41st European Photovoltaic Solar Energy Conference and Exhibition

This presentation was selected by the Sc. Committee of the EU PVSEC 2024 for submission of a full paper to one of the EU PVSEC's collaborating peer-reviewed journals.

OUTDOOR EXPOSURE STUDY ON THE PERFORMANCE OF NINE DIFFERENT TYPES OF INDUSTRIAL PV MODULES UNDER 35° AND UNDER 90° TILT

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ABSTRACT: For practical and aesthetic reasons, solar PV modules with black instead of white backsheets or with colored front glass are used in vertical building integrated PV installations. This double use of area is favorable for societal acceptance that is ever more important with the raising number of PV installations. Besides, the variety of installation angles implies a broadening of the electricity generation profile which is indeed advantageous. However, these non-optimized orientations and the use of all-black and of colored modules under non-optimized orientation result in a lower yield compared to optimal PV systems with modules with white backsheet or even bifacial modules. This experimental study quantifies the yield reduction for using an exemplary blue colored versus a reference CIGS module and black instead of white backsheets in a comparison of two CIGS and seven up to date silicon PV modules of various technologies (Silicon heterojunction monofacial black and white backsheet, bifacial, PERC half cells black and white backsheet, shingled with black backsheet, PERC IBC with white backsheet) monitored in parallel under optimum tilt and 90° South orientation. We found that in May vertical installations show a specific yield reduced by 44 % compared to 35° tilted installations on average over all investigated monofacial technologies, and a gain of 4 % in January. Modules with black backsheets installed vertically produced up to 7 % less in May than their counterparts with white backsheets, this loss being up to 4 % for 35° tilted modules. Also in May, the efficiency delta of 1%abs. between the CIGS module with blue-colored front glass and the reference resulted in a reduction of specific yield by 12% on the 90° tilted open rack. All these differences are less significant in winter. These numbers quantify the price to be paid for the advantages of customized non-optimum installations.

Keywords: BIPV, vertical installation, bifacial solar modules, colored solar modules, technology comparison

1 INTRODUCTION

The increasing demand for solar module installations as one renewable energy source has led to significant area need challenging social acceptance which is crucial for a successful energy transition from fossil to renewables. Currently 44% of the global PV capacity is made up of roof installations and 55% are field installations [1]. The expected ramp-up implies area conflicts and acceptance conflicts. Agri-PV and BIPV are growing topics in the PV field, since they are seen to mitigate those conflicts. Also, they could completely cover Europe's electricity demand when deploying those technologies at a large scale [2] [3]. The increasing installations also challenge grid management. Producing energy where it is consumed and under an increased variety of installation orientation, however, broadens the generation profile of these mixed PV installations, especially by the vertical installation in differently oriented facades, and supports morning and evening load requirements [4]. Undoubtedly, there will be more installations under non-optimum angles.

In BIPV applications, PV modules act as both electricity generating solar panels and as building elements. The latter function is the main property in the building skin and typically influences the electrical performance of the PV function. The performance of PV modules is influenced by various factors, mainly by the angles of incidence of sunlight, temperature and shading.

It is known that the non-optimum orientation comes at a cost, e.g. in respect to shallower angles of incidence of the incoming direct light and a resulting lower yield. Also, ventilation for module cooling is not a priority to architects. Sometimes a coloring is chosen which decreases the efficiency. The measurements under STC of a colored and a black module cannot directly be translated to an annual yield difference of a colored BIPV system – with all the contributions from non-perpendicular angles of incidence.

This paper quantifies the reduction in specific yield due to the choice of a black back sheet or a colored front glass and a vertical installation angle. By examining the modules under both optimal and facade orientation, this research seeks to provide insights into their practical application in architectural settings (and Agri-PV). The analysis is grounded in rigorous long-term outdoor exposure data, encompassing also a facade installation for comparison. It presents a comprehensive comparison of commercial PV modules of the below listed technologies oriented southward installed at Berlin, Germany at an optimum angle and under 90° as often the case in BIPV/Agri-PV. The chosen technologies are monofacial Silicon heterojunction modules with white and black backsheet, bifacial silicon heterojunction, PERC half-cells, shingled and IBC with white and black back shields as well as CIGS and CIGS with a blue coloring. Additionally, bifacial modules were oriented in 2024 facing east/west, standing upright (90° angle). The study aims to elucidate the variances in specific energy yield among these modules. A building integrated facade containing the blue colored CIGS modules delivers temperatures in the BIPV context in comparison to those measured in the open rack setup. The resulting reduction of 44% in May 2023 in Berlin by going vertical instead of optimal in a south facing installation is put into context. Installing bifacial modules vertically but east/west instead of south makes up for the difference to the optimal tilt in summer [5]. Black backsheets affect the performance under shallow incidence angles [6] [7] and their specific yield in case of the silicon heterojunction modules was 98% of that of the white backsheet module for that configuration. The blue-colored front glass had a bigger effect. Yet, as area is scarce and PV modules are cheap as well as energy generation in summer is vast, there will be more and more of such installations that do not aim for the highest yield but for the best solution in respect to societal acceptance, area use, etc. [3].

2 MATERIAL AND METHODS

In this contribution we evaluate the data of 9 types of modules installed in duplicate, one row vertically and one under optimum tilt, both rows facing south in Berlin, Germany (52.43°N,13.52°E). Data was acquired over more than one year, starting in Fall 2022.

Figure 1 a) is a picture of the installation. The nine modules installed in duplicate are from left to right:

- Passivated emitter rear cell, PERC, half-cell modules with white and black backsheets monofacial (*PERC HC wbs*, *PERC HC bbs*)
- Silicon heterojunction, SHJ, half-cell modules with black backsheet monofacial, bifacial, and, with white backsheet monofacial (*SHJ bbs, SHJ bifi, SHJ wbs*)
- Thin film CIGS blue-colored and a reference transparent double glass module monofacial (*CIGS blue*, *CIGS ref*)
- PERC shingled cell modules with black backsheet (*PERC sh bbs*)
- PERC interdigitated back contact, IBC, full cell module with white backsheet monofacial (*PERC IBC wbs*)

Figure 1 b) shows part of the setup under snowy conditions. The modules are kept in their maximum power point (MPP) individually with IV curves measured additionally every 10s. This data was complimented by continuous acquisition of module rear side temperatures by PT 1000 temperature sensors and irradiance measurements by silicon reference cells (Si-01TC/ IMT Technology) in the plane of array. Global and diffuse irradiance are measured in the horizontal plane by two Kipp and Zonen CMP 11 pyranometers using the shadow ring setup. The ambient temperature as well as wind speed, wind direction, humidity, air pressure and precipitation intensity are acquired by a weather station (from CLIMA SENSOR US/Adolf Thies GmbH & Co.). The latter equipment for the environmental data is connected to a DLx MET datalogger from Adolf Thies GmbH & Co. and records one-minute averaged data. The incident spectrum is recorded every 5 min by two EKO WISER spectroradiometers, tilted to 35°and 90°.

Fig. 1: Picture of the industrial module test setup in the roof laboratory in Berlin, Germany. All modules are MPP-tracked individually while rear side temperatures are measured as well as POA irradiance by monitoring cells. a) sunny day, b) after snow fall.

Figure 2 shows the two bifacial modules that were deinstalled by the end of 2023 and instead are mounted in 2024 in an East-West installation standing upright, one facing East with the optimized frontside and one facing West. Temperature sensors are placed so that they do not shade the active area.

Fig. 2: Picture of the installation of the bifacial modules facing east and west, respectively with the optimized side. The bifacial modules were taken off the open rack and installed as shown here in December 2023.

Figure 3 shows the facade integrated PV system consisting of the same blue CIGS modules. We use this system to compare the operating temperature of the open rack modules to the same modules installed in a facade. Facade installations are expected to result in higher temperatures. The ventilated curtain wall facade has areas of different air gaps between the modules and the underling insolation on the south facing side [9].

Fig. 3: Picture of the CIGS blue modules installed in the facade of the living lab for BIPV owned and monitored by Helmholtz Zentrum Berlin in Berlin, Germany. The modules are installed on the North, West and South facade. The system is equipped with string monitoring and sensors recording rear side temperatures as well as irradiance in the module plane. Weather data is acquired on the building roof.

3 RESULTS

An excerpt of the analysis of the MPP data of the eighteen PV modules are shown here. In 2023 all modules were exposed vertically and 35° tilted and oriented towards south. For a fair comparison we present here the specific yield. Note that we present data of single modules. More statistics would be needed to generalize the observations.

3.1 Technology comparison

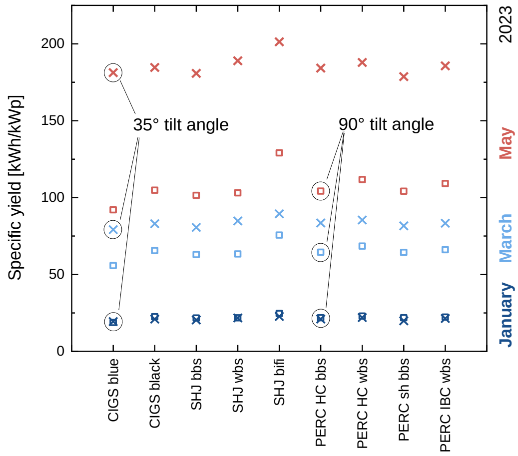

Fig. 4: Specific yield of all nine installed industrial modules as marked on the x-axis. Dark blue marks the specific yield for January 2023, light blue March 2023 and red May 2023. The crosses represent the data of the tilted raw (35°, south facing) while the squares represent the vertical installation (90°, south facing). The bifacial modules profit from the active rear side. Differences in specific yield are highest when there is more irradiance.

Figure 4 shows the measured yield divided by the respective nominal power of each module. For the peak power kWp values, in case of the CIGS modules the module name plate values were used. In all other cases, the STC power measured in specifically commissioned initial indoor characterizations were used.

As expected, the bifacial modules outperform all other modules under 35° and 90° south installation. In the indoor determination of the nominal power the rear side is not illuminated so that the denominator in calculating the specific yield is small. The bifaciality is not considered. Outdoors, the bifacial gain is highest among the shown data in May with more light reaching the rear side despite the suboptimal installation with a broad shadowing holder blocking some light at the rear side. The specific yield for all monofacial modules installed under 35° tilt is very similar with all modules with white backsheets having a slightly higher specific yield than those with black backsheet or blue front glass.

The monofacial modules installed under 90° tilt have on average 44% less specific yield than those under 35° in May. In January when angles of incoming light are flatter, there is a slight gain of on average 4%. The loss is large and if modules were scarce and area abundant, it would seem unwise to install PV modules in a suboptimal way. Yet, as stated in the introduction, varying installation angles brings about many advantages in respect to the broadening of the generation profile. Installing PV vertically also saves area.

When analyzing Fig. 4, one has to bear in mind that the specific yield as an indicator may lead to an overinterpretation of the performance of different module types. All these modules/module groups have different sizes. The yield summed up over all available data for 2023 per module is highest for PERC IBC and the SHJ modules and CIGS with the smaller module sizes generates less than half as much energy. The yield per m² brings all data closer together. Still CIGS with its lower efficiency performs accordingly.

3.2 Clear sky and seasons

Figure 5 shows exemplarily for the SHJ modules (monofacial bbs squares, wbs circles and bifi as triangles) the quotient of the specific yield over a part of the exposure time. Note that the bifi modules were taken off and installed East/West-facing in 2024, data points end here in December 2023. A color code marks clear days according to a simple calculation of

$$clear\ sky\ index = 1 - \frac{DHI}{GHI}$$

With DHI the diffuse irradiance and GHI being the global irradiance measured by the meteo station on the same roof. Data loss is due to system outage.

The data show that in the winter month on clear sky days, the 90° modules perform better than the 35° oriented modules, the quotient is above 100 %. For diffuse conditions, the 35° module as it sees more of the sky, performs better as is the case also for the direct light under higher angles of incidence.

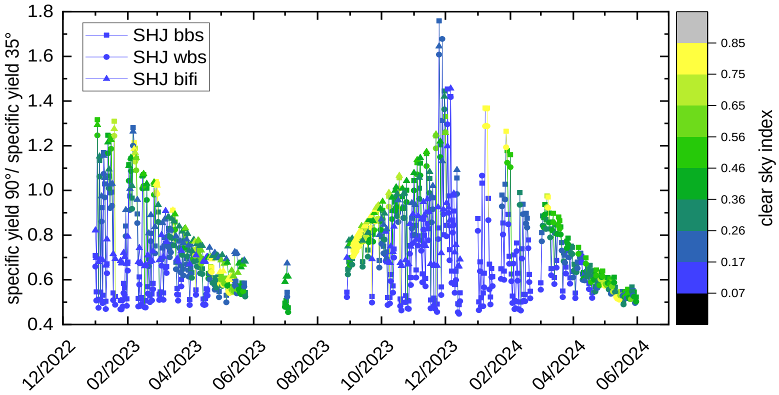

Fig. 4: Quotient of the specific yield of SHJ modules installed under 90° and 35° tilt. Circles mark wbs, squares mark bbs, triangles stand for the bifacial modules. The data is color coded by a simple clear sky index. The data point close to 01/12/2023 marks a snow event where the 35° module was partly covered with snow and the 90° module was free.

3.3 Black and white backsheets

The modules rear temperature for the vertical installations was on average only a few degrees higher for the bbs modules than for the wbs counterpart during the reporting time Jan-May 2023 with no strong change over that period of time.

Fig. 6 shows that for the same time the specific yield of the SHJ bbs is lower than that of the SHJ wbs. In January, when the sun is low and the incidence angles of the light is perpendicular to the 90°-tilted module surface, the quotient of specific yield of the black by the white backsheet is close to 1. For diffuse light and for the direct light in summer the quotient is smaller. Obviously the black backsheet results in losses under shallow angles. (The data under 35° tilt confirm that as the quotient over time has an upward trend in that case – as incidence angles are more fortunate in summer for that tilt.)

3.4 Colored modules and module rear temperature in open rack and in facade installation

The specific yield of CIGS blue (135 Wp) compared to the reference module (140 Wp) of the same series but with transparent front glass is reduced by 12%, 15% and 17% in the month May, March and January under 90°, see Fig. 4. The reduction amounts to 2%, 5% and 8% under 35° tilt. Under STC the efficiency of the CIGS blue module is only 1 % less.

In facade installations next to the less fortunate angle orientation of the modules, higher temperatures occur that do result in further yield reduction depending in the module’s temperature coefficient. Our setups allow us to compare the open rack module rear temperature to the temperature in the BIPV facade integration.

Figure 7 shows a histogram of the measured module rear side temperatures of the CIGS blue modules in open rack 90° and in the facade installation. The same color code as above is used to mark January, March and May data for the open rack modules while the facade module temperatures are respectively displayed in grey. Interestingly, the temperature difference is small in the winter month. In May we measure a difference of up to10 K higher temperatures in the facade than on the open rack for the same type of modules, CIGS blue.

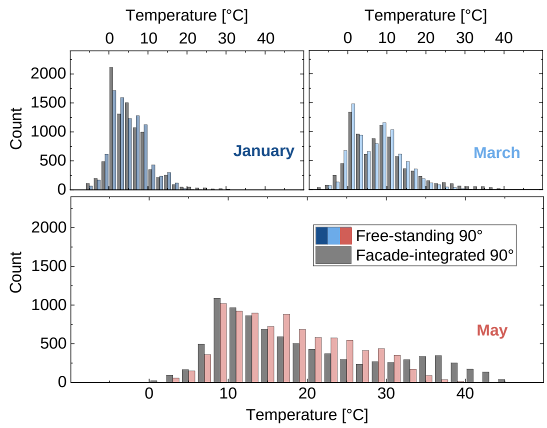

Fig. 7: Histogram of module rear side temperatures for the CIGS blue modules in the 90° open rack (color coded for a) January in blue, b) March in light blue and c) May in red) and the facade installation, respectively in gray for all months. Modules in the facade heat up more than in the open rack in May.

The reduction in specific yield due to the facade integration and color choice has to be put into context. Colored modules are used in the building environment where aesthetics matters more that energy yield [8]. They facilitate the entrance of PV into the market of building skin material that they replace and that would otherwise not produce any energy. The coloring opens opportunities for architects and foster acceptance. Another advantage of vertical modules is the reduced covering by snow, see Fig. 1b). Obviously, tilted open rack installations suffer more from snow shadowing than facades. In a study of a facade installation with the CIGS blue module, see Fig. 3, we found out that despite the lower yield generation, the module installation still amortizes well within the module lifetime [8].

3.5 Bifacial module in east/west configuration

Another typical occasion where vertical orientation is common are the east/west facing rows of bifacial modules in Agri-PV installations.

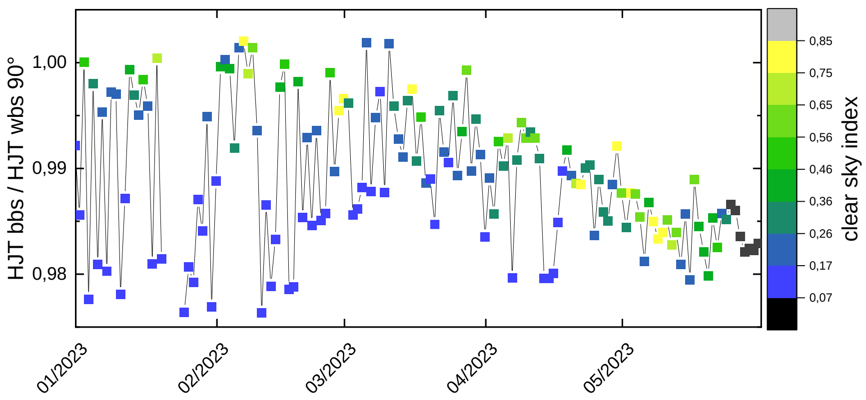

Fig. 6: Quotient of the specific yield of the SHJ bbs and wbs modules installed vertically. The color code is a simple clear sky index.

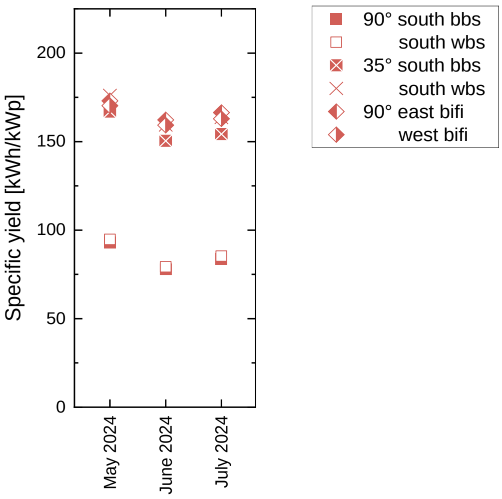

Fig. 5: Specific yield of the SHJ modules under 35° south facing with wbs and bbs compared to their 90° counterparts in May, June, July 2024. The diamonds mark the data of an east/west facing installation of the bifacial modules (optimized site oriented as marked in the legend). The bifaciality makes up for the disadvantage of the 90° tilt.

Figure 8 shows the data for three exemplary summer months in 2024, where the bifacial heterojunction modules were installed facing east/west as shown in the picture Fig. 2. For comparison the data of the vertically installed south-facing SHJ mono bbs (red filled square) and wbs (red open square) are shown. They are as much lower as in the data of 2023. The respective tilted modules (bbs red cross, wbs light red cross) perform as well as observed for May 2023. In June and July, sunshine hours were less than in May with hotter average temperature, the specific yield decreased slightly. The West and East facing modules SHJ bifi are marked by the diamonds with respective color code as given in the legend. It is expected that the specific yield for east facing is slightly higher than for West due to the favorable lower temperatures in the mornings (when sun shines on the east facing side). Additionally, we know that the module installed westwards is shaded in early mornings and late evenings. The data meet this expectation. For all the shown summer months May, June and July, the SHJ bifi modules installed under 90° facing east and the one facing west perform comparable to 35° SHJ bbs modules and SHJ wbs modules. The bifaciality makes up for the tilt loss under 90° in the summer months. This result is not unexpected and underlines the efforts of implementing vertical bifacial modules in east/west configuration in PV-fences and Agri-PV.

4 DISCUSSION

Some of the features shown in our measurements may come as no surprise, such as the outperforming of the bifacial module – even despite the wide bar that casts a shadow on the active rear. Bifacial modules are expected to dominate the market in future and the optimal tilt and south facing orientation delivers the highest specific yield. An east/west orientation was found to equal out the disadvantages of the 90° tilt and result in specific yields as high as under 35° tilt/south for summer months. PV is abundant in summer at noon and this east-west orientation advantageously broadens generation profiles towards mornings and afternoons. Without the activated rear, the reduction in yield by vertical tilts compared to the optimum tilt is notable. We quantify it to be 44 % in May as an average over all monofacial modules installed, while there is a small gain of 4% in winter. This reduction is significant, the gain is small. Yet, the PV module orientations in building facade integrations are usually vertical and not necessarily south-facing. There is a huge potential in covering facades and the practical advantage of installing PV in facades is that there is no additional land covered while integrated PV even replaces building material. For aesthetics the modules used in the building context are often colored or at least all-black. This change comes at the cost of a lower yield that we figured 12 % in May for the CIGS module that has a blue front glass and 1% less efficiency under STC conditions. Also, the module temperatures are expected to rise in a facade installation compared to the open rack. We measured the temperatures on the module rear side and found them to vary little. Only in summer we found that there was a maximum of 10 K difference in the maximum temperature. The reduction in yield in this installation is significant. However, it is not a showstopper. Seen from the point of view of the builder, such installations amortize well in the lifetime of the solar modules in an appealing building. The low prices make non-optimal installations affordable, the enormous ramp-up of PV in the next years make these installations necessary. Detailed yield simulations for bifacial, colored and all-black modules under non-optimum angles and installation conditions will be a topic of future research and the here presented acquired data serves for validating models.

5 ACKNOWLEDGMENTS

5.1 Funding

Niklas Albinius and Björn Rau acknowledge funding by the German Federal Ministry of Education and Research (BMBF) for the Solar TAP innovation platform under the Helmholtz Innovation Platforms funding line. Maximillian Riedel acknowledges funding by the European partnering project TAPAS (PIE-0015). Carolin Ulbrich and Björn Rau acknowledge funding by the Helmholtz Association under the program “Energy System Design” under grant number ZT-0 0 02.

5.2 Conflict of interest

The authors certify that there are no financial conflicts of interest (e.g., consultancies, stock ownership, equity interest, patent/licensing arrangements, etc.) in connection with this article. Note that six of the 18 modules that we investigated here were provided by one company for free. To comply with the NDA and disguise the origin of the modules, we present here the specific yield.

5.3 Data availability statement

Some of the data presented here was acquired under an NDA. The other data used in this paper will be made available upon request.

5.4 Author contribution statement

Conceptualization, C.U. and M.R.; Methodology, C.U. and M.R.; Software, L.W., N.A. and M.R.; Validation, C.U., M.R., N.A. and B.R.; Formal Analysis, C.U., M.R., N.A. and B.R.; Investigation, C.U., N.A., L.W., M.R., B.R.; Resources, M.R.; Data Curation, L.W.; Writing – Original Draft Preparation, C.U.; Writing – Review & Editing, C.U., N.A., B.R.; Visualization, C.U., M.R., L-W. and N.A.; Supervision, R.S.; Project Administration, C.U., B.R., R.S.; Funding Acquisition, C.U., B.R., R.S.

6 REFERENCES

[1] SolarPower Europe, "Global Market Outlook For Solar Power 2024-2028 - Focus on China," 2024.

[2] K. A. K. Niazi and M. Victoria, "Comparitive analysis of photovoltaic configurations for agrivoltaic systems in Europe," *Progress in Photovoltaics: Research and Applications,* vol. 31, pp. 1101-1113, 2023. https://doi.org/10.1002/pip.3727

[3] BIPV Boost, "BIPV market and stakeholder analysis," 2019.

[4] T. Baumann, H. Nussbaumer, M. Klenk, A. Dreisiebner, F. Carigiet and F. Baumgartner, "Photovoltaic systems with vertically mounted bifacial PV modules in combination with green roofs," *Solar Energy,* 2019. https://doi.org/10.1016/j.solener.2019.08.014

[5] L. Wang, Y. Tang, S. Zhang, F. Wang and J. Wang, "Energy yield analysis of different bifacial PV (photovoltaic) technologies: TOPCon, HJT, PERC in Hainan," *Solar Energy,* no. 238, 2022. https://doi.org/10.1016/j.solener.2022.03.038

[6] H. Lim, S. H. Cho, J. Moon, D. Y. Jun and S. H. Kim, "Effects of Reflectance of Backsheets and Spacing between Cells on Photovoltaic Modules," *Appl. Sci.*, vol. 12, no. 443, 2022. https://doi.org/10.3390/app12010443

[7] G. Makrides, M. Theristis, J. Bratcher, J. Pratt and G. E. Georghiou, "Five-year performance and reliability analysis of monocrystalline photovoltaic modules with different backsheet materials," *Solar Energy,* no. 171, 2018. https://doi.org/10.1016/jsolener.2018.06.110

[8] M. C. López-Escalante, E. Navarrete-Astorga, M. Gabáz Perez and J. R. Ramos-Barrado, "Photovoltaic modules designed for architectural integration without negative performance consequences," *Applied Energy,* no. 279, 2020. https://doi.org/10.1016./j.apenergy.2020.115741

[9] N. Albinius, C. Ulbrich, B. Rau, M. Riedel and R. Schlatmann, "A comprehensive case study of a full-size BIPV facade," *Mauscript submitted,* 2024.