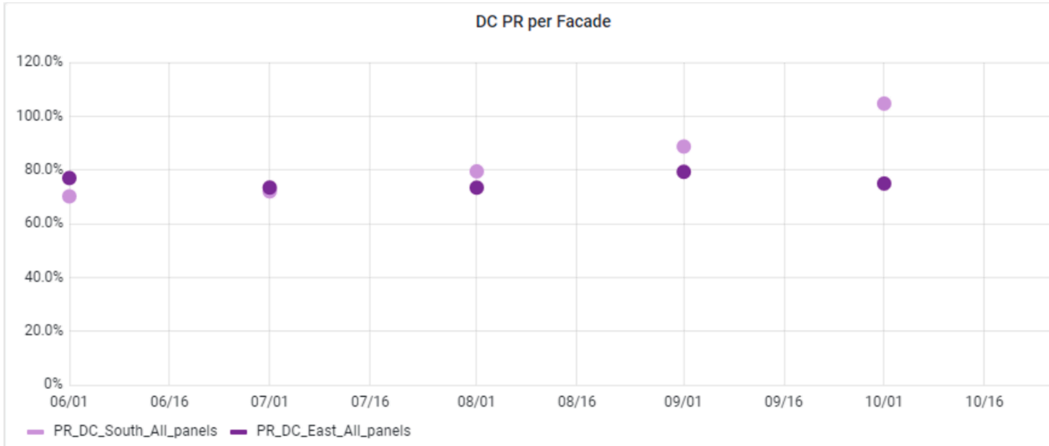

Fig. 11. PR_DC of South facade (light pink) and East façade (dark pink). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

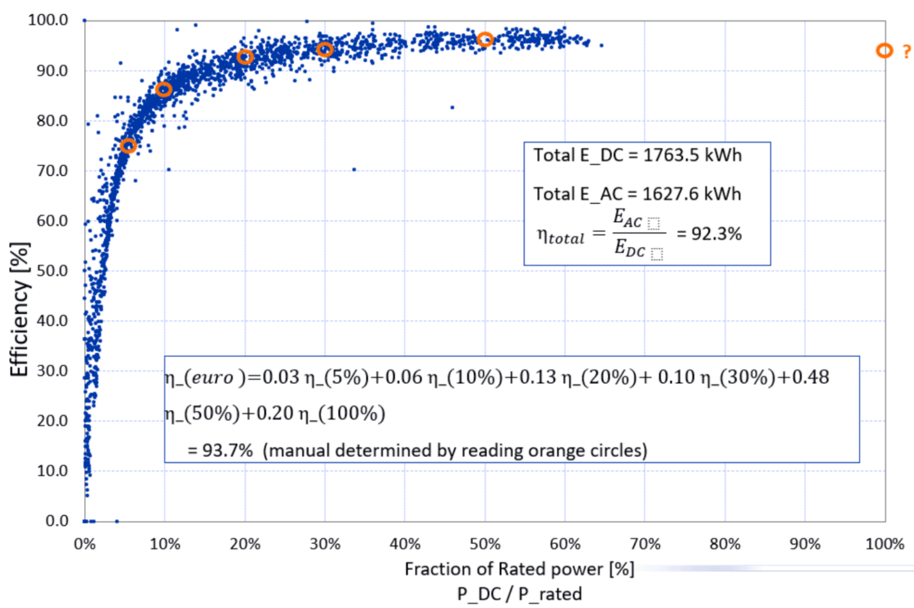

Fig. 12. SolarEdge SE5k inverter curve based on monitoring portal data with one hour measurement resolution.

investigate both in the remainder of this chapter. The full period PR_DC of the South Façade is 80.3 % and of the East Façade is 75.3 %.

As expected, the PR_AC is lower than the PR_DC due to the inverter losses. To investigate if this loss in our setup is according to expectations, we composed the efficiency curve of the inverter in Fig. 12. In this figure the DC Energy of all 44 elements is summed and divided by the 1 AC Energy value, for each hour of the full measurement period, based on SE monitoring portal data. This efficiency is plotted as function of power P_DC relative to the rated power P_rated of the central inverter (5 kW).

In the legend one can see the definition of Euro-efficiency and the determined value by reading manual the values from the curve. One should note that the accuracy of this method is limited, and we had to create a datapoint at 100 %, which did not occur in the measurement period. Given those inaccuracy, the overall Euro-efficiency is approximately 94 %. Looking to the efficiency of the system in the full period, we measured an efficiency of about 92 %. This underpins the smart choice of points in the definition of Euro-efficiency.

For a commercial installation, one should consider putting multiple elements in parallel on one PO. Secondly one should consider a smaller sized inverter. Both would be beneficial for the overall full year efficiency. However, for the research purpose of this system, we deliberately put each element on its own PO to be able to measure the individual elements performance. Last but not least, the Euro-efficiency in the datasheet is declared as 97.3 % [8]. Given the fact that we have determined the full curve in an outdoor setup, and given the inaccuracies, this is close enough to the 94 % that we found, to conclude that the system is performing electrically to expectations.

As mentioned, we have all electrical data of each element. A screenshot of the SE monitoring portal gives a nice impression of the complexity of this data stream; see Fig. 13.

The SE portal does not know the irradiance in each façade and also not the rated power of each element. However, after downloading the full data set, we can calculate specific energy and PR_DC per hour per element. These hourly data are quite noisy but the daily sums give nice insights. Please see in Fig. 14 the colour plotted PR_DC for three typical days: 2nd July being a clear sky hot day, 25th September being a clear sky cooler day, and 12th October being a very overcast day. When comparing these days, it can be clearly noted that for the dark day in October all POs operate in the very low part of their efficiency curve. The comparison between the clear sky days shows that higher

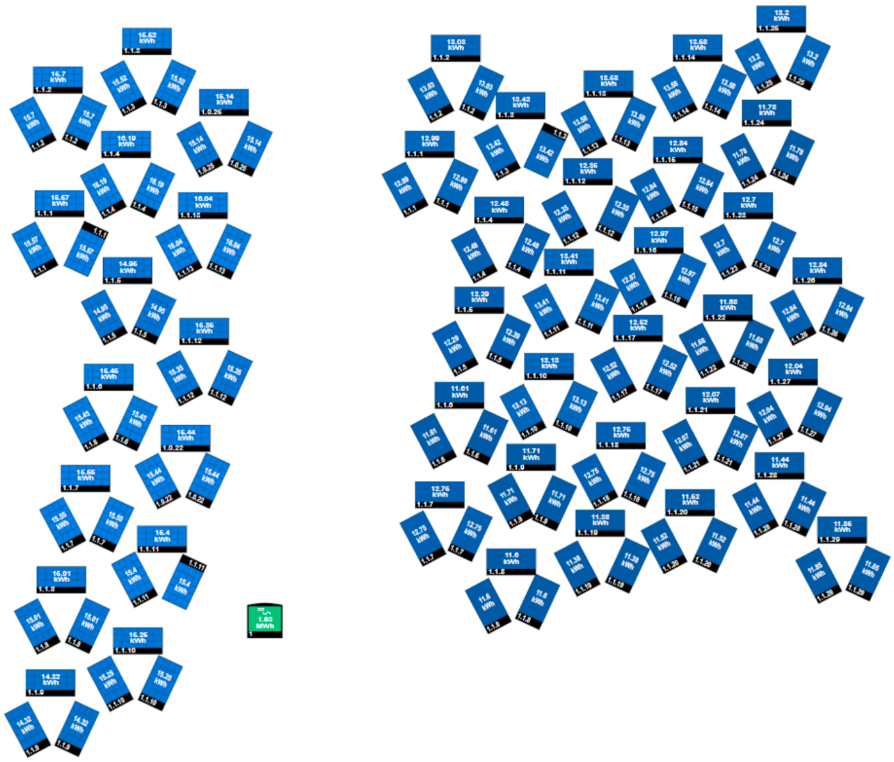

Fig. 13. Screenshot of the full period DC Energy produced by each element. For visualization purpose the energy of each element is divided equally over the 3 modules in that element.

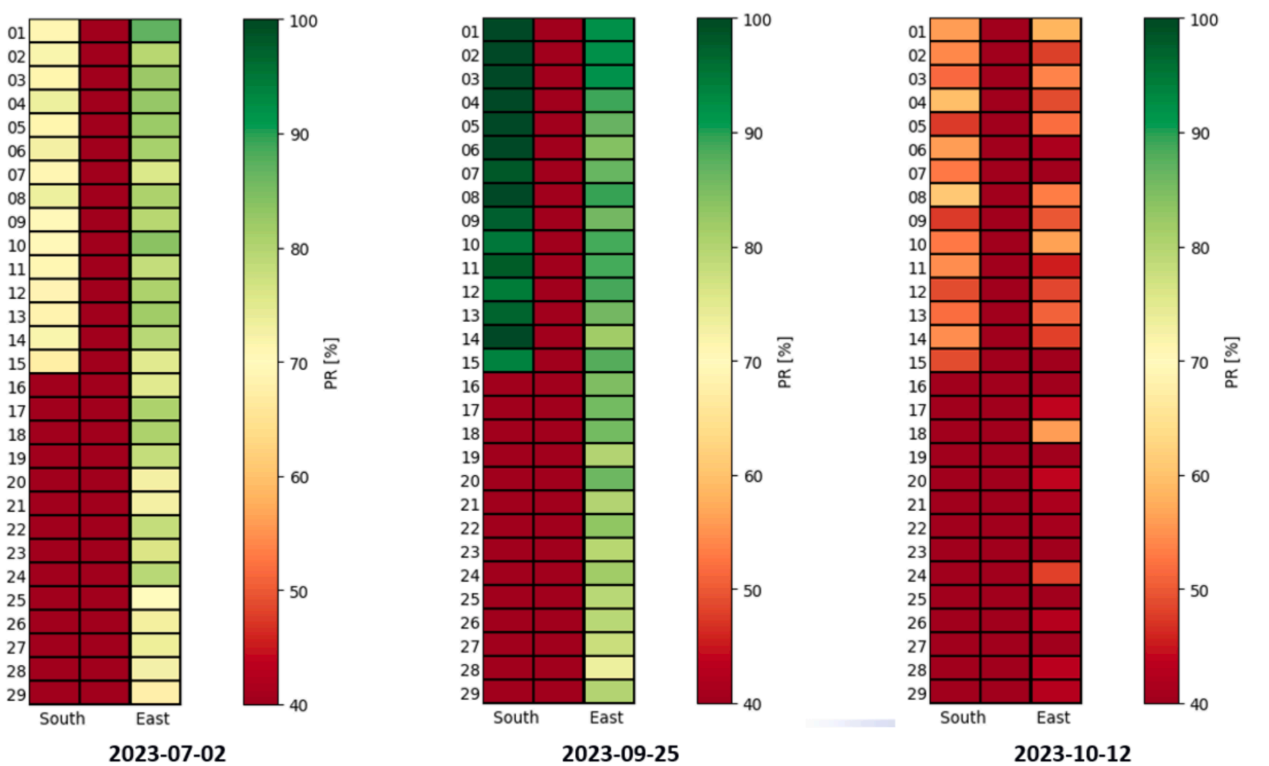

Fig. 14. Full day PR_DC of each element for 3 typical days. Please note that for ease of programming, the elements are displayed in columns. The 15 elements on the South facade are in the left column, the 29 elements on the East facade are on the right column, dark red is no element. In the real system the lowest element of the South and East façade are at the same height above ground. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

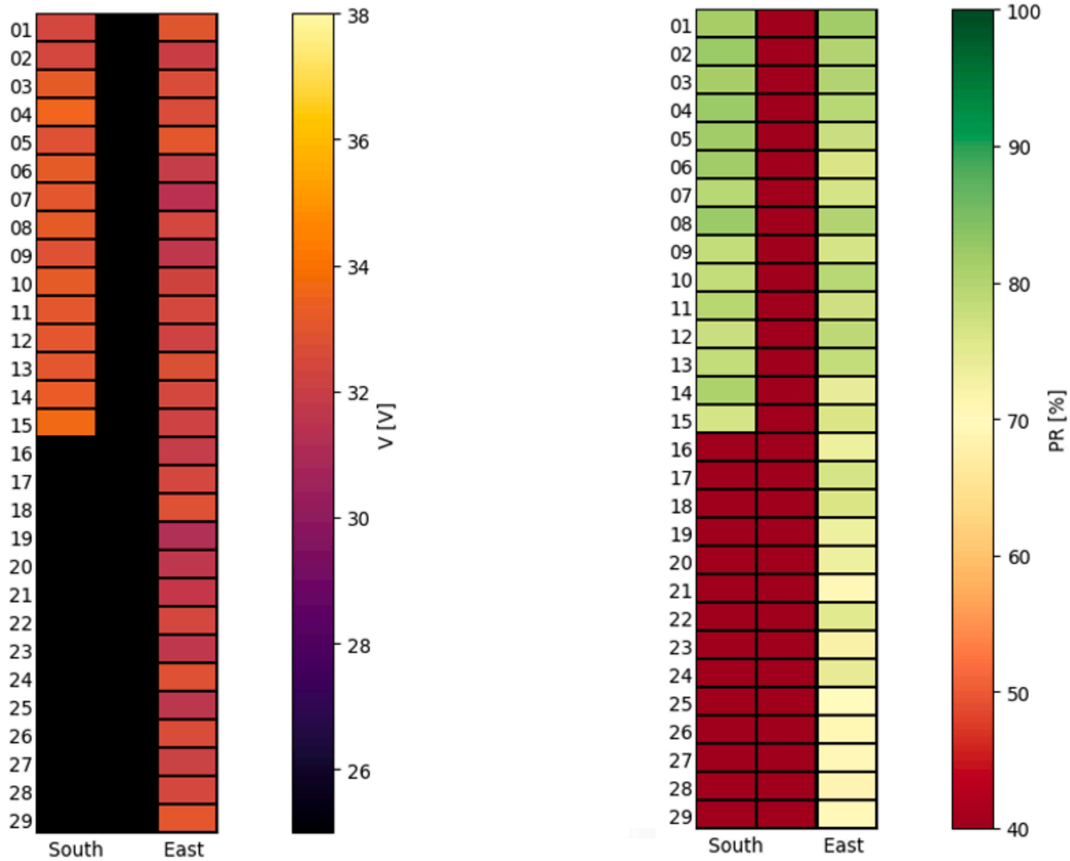

Fig. 15. Full period aggregation of DC Voltage (left) and PR_DC (right). Please note that voltage is based on about 150 days of 100 measurements per day, whereas the PR is based on 150 days with 24 measurements per day.

temperatures give a lower PR in general which is completely in line with the intrinsic negative temperature coefficient of the PV technology. Finally, a more subtle effect can be observed in the clear sky days (and many more days not plotted in this article). The PR seems to be getting marginally better for higher positions in the façade. This cannot be a temperature effect, because that would lead to the opposite behaviour. Moreover, the temperature chimney effect is not expected because the elements are installed as a cladding façade with a superb ventilation also by the holes in the elements. Therefore, the effect must be caused by the effect that the higher part of a façade gets more irradiance than the lower part and some very minor shading effects are influencing the lower elements more than the upper elements. This is in accordance with the general experience in the field of PV-façade installations that high-rise buildings get more irradiance in the upper parts of the facade compared to the lower parts, roughly as a linear gradient from bottom to top of the façade. This effect is related to the diffuse sky masking for lower solar altitudes. On the other hand, the taller the building gets, the easier it becomes to predict irradiance at low solar altitudes. It is particularly challenging to predict the precise irradiance for the lower floors [9].

The same analysis was done for the DC voltage of each element. The analysis shows a general trend that aggregated voltages are slightly correlated with the V_{MPP} of the indoor IV-measurements. However, both irradiance and temperature have an effect on V_{MPP}, which make it difficult to draw some hard conclusions on that data. Only the full period averaged voltage will be shown below together with the full period PR_DC; see Fig. 15.

The main conclusion from Fig. 15 is the fact that each element is still performing according to expectations. The variation from element-to-element is smaller than we expected beforehand, given the fact that this is the first larger production batch of these custom-made elements.

4. Conclusions and outlook

One of the bottlenecks for integration of PV in facades is the lack of freedom of design. Presently, coloured PV is available, but only with flat geometries. The aim of the project that is described in this paper was to demonstrate the feasibility of coloured 3D structured facade elements with PV. It has resulted in a demo on a building on the High Tech Campus in Eindhoven with a great visual attractiveness and good PV functionality. The demo system shows the applicability of composite materials for fabrication of 3D structured façade elements with PV.

It can be concluded that the system is running flawless since the start of operation at 1st June 2023. In the five-month measurement period the overall PR_DC is 75 % for the East façade and 80 % for the South façade. From the voltage measurements there is no suggestion that South façade elements get warmer in general. Hence, the difference is mainly caused by the fact that elements in the East façade are running for larger periods with lower power output and therefor are more in the unfavourable (left lower) part of the efficiency curve.

Overall, the PR_AC for the full system is around 72 %. This value can be increased in a commercial installation by putting two or three elements in parallel on each power optimizer, and by sizing the inverter smaller, which would shift a lot of measurement moments into higher efficiencies in the inverter efficiency curve.

The aim of the project is to continue the measurements at least one full year. Although this is not long enough to determine all potential aspects of long-term degradation, it will at least enable us to validate the indoor climate chamber reliability testing. If possible, the system will be installed and monitored for an even longer period. This would give valuable information, because long-term data for façade systems (with a high resolution and specific for each element/module) is not that much reported yet in literature.

Declaration of Generative AI and AI-assisted technologies in the writing process

The authors did not use AI and AI-assisted technologies in the writing process.

Credit authorship contribution statement

Wim Soppe: Writing – review & editing, Writing – original draft, Investigation. **Dorrit Roosen:** Investigation. **Stefan Smit:** Conceptualization, Methodology, Resources. **Roland Valckenborg:** Supervision, Software, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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