EPJ Photovoltaics **16**, 1 (2025)

https://doi.org/10.1051/epjpv/2024041

Available online at:
www.epj-pv.org

Special Issue on 'EU PVSEC 2024: State of the Art and Developments in Photovoltaics', edited by Robert Kenny and Gabriele Eder

ORIGINAL ARTICLE | OPEN ACCESS

Lightweight photovoltaic modules technologies: reliability evaluation and market opportunity

Julien Dupuis[1,*], Christine Abdel Nour[1], João Victor Oliveira Santos[1], and Paul Lefillastre[2]

[1] EDF R&D, EDF Lab Les Renardières, Avenue des Renardières, Moret Loing et Orvanne 77250, France
[2] EDF Renouvelables, 43 Boulevard des Bouvets CS 90310, Nanterre Cedex 92741, France

Received: 28 June 2024 / Accepted: 14 November 2024

Abstract. This study aims at performing an assessment of lightweight photovoltaic (PV) module's reliability by comparing module's performances and reliability of several manufacturers. Lightweight modules are characterized by a reduced weight compared to classical PV modules with usually less than 10 kg/m^2 allowing its installation on rooftops with low bearing capacity without the need of reinforcing the roof structure. Even if this PV technology has higher costs than classical modules due to lower capacity production and often specific module material like transparent composite instead of glass, it represents an efficient technical and commercial solution for specific applications with lower transportation, installation, and maintenance costs. Nevertheless, very few information is available on the reliability of these emerging products. The large variety of module components used by the manufacturers do not help into selecting the best modules available on the market. In this work, after introducing the potential capacity of low bearing rooftop market for France, we detailed a first reliability benchmark of market available lightweight module's products. This benchmark was carried out through indoor experimental work under accelerated aging testing as well as outdoor exposure conditions based on IEC61215 and IEC61730 qualification standards. The accelerated aging sequence results highlight high power degradation discrepancies between the five technologies investigated with some of them degrading more than 50% after a damp heat − UV − thermal cycling testing sequence. The power generation obtained in outdoor conditions underlines lower energy yield obtained by installing photovoltaic module directly on a flat roof caused by their orientation and tilt (0 to 10°) entailing sometimes higher soling losses. Based on all these results, LCOE estimations are performed and show an over-cost between 10 and 100% compared to the use of standard module option with roof reinforcement.

Keywords: Photovoltaic module / lightweight / reliability / yield / LCOE

1 Introduction

With its versatility and low cost, electricity provided by photovoltaic energy has become one of the best options for setting up new power plant. One drawback of this technology is the place needed for the power plant itself which can limit utility scale system in some countries. Putting these photovoltaic systems on rooftop is then an ideal choice, Solar Power Europe has shown that in 2023, 196 GW of the global 447 GW set up in the world was on rooftop [1]. As the cost depends on the size of the system and the ease of the installation, the bigger and the flatter the roof, the lower can be the installation cost.

C&I and Agricultural buildings have great potentials in reason with their high roof surface availability but there is often an issue with the high percentage of roof which can't bear too much weight (low bearing roof). For instance, in France, based on the rooftop data available [2–4] for Agricultural, commercial, and industrial buildings, we have estimated that 26% of the 2 Gm^2 of the rooftop surface cannot bear more than 15 kg/m^2, i.e., the weight of a classical module with its roof structure, but it can at least bear 5kg/m^2. Considering that only 30% of this surface is available and photovoltaic system efficiency of 20%, the potential will be slightly more than 30 GWp for lightweight module solutions.

Today, structure reinforcement is the main option for deploying photovoltaic on low bearing roofs. The reinforcement option is usually quite expensive and gives often a non-acceptable cost to the PV plant project which is then abandoned.

* e-mail: julien.dupuis@edf.fr

Table 1. Tested Lightweight PV modules technologies and efficiencies. The efficiencies were measured at the EDF R&D's laboratory before putting the modules outside.

Manufacturer	A	B	C	D	E
Type	Composite / Polymer	Glass / Polymer	Composite / Polymer	Glass / Polymer	Composite / Polymer
Efficiency	16.7%	17.1%	20.6%	18.9%	18.3%
Solar cell's technology	*p*-type PERC	*p*-type PERC	*n*-type IBC	*p*-type PERC	*p*-type PERC
Frame	No	No	No	Yes	Yes
Thickness (frame excluded)	2.5 mm	3.0 mm	4.0 mm	2.5 mm	2.0 mm
Weight /sqm	3.3 kg	5.9 kg	6.2 kg	8.4 kg	8.1 kg

Table 2. Details of the sequential accelerated aging sequences.

Sequence	Current induced degradation (CID)	Damp heat (DH)	Current induced regeneration (CIR)	UV exposure	Thermal cycling (TC)
Parameters	Isc @ 75 °C	85 °C @ 85RH	Isc @ 75 °C	100 W/m^2 @ 60 °C	–40 °C to 85 °C
Duration	3 × 48 h	1000 h	48 h	450 h	1200 h (200 cycles)

The continuous decrease of PV costs and technological progress give opportunities for lightweight modules solutions to be used for this kind of roofs. However, lightweight modules are more expensive than classical PV modules (two to four times now), are not always set up with a high tilt to optimize sun light on the plane of array and are fabricated with specific bill of materials that questions their long-term reliability.

The approach studied here consists first, in evaluating the reliability of various lightweight module types from several manufacturers and with different architectures and composition (with or without glass, module for structure fixation or for rooftop direct installation, etc.) using sequential aging tests. Secondly, the qualification of the PV module's yield in outdoor environment in a representative tilt is observed. Lastly, a conclusion about the interest in using these modules in a project is discussed by estimating the levelized cost of electricity of a representative project using the previous results.

2 Material and methods

The lightweight module relevance is performed by assessing PV modules from five different manufacturers (referred as A, B, C, D and E in Tab. 1). Two types of lightweight modules are tested: composite/polymer often based on ETFE and/or fiberglass reinforced plastics and glass/polymer modules with a maximum power varying between 200 and 380 Wp. Glass/polymer modules used thin glass between 0.5 and 2 mm thickness to keep low weight properties. Solar cells in the modules can be *p*-type Passivated Emitter and Rear Cells (PERC) or *p*-type Interdigitated Back Contacts cells (IBC) depending on the manufacturer. For module with frame, additional crossbars were added to mechanically strengthen them. The study was carried out through an original indoor sequential testing procedure including main environmental stresses (Tab. 2) to get global feedback on the module reliability. The sequences of the testing protocol were based on IEC 61215 and IEC 61730 qualification standards:

– Carrier Induced Degradation step (CID) was used as a preconditioning step to avoid any impact of Light Induced Degradation or Light and elevated Induced Degradation (LeTID) as detailed in IEC TS 63342. High injection current is used to get preconditioned modules in a limited amount of time [5].
– Damp heat is then used to see the impact on water ingress of these unusual materials (ETFE/fiberglass in particular) as the testing is already relevant to evaluate the reliability of classical encapsulant like EVA.
– Current Indued Regeneration (CIR) step is used after the damp heat step to avoid any LID or LeTID impact as they can appear after an exposition to a dark and hot environment [6].
– UV step will also test the encapsulant resistance as well as the passivation layer of the solar cells. If damp heat has weakened the encapsulant quality, UV will be even more detrimental.
– Thermal cycle in the end will evaluate the module soldering robustness and emphasis micro-cracks appearance caused by module transportation or by change in the encapsulant properties.

Framed modules were tested normally, frameless modules were glued on a glass (A and C manufacturers) or were put in a removable frame (B manufacturer) in order to test them vertically in the climatic chamber. We chose to not add mechanical stress in our testing sequence as we

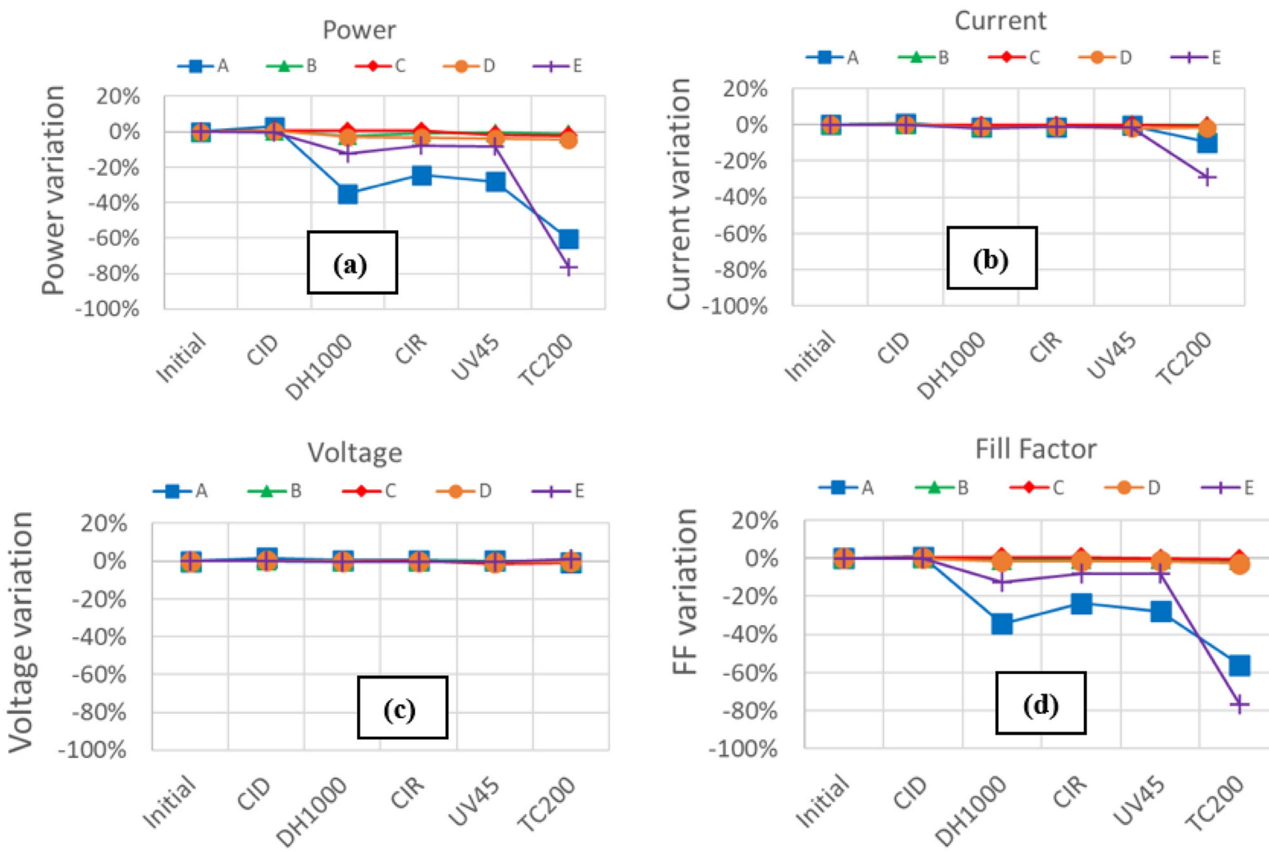

Fig. 1. Electrical performances losses after each accelerated aging sequence (average of two modules per manufacturer): (a) power losses, (b) Isc losses, (c) Voc losses, (d) Fill factor losses.

wanted to focus on flat and rigid surface application. But it has to be noted that mechanical evaluation of lightweight and flexible modules can be useful for curved surface like Vehicle Integrated application (VIPV) [7,8].

Two modules from each manufacturer were evaluated. Electrical characterization (IV) of the PV modules was carried out using a PASAN flash tester SunSim 3b with class AAA equipped with a Dragon Back system. Electroluminescence (EL) measurements were done using a 150 MPixel XT IQ4 Phase One camera with its infrared filter removed and a current injection of Isc in the modules.

Then, an outdoor testing platform was also installed at our EDF R&D site near Paris since September 2023 to evaluate the module's performances over one year operation under real conditions. The modules were installed south oriented with two tilt angles: 0° and/or 10° representative of what can be found on flat rooftops PV installations. These configurations were selected to study the energy yield of the module technologies compared to classical PV installations. Not all module types could be tested with both tilts due to limited samples and monitoring availability. Each module is connected to an IQ7+ microinverter allowing electrical performances monitoring under real conditions. This installation is also equipped with meteorological sensors to analyze the behavior of the modules under specific weather conditions. A reference classical installation south oriented with a tilt of 30° in the same outdoor testing platform is used for efficiency comparison.

To compare the different lightweight module's technologies performances under real conditions, the average efficiency of each technology compared to the expected initial value was considered. The comparison with the reference installation was done according to Yield calculation following the equation:

$$\text{Yield (kWh/kWp)} = \frac{\text{Generated Energy of the module (kWh)}}{\text{PV module maximum power (kWp)}}. \quad (1)$$

The yield losses of each lightweight technology were computed according to the yield of the reference installation under the same meteorological conditions in order to perform an evaluation of the technology and tilt angle impact on the photovoltaic energy generation.

3 Reliability testing results

Figure 1 and Table 3 present the IV parameters evolution after each step of the sequential testing. The results shown are the measurement average of the two tested modules per manufacturer.

As shown in Figure 1 and Table 3, B, C and D modules got excellent results with less than 5% degradation after the whole testing sequence. In contrast, a strong degradation after damp heat testing was visible on A and E modules mainly caused by a high increase in series resistance shown

Table 3. Average of power losses after each accelerated aging sequence compared to initial module state. Only modules from manufacturer E present high value discrepancy.

Manufacturer	CID (%)	DH 1000h (%)	CIR (%)	UV45 kWh (%)	TC 200 (%)
A	2.9 ± 0.1	–34.9 ± 0.3	–24.4 ± 1.2	–28.1 ± 1.7	–60.4 ± 2.2
B	0.4 ± 0.1	–2.3 ± 0.1	–0.8 ± 0.2	–0.5 ± 0.1	–1.2 ± 0.1
C	0.6 ± 0.6	0.4 ± 0.8	0.4 ± 0.8	–1.8 ± 0.8	–2.4 ± 0.8
D	0.5 ± 0.2	–3.1 ± 0.3	–3.2 ± 0.2	–3.7 ± 0.2	–4.6 ± 0.2
E	–0.2 ± 0.1	–12.3 ± 5.5	–8 ± 2.2	–8.3 ± 2.1	–76.6 ± 22.2

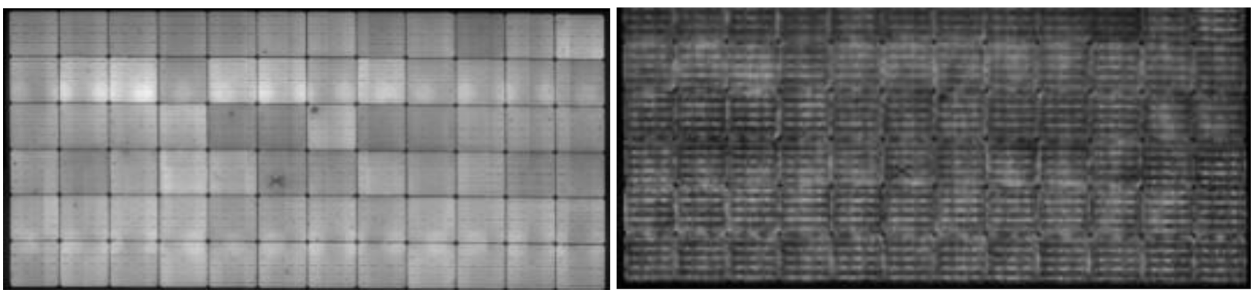

Fig. 2. EL images evolution of a module from manufacturer A at initial state (left); after DH 1000h (right).

on Figure 1 through the fill factor (FF) evolution and highlighted on the EL images compared to initial state through a global solar cell darkening except around the contacting ribbons as presented in Figure 2. A and E modules did nt even pass the requirement of the IEC61215 standard after damp heat with more than 5% degradation.

UV exposure did not entail a significant decrease for all modules tested but strong series resistances increase of modules A and E were also observed after thermal cycling sequences. To better quantify this series resistance changes, EL measurements were conducted at 10% and 100% of the short circuit current for these modules. A quantitative approach was performed using the adapted processing routine from [9] and [10] to account for noise, vignetting and perspective present on the images. The steps are the following:

- Noise processing: remove impact of single-time effect (like cosmic radiations), thermal noise, background substraction.
- Vignetting correction: A simple method based on the radial profile r is used [NEW6] based on the following equation:

$$\varphi_{vig}(r) = \varphi(r)\left(1 - f\cdot\frac{r}{r_{\max}}\right); f\in[0;1] \quad (2)$$

where:

- f factor is the degree of vignetting of the image.
- φ_{vig} is the vignetted intensity.
- $r=0$ correspond to the image center.
- $r=r_{max}$ correspond to the image corners.
- Noise from background substraction removal using a threshold median filter.
- Perspective correction using a binary mask and a threshold to separate foreground and background areas.

Then, a segmentation procedure was conducted so that each cell could be treated separately. Finally, the estimation algorithm proposed by [11] was applied to generate a series resistance map. This method considers a low and a high bias acquisition to determine the series resistance. We can see for a module from manufacturer A (Fig. 3), the series resistance map before (left) and after (right) the thermal cycling sequences highlighting a doubling of the series resistance globally in the modules entailing appearance of lots of cell cracks. No evident solder bond defect was visible, the mapping confirms a quite homogeneous series resistance increase in the module.

This high number of cell cracks could be linked to materials degradation and an increase of residual stresses in the module from A and E manufacturers. This is illustrated in Figure 4 with a picture of one of the module after DH1000 showing bended solar cells.

To summarize, for the five manufacturers evaluated, the absence of glass and replacement by composite materials have given mitigate reliability results as only modules from manufacturer C got low degradation rates after the testing sequences. Glass / polymer modules, with a thinner glass compared to classical modules, seem to be a better choice to ensure long term reliability regarding the results.

4 Yield comparison in outdoor environment

As described previously, a performance assessment of the PV module's yield in outdoor environment was carried out as well. One or two modules of each manufacturer were set in outdoor conditions from September 2023 to June 2024. The outdoor platform was composed of 2 modules from manufacturer A, one with 10° and one with 0° tilt, one

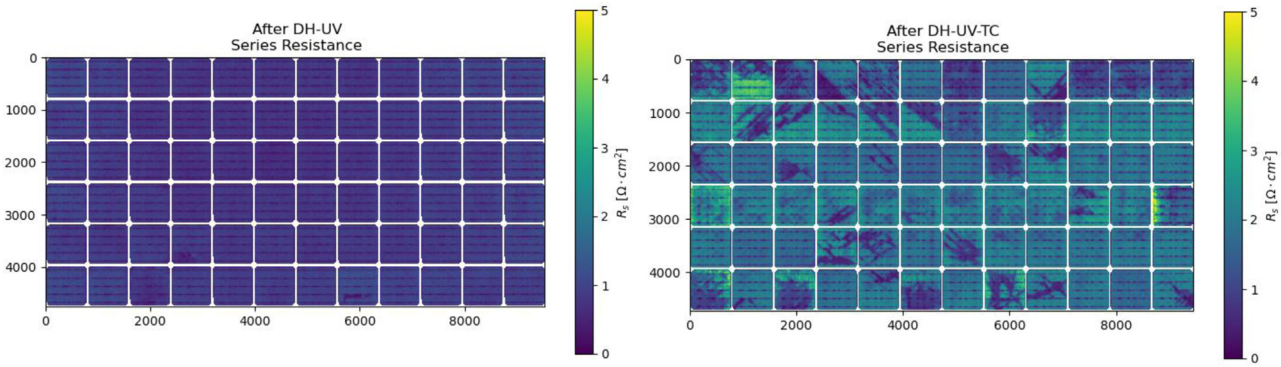

Fig. 3. Series resistance measured on cells from a module of manufacturer A. On the left, values obtained after DH and UV sequences. On the right, the same cells after DH, UV and TC tests.

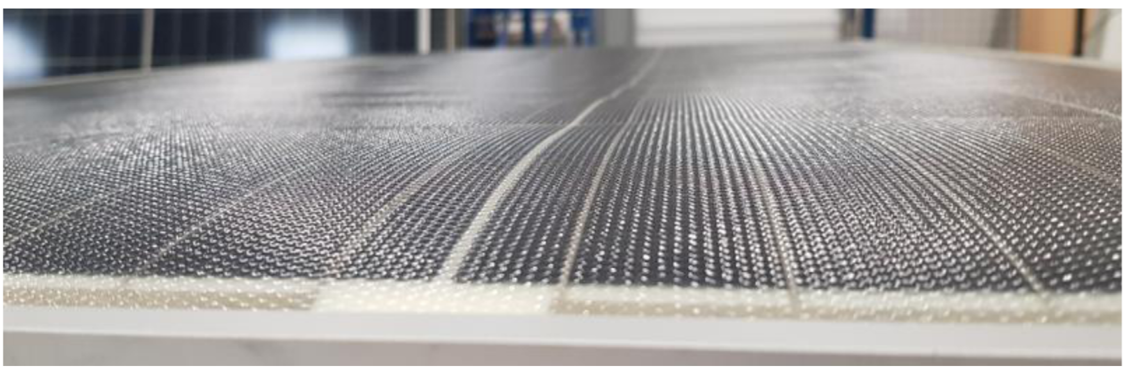

Fig. 4. Overview of a module showing solar cells bending after DH1000 testing sequence.

module from each of manufacturers B, D and E with 10° tilt and C with 0° tilt. No module was cleaned during all the period of the study to analyze the impact of soiling losses. 0° tilted modules are glued on a glass and the glass is fixed on our outdoor platform's concrete surface. The outdoor platform is presented in Figure 5. The power losses results were computed using PVNOV, a modelling tool developed by EDF to simulate a PV system in a 3D environment and calculate its yield using ray-tracing model [12–14]. The simulation results obtained show power losses varying between 5% and 15% of such configurations compared to classical PV installation with 30° tilt, South oriented with the same global horizontal irradiance.

This behavior was expected since optimal tilt angle for our installation's latitudes maximizing the irradiance in the plane of array is between 30° and 35°. However, we are aware that for rooftops applications we are usually limited by 0–10° tilt configuration. In addition, lower tilts can increase the soiling on module's surfaces and makes it more difficult to evacuate dust with the rain.

To better consider module efficiency for various irradiation levels, incidence angle and soiling impacts on the production, an outdoor performance efficiency comparison was carried out over clear sky conditions period in October 2023, May and June 2024 highlighting high efficiencies for C and E modules (Fig. 6) compared to their initial efficiencies (see Tab. 1).

The computed efficiency was calculated following the equation:

$$\text{Efficiency}\,(\%) = \frac{\text{Measured power}(W)}{\text{In plane Irradiance}\left(\frac{W}{\text{m}^2}\right) \times \text{Module's surface}\left(\text{m}^2\right)} \times 100. \quad (3)$$

Additionally, a comparison was established between lightweight modules outdoor platform and a reference PV installation of bifacial technology installed nearby. An assessment of lower tilt angles of lightweight modules adapted for rooftop installations with 0° and 10° modules tilt compared with the reference installation with 30° modules tilt was carried out. For that purpose, the efficiency and energy yields of each studied lightweight module technology were computed and compared to the yield of the reference installation under the same meteorological conditions. The average power losses over the studied period compared to the reference installation were between 8% and 17%.

These losses can reach higher values in some periods as illustrated in Figure 7. This figure shows the energy yield losses obtained for a clear sky conditions day during the month of June 2024 compared to the reference installation. The results of module B technology weren't computed for this specific day due to a failure in the micro-inverter connected to this module during the investigated period. The energy yield (kWh/kWp) for modules A, C, D and E

Fig. 5. Overview of the outdoor platform.

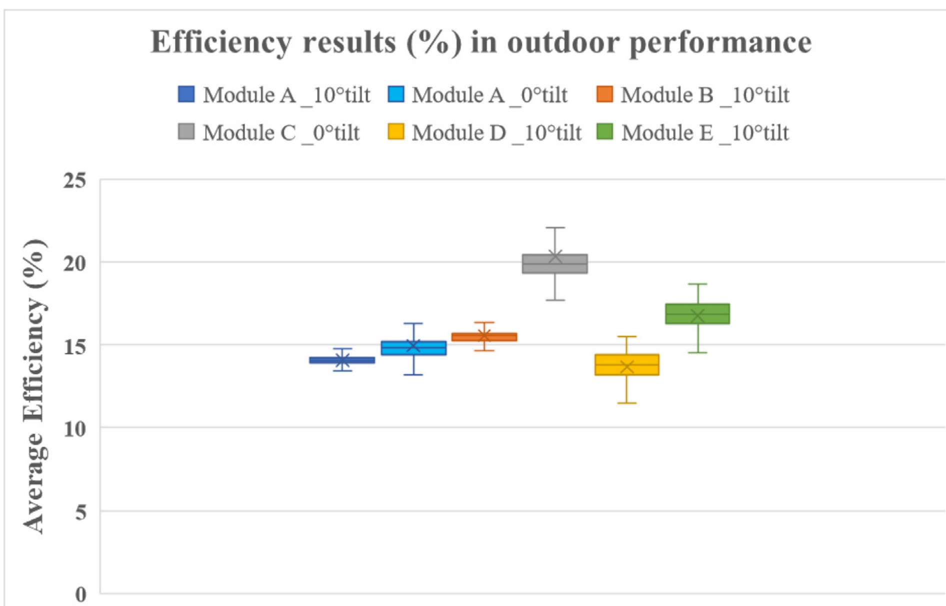

Fig. 6. Average efficiency of lightweight modules under real conditions.

were computed with higher losses obtained for Module C reaching 26%. Module C, set up with a 0° tilt presented higher power losses compared to the other technologies with 10° modules tilt. Module A with 0° tilt did not present higher losses than the one with 10°, the efficiency measured for the first one was slightly higher (Fig. 5) which can contribute to the yield losses results. The lower energy losses for this day were around 16% for module E with 10° tilt to the horizontal plane. In the month of June, the solar elevation angle is high, thus modules tilt between 0 and 30° should generate similar power with a difference calculated theoretically around ±2%. However, several factors contributed to these high losses:

– With lower modules tilts, increased soiling was observed on the lightweight modules that wasn't evacuated by the rain compared to the reference installation.
– A contribution of the bifaciality factor of the reference installation since it's composed of bifacial modules. According to the albedo measurements collected at the reference installation and simulations performed in our PVNOV modelling tool an average of 5% of bifacial gain is achieved.

Considering that very few days of clear sky conditions data were collected for the results analysis due to the meteorological conditions in the last months of the study, we can conclude that all modules tilted at 10° observed an additional 10% yield losses in June compared to the 30° reference PV plant which could be attributed to an additional soiling.

For 0° tilt, results differ between modules from A and C manufacturers with a 10–20% yield losses compared to the reference (excluding bifacial gain). Two elements can explain the losses:

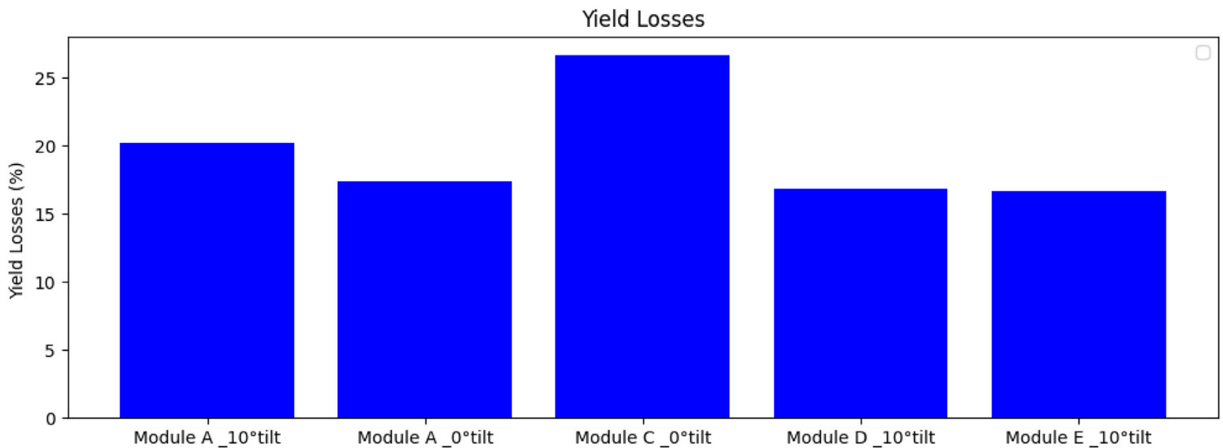

Fig. 7. Energy yield losses of each lightweight technology. Two modules were set at 0° tilt (manufacturer A and C) and the other ones at 10° tilt.

- A higher module temperature for the C module compared to the A module. This would have a negative impact on power generation. As these modules were fixed on the soil, it was not possible to measure the module temperature.
- A difference in rear side rugosity: the aspect of the front side of the modules from the A manufacturer is not uniform and has some round texturing contrary to the surface of modules from manufacturer C which is almost flat. The impact of the front side rugosity on soiling aspect needs a specific study to confirm this trend.

For such PV plant systems, these losses will eventually depend on the location of the installation and the cleaning frequency of the modules. For 0° tilted modules, additional cleaning maintenance should be planned to avoid too many losses.

5 Levelized cost of electricity

Based on reliability, outdoor results, internal cost for system installation and manufacturer discussions, we can estimate the levelized cost of electricity (LCOE) difference between a classical PV module plant versus a lightweight PV module plant. The following assumptions are taken:

- Effective irradiance: we consider setting up a plant at our facility near Paris in France, South oriented, with a tilt of 10° or 0°.
- Performance ratio: 80% is considered for the systems tilted at 10° based on the previous yield results (higher soiling but also more risk of shadowing due to existing rooftop objects). For 0° tilted module, 75% ratio is considered for additional soiling losses.
- Module degradation: considered 0.5%/year for glass/backsheet modules. This degradation is double for composite/polymer modules based on lower reliability results obtained in this study.
- Module cost: considered 20c €/Wp for standard. The price is double for lightweight glass backsheet technologies due to specific materials used and lower production capacity. The price is quadruple for lightweight all polymer-composite modules for the same reason, knowing that more specific components are used (glass replacement in particular).
- System installation: considered 30c €/Wp for 10° option which corresponds to a classical module + structure architecture. The cost is reduced to 20c €/Wp for system directly bonded on flat roof due to the simpler installation.
- Structure reinforcement: in case of standard module on low bearing roof, the roof reinforcement is an option. An over-cost of 10c €/Wp is arbitrary taken knowing that the reinforcement cost can vary a lot depending on the project.
- Other Balance of System costs: considered 30c €/Wp for all modules.
- Operation and maintenance costs (OPEX): considered 30c €/Wp for 10° tilt. System bonded directly to the roof with a 0° tilt may need more cleaning and can be subject to additional defects (for instance, cable and J-Box are directly exposed to the sun; some difficulties may exist for un-bonding modules from the roof, etc.). A 10% over-cost is then taken in this case. No yearly OPEX cost variation during the project lifetime is considered.
- Weighted Average Cost of Capital (WACC): taken at 7% for standard modules. 0.5% is added for modules glued on the roof and also for composite-polymer modules as there is lower return of experience on these technologies and there is a higher risk of module degradation as discussed previously.
- Interest rate: no interest rate is considered.
- Power plant lifetime: 25 years for all configurations.

The LCOE formula is taken as:

$$\mathrm{LCOE} = \frac{\text{Total investment} * \text{Actu} + \text{OPEX}}{\text{NPV of Production}} \tag{4}$$

with the Actualization factor defined as:

$$\mathrm{Actu} = \mathrm{WACC} * \frac{(\mathrm{WACC}+1)^{y}}{(\mathrm{WACC}+1)^{y}-1}. \tag{5}$$

The results are presented in Table 4.

Table 4. Technical-economical study using lightweight modules.

Modules	Standard with reinforcement	Lightweight glass / backsheet		Lightweight composite / polymer	
Production					
Effective irradiation per year	1335 kWh/m^2	1335 kWh/m^2	1240 kWh/m^2	1335 kWh/m^2	1240 kWh/m^2
Incidence angle	10°	10°	0°	10°	0°
Performance ratio	80%	80%	75%	80%	75%
Module degradation rate	0.5%/year	0.5%/year	0.5%/year	1.0%/year	1.0%/year
CAPEX (Investment)					
Module	20 c €/Wp	40 c €/Wp	40 c €/Wp	80 c €/Wp	80 c €/Wp
BOS and Soft cost	30 c €/Wp	30 c €/Wp	30 c €/Wp	30 c €/Wp	30 c €/Wp
Roof reinforcement	10 c €/Wp	–	–	–	–
System installation	30 c €/Wp	30 c €/Wp	20 c €/Wp	30 c €/Wp	20 c €/Wp
OPEX					
Operation and maintenance + other OPEX	30 c €/Wp	30 c €/Wp	33 c €/Wp	30 c €/Wp	33 c €/Wp
Financial					
WACC	7.0%	7.5%	8.0%	8.0%	8.5%
Plant lifetime	25 years	25 years	25 years	25 years	25 years
LCOE					
Levelized Cost of Electricity	107 €/MWh	119 €/MWh	143 €/MWh	170 €/MWh	207 €/MWh
Over-cost / standard	–	12%	35%	59%	95%

The use of lightweight modules is increasing the LCOE from 10% to 100% based on the hypothesis considered here. Note that without the 10c €/Wp taken for the reinforcement, the LCOE is decreased to 98 €/MWh. Even if the use of lightweight solution can be relevant even with its higher cost, the interest in these systems will be strongly linked to the cost of the client's electricity. In addition, several options exist to decrease the cost of these systems: more return of experience will limit the WACC increase, better module reliability will give a lower degradation rate and standardization of the product will lead to a cost decrease of the modules.

6 Conclusion

Lightweight modules are a robust solution to address low bearing roof market estimated at several tenth of GW in France only. Despite this potential huge market, we have highlighted some existing issues on today lightweight products present on the market with possible reliability issues, especially for composite/polymer modules. Outdoor performance study put in evidence the risk of having low tilted modules in term of yield but also the impact of soiling that may differ greatly depending on the localization of the PV plant but also on the surface rugosity and, certainly, module operating temperature in a 0° tilt configuration. Based on all the results obtained, an estimation of the levelized cost of electricity for different hypothesis and configuration explicit an over-cost of 10–100% compared to a classical module solution with a roof reinforcement.

Lightweight modules are still new products on the market, as more and more products are coming, manufactured now buy big photovoltaic players, their robustness and cost should improve soon. Nevertheless, reliability testing needs to be carried out and more data from outdoor performance studies are necessary to anticipate the effective yield of such PV plants. Outdoor testing is still undergoing at our laboratory to collect additional data with clear sky and high irradiance levels conditions covering the summer period. Additional monitoring tools like module temperature sensors will be added to better assess the yield difference. The global assessment of the yield comparison in outdoor environment will be finalized after completing the full year data analysis.

Acknowledgments

The authors are very grateful to the EDF R&D laboratory team for the help provided in performing module testing.

Funding

This research received no external funding.

Conflicts of interest

The authors have nothing to disclose.

Data availability statement

All relevant anonymized data used in the article and can be asked directly to the authors.

Author contribution statement

J. Dupuis: Conceptualization, Methodology, Formal Analysis, Writing – Original Draft Preparation. C. Abdel Nour: Methodology, Formal Analysis, Writing – Review & Editing. J. V. Oliveira Santos: Formal analysis, Visualization. P. Lefillastre: Validation, Funding acquisition.

References

1. W. Hemetsberger, M. Schmela, S. Dunlo, Global Market Outlook for Solar Power 2024 (2024)
2. K. Bódis, I. Kougias, A. Jäger-Waldau, N. Taylor, S. Szabó, A high-resolution geospatial assessment of the rooftop solar photovoltaic potential in the European Union, Renew. Sustain. Energy Rev. **114**, 109309 (2019). https://doi.org/10.1016/j.rser.2019.109309
3. ADEME, Artelys, ARMINES-PERSEE, ENERGIES DEMAIN, A 100% renewable electricity mix? Analysis and optimization, Agence de l'Environnement et de la Maitrise de l'Energie (ADEME) (2016). https://librairie.ademe.fr/urbanisme-et-batiment/2639-a-100-renewable-electricity-mix-analyses-and-optimisations.html
4. S. Joshi et al., High resolution global spatiotemporal assessment of rooftop solar photovoltaics potential for renewable electricity generation, Nat. Commun. **12**, 5738 (2021)
5. J. Dupuis, G. Plessis, G. El Hajje et al., Light- and elevated temperature-induced degradation impact on bifacial modules using accelerated aging tests, electroluminescence, and photovoltaic plant modeling, Prog. Photovolt. Res. Appl. **29**, 694 (2021). https://doi.org/10.1002/pip.3345
6. F. Kersten, F. Frühauf, R. Lantzsch et al., Stability investigations of Cz-PERC modules during damp heat testing and transport: the impact of the boron-oxygen defect, AIP Conf. Proc. **2147**, 090001 (2019). https://doi.org/10.1063/1.5123869
7. U. Desai, K. Nicolet, S. Prabhudesai et al., Stress tolerance of lightweight glass-free PV modules for vehicle integration, EPJ Photovolt. **15**, 10 (2024). https://doi.org/10.1051/epjpv/2024003
8. U. Desai, A. Singh, Assessment of mechanical robustness of conventional and CFRP-based lightweight PV module architectures under static loads, in *2022 IEEE 49th Photovoltaics Specialists Conference* (*PVSC*) (Philadelphia, PA, USA, 2022), pp. 0512–0515. https://doi.org/10.1109/PVSC48317.2022.9938905
9. K.G. Bedrich, M. Bliss, T.R. Betts, R. Gottschalg, Electroluminescence imaging of PV devices: Camera calibration and image correction, in *2016 IEEE 43rd Photovoltaic Specialists Conference (PVSC)* (Portland, OR, USA, 2016), pp. 1532–1537. https://doi,org/10.1109/PVSC.2016.7749875
10. T.S. Ramsay, Edge-based vignetting factor estimation and correction comparative Sanalysis, Imag. Sci. J. **65**, 299 (2017). https://doi.org/10.1080/13682199.2017.1337284
11. A. Rajput et al., Quantitative estimation of electrical performance parameters of individual solar cells in silicon photovoltaic modules using electroluminescence imaging, Sol. Energy **173**, 201 (2018). https://doi.org/10.1016/j.solener.2018.07.046
12. A. Lindsay, M. Chiodetti, P. Dupeyrat, D. Binesti, E. Lutun, K. Radouane, Key elements in the design of bifacial PV power plants, in *Proceedings of the 31st European Photovoltaic Solar Energy Conference* (Hamburg, Germany, 2015), pp. 1764–1769
13. A. Lindsay, M. Chiodetti, D. Binesti et al., Modelling of single-axis tracking gain for bifacial PV systems, in *Proceedings of the 32nd European Photovoltaic Solar Energy Conference* (Munich, Germany, 2016), pp. 1610–1617
14. M. Chiodetti, A. Lindsay, P. Dupeyrat, D. Binesti, E. Lutun, K. Radouane, S. Mousel, PV bifacial yield simulation with a variable albedo model, in *Proceedings of the 32nd European Photovoltaic Solar Energy Conference* (Munich, Germany, 2016), pp. 1449–1455

Cite this article as: Julien Dupuis, Christine Abdel Nour, João Victor Oliveira Santos, Paul Lefillastre, Lightweight photovoltaic modules technologies: reliability evaluation and market opportunity, EPJ Photovolt. **16**, 1 (2025)