Prefabricated Renewable Energy Façades For Cost-Effective Buildings (Prefab)

Corry de Keizer[1], Maarten Dörenkämper[1] and Simona Villa[1]

[1] TNO Energy Transition, Eindhoven (the Netherlands)

Abstract

The integration of solar energy in prefabricated façade elements is a promising technology. The energy transition requires a large amount of space, and especially for high-rise buildings the roof area is not sufficient to comply with modern building codes regarding energy performance. Prefabricated or ‘industrial’ building is getting more popular, as it leads to lower costs for installation and allows for better quality control. Within this project, a consortium developed prefab façade elements with integrated photovoltaic (PV) modules. A demonstrator was designed and constructed, which includes PV modules with several innovative technologies with regards to size, form, colour and transparency. Different colour techniques were used. The performance of the demonstrator is extensively analysed based on measurements and detailed modelling.

Keywords: BIPV, façade, industrial building, coloured PV, prefab

1. Introduction

The energy transition requires a lot of space for implementing renewable energy technologies. Solar energy systems are especially suited to be integrated in e.g. roofs, facades or infrastructure. Especially for high rise buildings, the roof surface alone is insufficient to meet the energy demand and therefore integration of photovoltaics in the façade offers an interesting opportunity. In the Netherlands, there is a potential of about 660 km^2 for solar energy integration in the façade (Van Hooff, et al., 2021). Solar façades could potentially produce 32 TWh per year which is nearly 30% of the electricity demand of the Netherlands (CBS, 2021).

There are many examples of photovoltaics integrated or added to facades (Corti et al., 2020). Demonstration projects with different technologies, colours and ways of integration have been implemented since the 1990’s. There are several ways to integrate PV in the building skin that depend on the construction of the façade. Rainscreens, also known as cold or ventilated façades consist of a load-bearing substructure, an air gap and a cladding. Usually, PV modules are integrated in a similar way to non-PV claddings. Curtain wall façades are external and not ventilated, these can be totally or partially glazed and are supported by a substructure. It is designed to resist air and water infiltration. PV elements can replace the non-PV glass. A double skin façade consists of two glazed skins, photovoltaics is integrated in the outer skin that should be able to withstand wind loads. The cavity functions as insulation and can be actively ventilated. Accessory façade are for example balconies with bifacial PV. Lastly prefabricated or multifunctional facades are preassembled and have multiple functions like thermal and acoustic insulation, weather protection, energy production, etc. (ICARES, 2019).

The aim of the PREFAB project is to develop integration of PV into prefabricated façade elements that are aesthetically pleasing and affordable. The potential advantage of integrating PV into prefabricated façade elements is an improved process efficiency, lower installation cost and avoided costs for cladding materials, improved quality and safety management. It can also result in a reduced installation time on often busy building locations and less transport movements and therefore lower CO_2 emissions. Further advantages may include a better freedom of design. It is expected that integrating PV in facades of high-rise and low-rise office buildings or dwellings will become important in the next decade, especially in densely populated countries like the Netherlands.

In the PREFAB project, we have been working on developing technologies that allow aesthetic solar panels to be integrated into prefabricated façades of buildings. Several innovative technologies with regards to the size, 3D shape, colour and transparency of the PV modules are researched and implemented in a demonstrator. The

doi:10.18086/eurosun.2022.07.11 Available at http://proceedings.ises.org

demonstrator includes modules with several PV technologies, different PV colouring technologies, module packaging and mounting method. The PREFAB demonstrator was installed on an outdoor research location and extensively measured for a year. Furthermore, the PV performance model BIGEYE (Janssen, 2018; Burgers, 2018) is validated for PV panels in the façade by using measured data from the PREFAB demonstrator.

The PREFAB project has been running from 2019 to 2022 and was carried out by a broad consortium that includes prefab building companies (TGM, Emergo), a BIPV façade supplier (Studio Solarix), engineering and installing companies (Sanko Solar, SCX Solar), a company on composites who integrate PV (Flexipol), software developers (Novasole) and a research institute (TNO). The ambition of the commercial project partners is to develop products that can be introduced to the market after the end of the project.

In this paper, we will focus on the design and different technologies of the demonstrator and installed measurement equipment (Chapter 2). The field test (chapter 3) is described with a focus on the analysis of weather and performance of the individual modules. Furthermore, electrical PV simulations on the PREFAB system are performed in order to investigate further the electricity generation potential of such a BIPV system, as well as to improve the understanding on specific aspects, such as shading and albedo effect (Chapter 4).

2. PREFAB demonstrator

2.1 The PREFAB demonstrator

The demonstrator is shown in Figure 1, while the installation of a prefab element is shown in Figure 2. The demonstrator consists of two prototypes. The left prototype (1.80 m wide, approx. 4 m high) has an aluminium frame as is typically used for high-rise office or residential buildings. This façade element was assembled in the factory and mounted directly from a crane. The right side prototype has a wooden frame typically used in low-rise dwellings. The PV modules are mounted on site.

Several different (PV) technologies are implemented in the demonstrator:

- PV cell types: Crystalline silicon and CIGS
- Colouring technology: coloured foil and ceramic printed ink on glass
- Module packaging: frontsheet – backsheet (solar foil), glass-backsheet and glass-glass modules
- Form and size: CIGS PV foil is integrated in a 3D composite module, the cells are in two surfaces facing different directions.
- Prefabrication and mounting: one façade element is fully assembled in the factory and mounted from a crane, the other one is partially prefabricated (including window) and PV modules are mounted on site.

Fig. 1: PREFAB demonstrator, consisting of two façade elements, on the outdoor research facility

Fig. 2: Installation of a PREFAB element

The specifications of the installed modules and the colouring technology are described in Table 1. Solarix supplied the coloured foils for the different modules and the coloured etched glass of module J1. They supplied modules A, C2, E and D. Module J1 was produced by TNO. The CIGS module (foil) for panels G, H and I were produced by TNO part of Solliance. The CIGS foil was laminated within a composite 3D shaped module by Flexipol. A printed foil is used to colour the modules. The STC rated power was measured by TNO and is shown in the last column per m^2 cell area. This column shows quite some differences due to the reference technologies and the method for the colour technology. A print with ceramic ink results in lower losses due to colour. The printed foil was a first innovative solution and will be further improved with regards to losses due to colour. Due to the different dimensions, all modules have a different part of the area of the module that is filled with cells,.

The demonstrator is installed on SolarBEAT, the outdoor research location of TNO on the TU Eindhoven campus. The façade of the demonstrator is oriented towards the south. A full year performance was measured from August 2021 to July 2022.

Tab 1: Specification of the modules in the demonstrator

Panel	Cell-type	Colour technology	P_{mpp} (W)	Module area (m^2)	Cell area (m^2)	Area Fill (%)	Rated W/m$^2_{cell}$
J1	c-Si (MWT*)	Ceramic ink on glass	165.0	1.55	1.22	79	135
E	c-Si	Printed foil	48.5	0.85	0.54	63	90
D	c-Si	Printed foil	107.9	1.47	1.17	80	92
A	c-Si	Ceramic ink on glass	143.5	1.41	1.10	78	130
C2	c-Si	Ceramic ink on glass	114.4	1.11	0.81	73	141
G	CIGS	Printed foil	27.3	0.48	0.29	61	93
H	CIGS	Printed foil	33.7	0.53	0.33	63	101
I	CIGS	Printed foil	21.7	0.48	0.29	61	74

* Metal Wrap Through (MWT) back contact technology

2.2 Installation and measurement equipment

The PV modules are kept in maximum power point and are connected to the grid by making use of DC-DC power optimizers and a inverter (SolarEdge). For every module (except module E), the DC current, voltage and power are measured with a AcuDC 243 power analyser that is installed between the power optimizer and the PV module. Since module E had a too low V_{OC} for the power optimizer, this module is measured using an IV tracer. T-type thermocouples are mounted on the rear side of the PV panels. In the case of the composite panels (G, H, I), the thermocouples are laminated within the composite structure. Irradiance in the plane of the façade is measured using two EKO MS80 pyranometers, which are mounted at two different heights on the west-side of the demonstrator (see Figure 1). The different irradiance levels at different heights are further measured by 8 different photodiodes (EKO ML-01) installed on a so-called irradiance beam located in the middle of the setup.

On SolarBEAT a solar measurement station is installed that measures Global Horizontal Irradiance (GHI) using an EKO MS-802 pyranometer. Diffuse Horizontal Irradiance (DHI) is measured with a similar pyranometer combined with a EKO MB-12 shading ball, which is mounted on a EKO Str-22G sun-tracker. On the same sun-tracker, Direct Normal Irradiance (DNI) is measured with a pyrheliometer of the type EKO MS-86. Furthermore, several meteorological parameters (ambient temperature, wind speed, wind direction, air pressure, precipitation) are measured using a Lufft WS 600 weather-station.

Every day all measured data with a time resolution of 1 minute is uploaded to an SQL-database.

3. Performance analysis

3.1 Irradiation and wind speed

The irradiation profile over a year is very different for a façade in comparison to the irradiation for a horizontal or optimally inclined plane. Figure 3 shows the monthly measured in-plane or plane of array irradiation (POA) in the façade and the monthly measured global horizontal irradiation (GHI). The highest monthly irradiation for the façade is not found in the summer months, but during spring and autumn as the elevation angle of the sun is more advantageous for planes with a tilt angle of 90°. During summer, the sun is high in the sky and often beyond the vertical façade, which sees a smaller sky portion than, for instance, an horizontal or slightly tilted PV module. Also direct irradiation from northeast or northwest is not received by a south facing façade. The annual irradiation on the south façade from August 2021 to July 2022 was 917 kWh/m^2, this is approximately 18% lower than the global horizontal irradiation and 27% lower than irradiance on a 35° tilted roof. It was a very sunny year.

The wind compass in Figure 4 shows the frequency of wind speed and direction. The building on the north influences the wind profile.

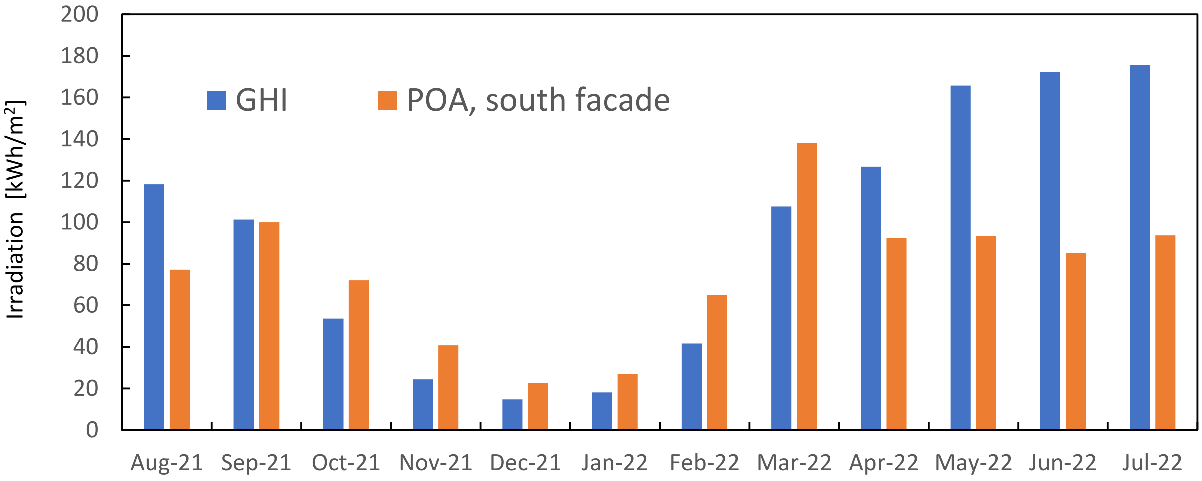

Fig. 3: Measured monthly in-plane irradiation (POA) in the south façade and the monthly global horizontal irradiation (GHI)

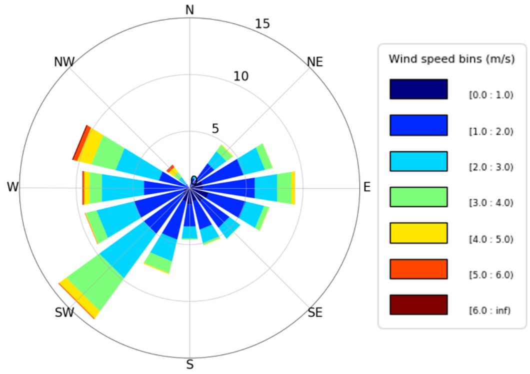

Fig. 4: Wind compass

3.2 Energy performance of the coloured modules

In this section, we evaluate the DC performance of the different PV modules. The PREFAB elements and the individual PV panels were affected by external factors, like shade (see Figure 5), and factors that are system specific. To allow for a fair comparison between the different PV modules, data during times when at least one of the PV panels is affected has been filtered out. The following filters have been applied to the data set:

- Shading: The azimuth angle should be between 130° and 242° (with 180° as south) and an elevation angle higher than 14°
- Voltage blocking effect due to the many different module sizing and specifications in combination with the DC-bus of the Solar Edge system: the output voltage of the power optimizer should be lower than 78V.
- All modules should be functioning, times when some power optimizers start up late, due to the rated power of the modules, are excluded

This results in a smaller dataset, where about one-third of the annual irradiance is still included. The effect of shading (see also Figure 5) will be evaluated by simulations in Chapter 4.

Figure 5: Left: Shade patterns in the morning of the 17th of April of 2022 caused by the neighbouring PV setup (ZigZag) Right: Shade on panel D, caused by the protruding part of panel C2 in the afternoon of the 17th of April 2022.

Figure 6 shows the monthly DC performance ratio (PR_{DC}) for three of the modules.

$$PR_{DC} = \frac{E_{DC} \cdot G_{STC}}{P_{STC} \cdot I_{POA}}$$

Where E_{DC} is the DC energy yield, G_{STC} the irradiance at standard test conditions (1000 W/m^2, 25°C), P_{STC} is the installed DC power and I_{POA} is the solar irradiation.

The trend throughout the year shows slightly higher performance ratios in winter and slightly lower performance ratios in summer, probably due to temperature effects. The slightly lower PR of the foil coloured modules could be due to inaccuracies in STC power ratings. The lower PR of the CIGS modules is possible caused by a mismatch due to irradiance on two planes. Figure 7 shows the 30-minute instantaneous PR_{DC} of module G. It clearly shows a dependence on the azimuth of the direct sunlight that is caused by the cells in two different planes. Figure 8 shows the DC performance ratio and the annual expected DC yield for an unshaded situation in kWh/m^2 cell area. The modules with a ceramic ink colouring show a higher calculated annual yield due to a higher peak power, as well as a higher performance ratio. The expected DC yield for the unshaded situation is calculated by multiplying the module specific rated peak power (W/m^2) with the performance ratio and the annual irradiation.

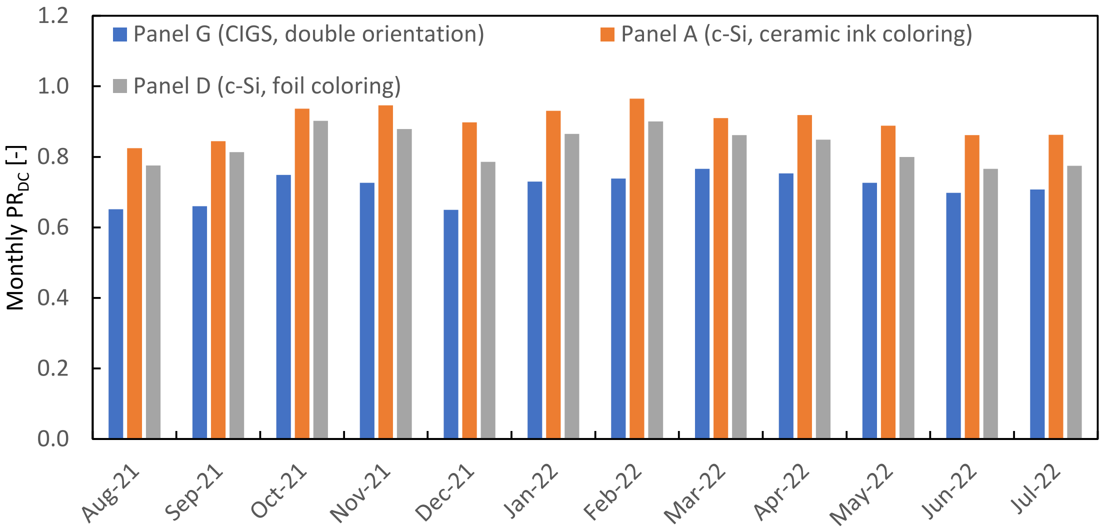

Figure 6: Monthly DC performance ratio for selected modules

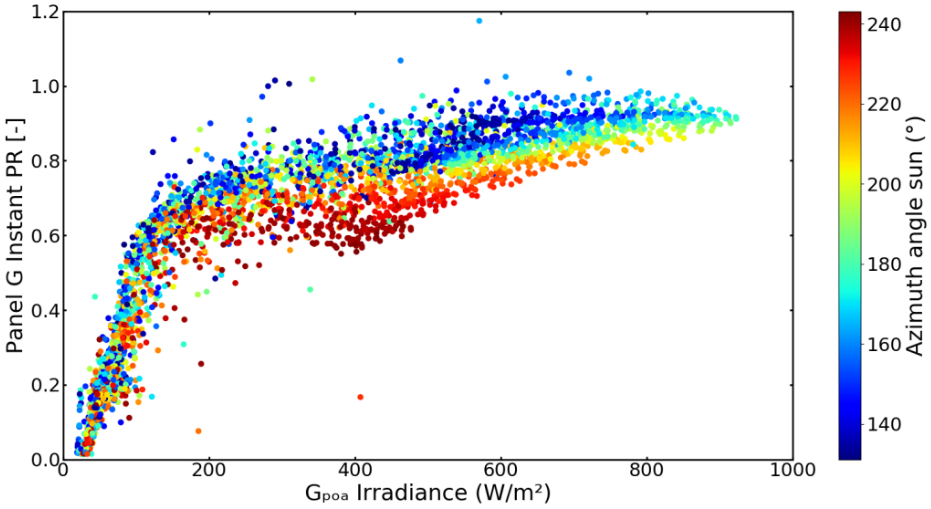

Figure 7 Temperature corrected instantaneous PR_{DC} of panel G as a function of the G_{POA} irradiance. The colour code represents the azimuthal position of the sun. One datapoint represents 30minutes.

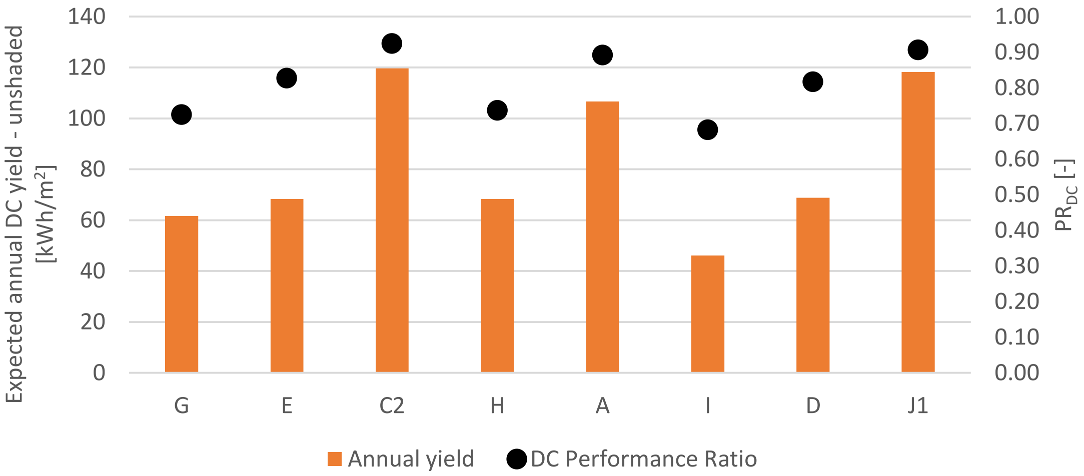

Figure 8 Annual DC performance ratio for unshaded situation as measured (on the right axis) and expected DC annual yield (on the left axis) for an unshaded situation. The DC annual yield is calculated by multiplying PR_{DC} with irradiation and rated specific module power.

4. Simulation of annual energy yield

4.1. BIGEYE Model

The energy yield is modelled with BIGEYE, an in-house developed software for PV system modelling (Janssen et. al., 2018, Burgers et.al.,2018). The effect of self-shading (from the construction itself) will be evaluated. At first, we model the PREFAB modules as closely as possible to the real demonstrator built at SolarBEAT, considering the real geometry of the system with all its sources of shade. In such a way, we can validate the model using the real outdoor measured data. Then, typical meteorological year data are used to estimate the annual generation potential of the PREFAB façade mockup in its current configuration.

With BIGEYE, PV systems at any location and of any configuration (e.g. bifacial) can be modelled. Using weather and environmental data, the electricity produced can be calculated on a minutely, hourly, daily, monthly or yearly basis. With the software it is possible to accurately reproduce the geometry of the studied system, and account for external shading objects, which will act in the model as dummy elements. BIGEYE user interface requires two input files: a geometry file and a meteorological file.

In the PREFAB modelling work, the most challenging part resulted to be the realization of the geometry file, due to the high customization of the façade and variety of modules' shapes, dimensions and orientations. In order to take into account the mutual shading, it was crucial to accurately reproduce not only the PV modules, but also all the dummy non-PV active panels which are part of the facade, with their exact dimension and relative spacing. In fact, most of the modules within the PREFAB system are subjected to multiple sources of shading, such as construction-shading from their own support or shading from external objects (e.g. the other cabins at SolarBEAT). Figure 9 shows the schematic of the modelled geometry of the system in BIGEYE, including both the PV-active elements (A, C2, D, E and J1) and the dummy elements responsible for casting shades. Modules G, H and I are not modelled.

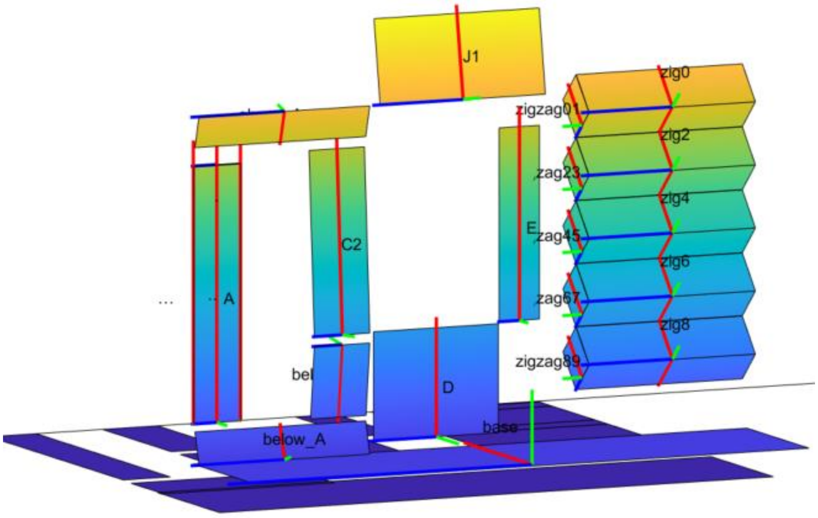

Figure 9. BIGEYE modelled geometry of the PREFAB system, including both PV active elements (A, C2, J1, D, E) and dummies.

The losses due to the colour coatings (ink printed dots on glass or coloured foil) on the actual PREFAB modules are almost purely optical, meaning that they mainly translate in a current decrease.

4.2. Validation of the model

The module was validated by comparing measured and simulated power for several sunny and cloudy days in different seasons. An example for module J1 on the April 17, 2022 is shown in Figure 10. From the results of the validation we can state that BIGEYE is successful in accurately modelling the current, voltage and power output of the different modules. With a good degree of accuracy (typically $R^2 > 0{,}996$), we could validate the model with the measured data.

The simulations also helped in understanding specific issues that were encountered in the real life demonstrator, such as specific shading patterns and power electronics issue. For example, on the selected sunny day, we can see the effect of the power optimizer issue (i.e. voltage blocking) on module J1 (Figure 10). It can be observed that, before 9:30 am and after 17:30 the measured Impp slightly decreases (limited by the reached max PO voltage) while the Vmpp slightly increases, when compared to the simulated curves which present instead smooth profiles.

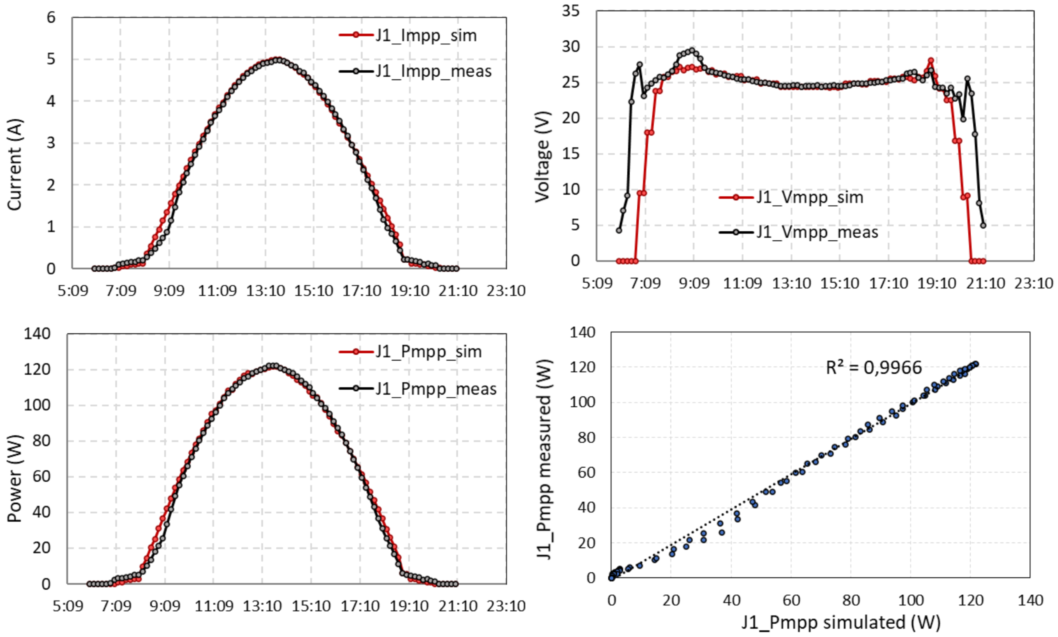

Figure 10. Model validation module J1 (sunny day 17/04/2022): comparison measured data vs simulation.

4.3. Shading losses

For each simulation, BIGEYE also allows to compare the electrical power output both including and excluding the presence of shading elements. In such a way it is immediately possible to see to what extent shading affected and limited the power production. For the same reference sunny day as before, this is shown in Figure 11. For each module we compare the simulated power generation including all sources of shade (as in real life – red curves) versus the hypothetical power production if no shading sources would be present (blue curves). It can be seen that for this sunny day, modules D and E are the most affected by the shade, reporting a loss of more than 9%. In that case the shade is coming mainly from the zigzag structure next to the PREFAB one, as visible from the webcam photo in Figure 5. Module A shows a 7% loss (over this day) which is attributed to its own support structure and the titled dummy panel above it. On the other hand, modules C2 and J1, which are not vertical but slightly tilted towards the sky (3° and 5° respectively), are not affected by any shade, thus reporting no loss.

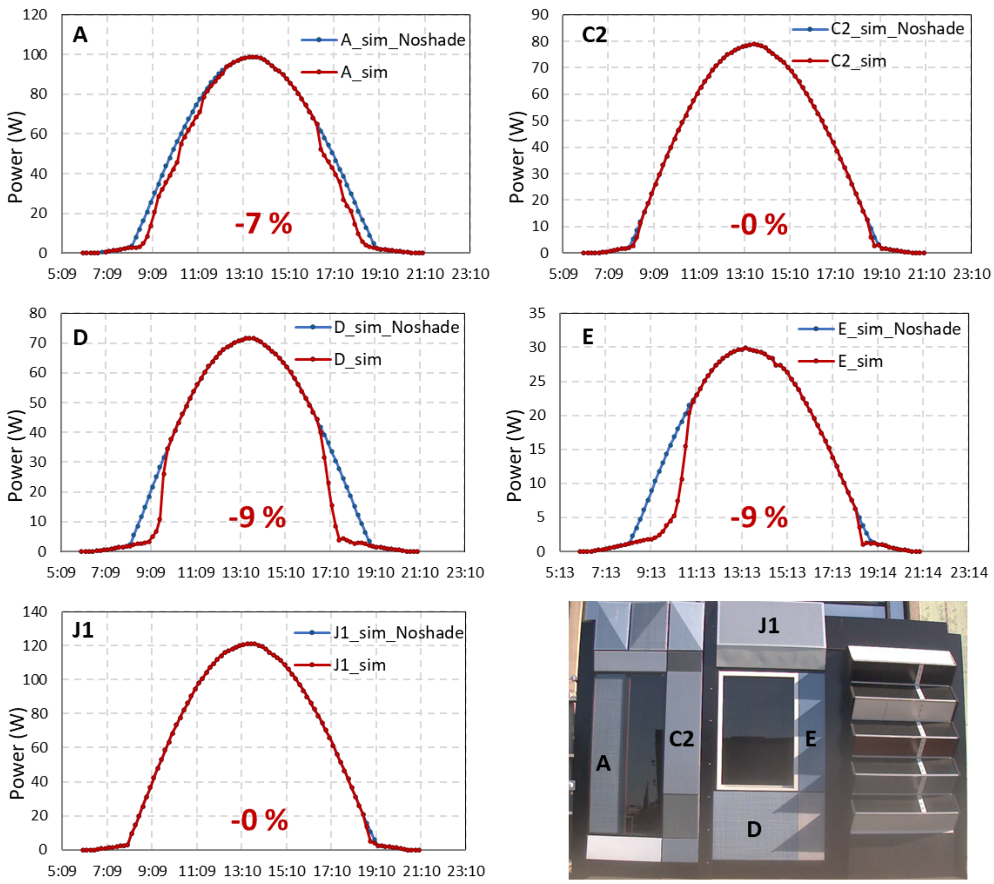

Figure 11. Simulations showing power loss due to shading for each module during sunny day 17/04/2022. The power production including all sources of shade (in red) is compared to the hypothetical power production in case of no shading elements (in blue). The percentage indicates the total daily power loss.

4.3. Simulation for a typical meteorological year

A full year simulation was performed for one representative module of the PREFAB system, i.e. module D. The simulation is run using weather data for a typical meteorological year (TMY) from Meteonorm software, with a 1-h timestamp. Please note that the irradiation of the TMY is significantly lower than the measured weather data during the PREFAB field test. Figure 12 shows the results of the simulation as a monthly energy yield bar plot, where we also compare the energy generation in case of presence and absence of shading. The presence of shading elements as we have them at SolarBEAT is actually representative of a real case scenario, where such a module would be installed in the façade (south-facing, in this case) of a building in a city environment, which is plenty of possible sources of shade (other buildings, trees, etc.). In the simulated case, we found that most shading losses are in spring/autumn and summer, and for the full year they account for around 4 to 5%. The simulation also shows that the energy yield is the highest in the spring and autumn season, and slightly decreased in summer. All in all, the energy production of a vertical façade system is more evenly distributed over the year than a standard tiled-roof top installation. This aspect, in particular, is relevant now that we are facing problems like energy grid congestion issues and grid overload. Avoiding excess energy production when there is less demand (i.e. sunny summer day) while producing more when there is more need (e.g. winter) is a beneficial aspect of vertical PV façade installations.

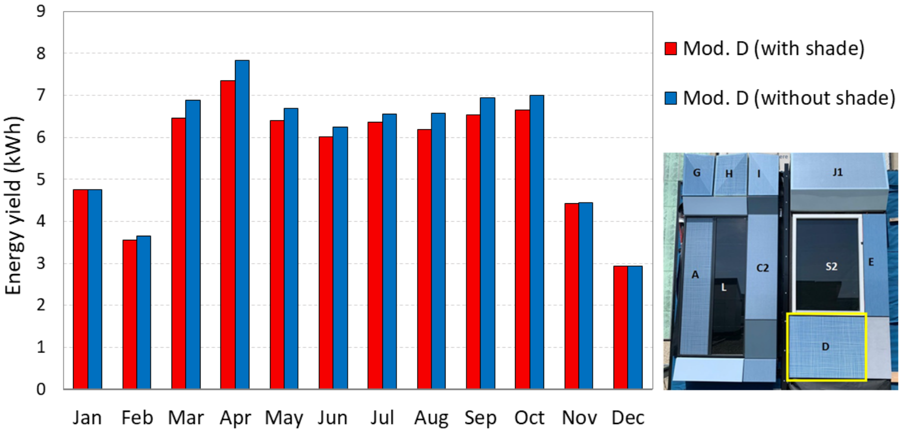

Figure 12. Modelled monthly energy production of one of the PREFAB modules (module D), both including (in red) and excluding (in blue) the presence of shading elements. The simulation is run with a TMY meteo file.

5. Conclusion

Within the PREFAB project, a consortium developed prefab façade elements with integrated photovoltaic (PV) modules. A demonstrator was designed and installed, which includes PV modules with several innovative technologies with regards to size, form, colour and transparency. One of the elements was mounted directly from a crane. Different module colour techniques were used.

The performance of the demonstrator was extensively analysed based on measurements and modelling. The DC yield and PR of the very versatile panels, in terms of colour, shape and PV-technology, has been presented. Mismatch losses can occur when a single PV panel has multiple orientations. The dependence of the azimuthal angle of the sun on the performance of the 3D shaped panel used in the PREFAB demonstrator has been visualized.

The advanced simulation tool BIGEYE resulted to be suitable for modelling opaque aesthetical BIPV façades. Despite the complexity and diversification of the PREFAB system, we could successfully validate the model with the measured data. The model could be further improved by fine tuning the geometrical input file according to an even more precise representation of all dimensions and spacing between the modules and dummy elements casting a shade on them. The current model however gives already very good correlations.

Additionally, the model also allowed to quantify the losses due to shading to the total power generation. The (TMY) year simulation provided an estimation of the total energy yield that could be generated by one of the coloured PREFAB modules when placed in a south-facing vertical façade, both in a shaded and shade-free scenario.

6. Acknowledgments

This work is supported by the Netherlands Enterprise Agency (RVO) and the Dutch Topteam Energy via the project: ‘PREFAB’, TKI Hernieuwbare Energie with grant number TEHE118026.

7. References

Burgers, A.R., Janssen, G.J.M., van Aken, B.B., 2018. BIGEYE: Accurate energy yield prediction of bifacial PV systems. In: BifiPV Workshop, Denver, USA, September 10-11

CBS, 2021. https://www.cbs.nl/nl-nl/nieuws/2021/09/elektriciteitsproductie-stijgt-in-2020-naar-recordhoogte, accessed 9 September 2022.

Corti, P., Bonomo, P., Frontini, F., Macé, P., Bosch, E., 2020. Building Integrated Photovoltaics: A practical handbook for solar buildings' stakeholder; Status Report, SUPSI, Becquerel Institute.

Hooff, W. van, Kuijers, T., Quax, R., Witte, J., 2021. Ruimtelijk potentieel van zonnestroom in Nederland, Generation.Energy / TKI Urban Energy, Netherlands https://www.topsectorenergie.nl/sites/default/files/uploads/Urban energy/publicaties/Ruimtelijk potentieel van zonnestroom in Nederland.pdf (topsectorenergie.nl)

ICARES (Becquerel Institute), 2019. BIPV market and stakeholder analysis, BIPV Boost. https://bipvboost.eu/public-reports/download/update-on-bipv-market-and-stakeholder-analysis, accessed 9 September 2022.

Janssen, G.J.M., Burgers, A.R., Binani, A. Carr, A.J., Van Aken, B.B., Romijn, I.G., Klenk, M., Nussbaumer, H. and Baumann, T., 2018. How to Maximize the kWh/kWp Ratio: Simulations of Single-Axis Tracking in Bifacial Systems. In: Proceedings of the 35th European Photovoltaic Solar Energy Conference and Exhibition, 1573-1577. https://doi.org/10.4229/35thEUPVSEC20182018-6BO.7.5.