

Architecture of symmetrical bifacial perovskite/Si/perovskite PV modules and LCOE comparison in bifacial applications

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Abstract. Perovskite on silicon tandem technologies offer a promising way to overcome the efficiency limit of single-junction crystalline silicon modules and are therefore widely studied. Besides the cost reduction potential of using tandem modules in utility-scale PV plants, the application of bifacial PV modules offers additional opportunities to reduce costs by increasing the energy yield. However, the bifaciality factor of tandem PV modules using bifacial crystalline silicon solar cells is typically lower than that of single-junction bifacial modules, considering the asymmetric architecture of the module with higher front-side than rear-side efficiency. In this study, we assess a symmetrical bifacial triple-junction perovskite/silicon/perovskite PV module architecture which allows for a significant improvement of the PV module rear side efficiency. Cost of ownership, energy yield and levelized cost of energy modeling show the superior performance of such modules compared to crystalline silicon and perovskite/silicon tandem modules specifically in vertical mounting applications that are used e.g. in AgriPV or noise protection PV walls on highways.

Keywords: Perovskite / tandem / triple junction / LCOE / vertical PV / bifaciality / agrivoltaic

1 Introduction

The on-going climate change currently represents one of the biggest threats for humanity and worldwide ecological balance. To address this major challenge, international plans of action such as the Paris agreement have been signed by most of the countries to implement decarbonized energy policies. The European Commission established in 2020 an ambitious package of initiatives that aims to make Europe a carbon-neutral continent by 2050. One of the main actions planned by this European Green Deal is to achieve a reduction of the greenhouse gas emissions by 55% by 2030 [1,2]. Among all renewable energy sources, photovoltaics currently represents a share of 5.5% of the total European electric production [3]. Despite an inherent low capacity factor (10–25%) [4] that makes electricity production variable at different timescale (intra-days to months), photovoltaics has proven to be a cheap and rapidly deployable solution to accelerate the transition to decarbonized sources of energy. Therefore, the European Commission established an ambitious plan for increasing the share of photovoltaic energy production from 3% to

15% of the total power production by 2030 [5]. To reach such a production capacity, new technical solutions for photovoltaic installations have to be developed, both increasing the module efficiency and implementing novel installation designs. The use of perovskite for tandem perovskite/silicon modules, which quickly became one of the main areas of interest of many photovoltaic research institutes, currently seems to hold the biggest potential to increase efficiency up to 30% [6] and beyond. Furthermore, the development of new concepts to optimize the usage of space have seen the emergence of novel ways of photovoltaic system installations, such as Building Integrated PV (BIPV), Floating PV, Vehicle Integrated PV (VIPV) or agrivoltaics (APV). Among these solutions, agrivoltaics holds a very high potential for deployment of photovoltaics, as agricultural land use accounts for 32% of the European territory [4].

Here we present a novel bifacial triple-junction tandem module concept using a fully symmetric structure of perovskite/Si/perovskite with the same bandgap of the two perovskite layers, in order to maximize the bifaciality factor of such tandem module and investigate the energy yield and the levelized cost of energy (LCOE) benefits for ground-mounted applications incl. vertical mounting for three locations and albedos. Bifacial perovskite/Si tandem

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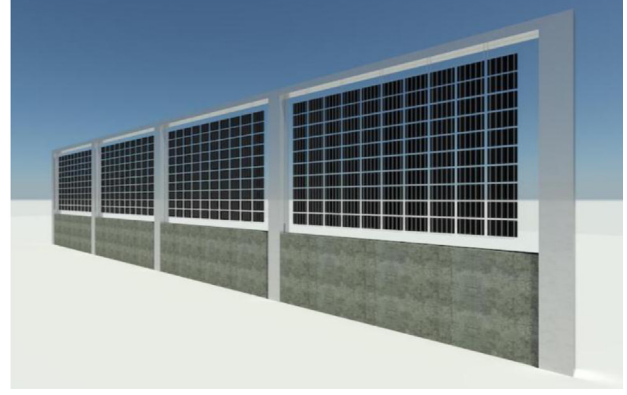


Fig. 1. Example of vertically mounted PV modules for AgriPV applications [9] (left), and for noise protection walls on highways [10] (right).

modules with their asymmetric high-/low bandgap structure inherently suffer from a lower bifaciality factor compared to a crystalline silicon module using the same bifacial silicon solar cell type. However, high bifaciality factors are particularly important for applications that enable similar light collection on the rear side as on the front side, e.g., in vertical mounting of PV modules in AgriPV [7] or for noise protection walls on highways [8], see Figure 1. To overcome the deficiencies of tandem modules in bifaciality, this work proposes a novel bifacial triple-junction module architecture that shows a superior energy yield and LCOE performance compared to crystalline silicon and perovskite/silicon tandem modules specifically in vertical mounting applications. We combine a bottom-up module cost assessment based on perovskite process flows developed at IPVF with energy yield and LCOE calculations using PVsyst to assess this novel module architecture.

2 Methodology

We propose a fully symmetrical bifacial perovskite/Si/perovskite module in a non-monolithic configuration using perovskite layers with the same bandgap at the front and rear sides of the module to maximize the rear side module efficiency. The structure and interconnection scheme of such triple-junction module are shown in Figure 2. The concept of a triple junction perovskite/Si/perovskite PV module has already been mentioned in the literature [11], although the concept was based on monolithically integrated tandem Si/perovskite structure with a parallel connected perovskite module on the backside, which differs from the concept simulated here where the three PV junctions are connected in parallel. It should also not be mixed up with that of a triple-junction perovskite/perovskite/Si PV module with different bandgaps of the perovskite layers, which has been under study for several years [12]. Note that we assume silicon heterojunction (Si HJ) technology for the crystalline Si cell due its high cell efficiency and bifaciality factor [13].

The core innovation of the symmetric triple-junction PV module is the non-monolithic integration of three PV junctions in which front and rear perovskite junctions possess the same bandgap of 1.65 eV with a flexible design

in the number of solar cells on the rear side adapted to the albedo at the installation site. As a proper connection of such non-monolithic structure is based on the voltage matching of each sub-module, the number of perovskite cells connected in series should be adapted to the amount of light reaching each side.

The issue of voltage matching for such a symmetrical bifacial triple junction can be solved by knowing the actual irradiance reflected on the rear side of the module as shown in the “results and discussion” section. This voltage matching of the three junctions can be described by equation (1):

$$V_{PKT1} \times N_{PKT1} = V_{Si} \times N_{Si} = V_{PKT2} \times N_{PKT2}, \quad (1)$$

V_{PKT1} : Voltage at Maximum Power Point (mpp) of one perovskite solar cell.

N_{PKT1} : Number of cells connected in series in the top sub-module.

V_{Si} : Voltage at mpp of one bifacial silicon solar cell.

N_{Si} : Number of cells connected in series in the middle sub-module.

V_{PKT2} : Voltage at mpp of the rear perovskite solar cell.

N_{PKT2} : Number of cells connected in series in the rear sub-module.

The physical structure of this symmetrical triple junction, as shown in Figure 2 (left), is based on the well-studied 4-terminal perovskite/Si tandem module [14] where the additional power generated by the perovskite layer is collected through the parallel connection of both junctions, allowing the addition of their respective generated current, assuming that the voltage matching has been properly designed by calculating the required number of perovskite solar cells as explained before in equation (1).

In the novel concept studied here, although the number of perovskite cells is going to be higher on the rear side of the module to compensate for the lower irradiance in a ground mounted application, the case of vertical mounted PV modules will not involve any change in the number of cells and will maintain a fully symmetrical structure. Note that the vertical mounting therefore implies simplifications for the module manufacturing as the number of perovskite cells on the rear side does not need to be adapted to the

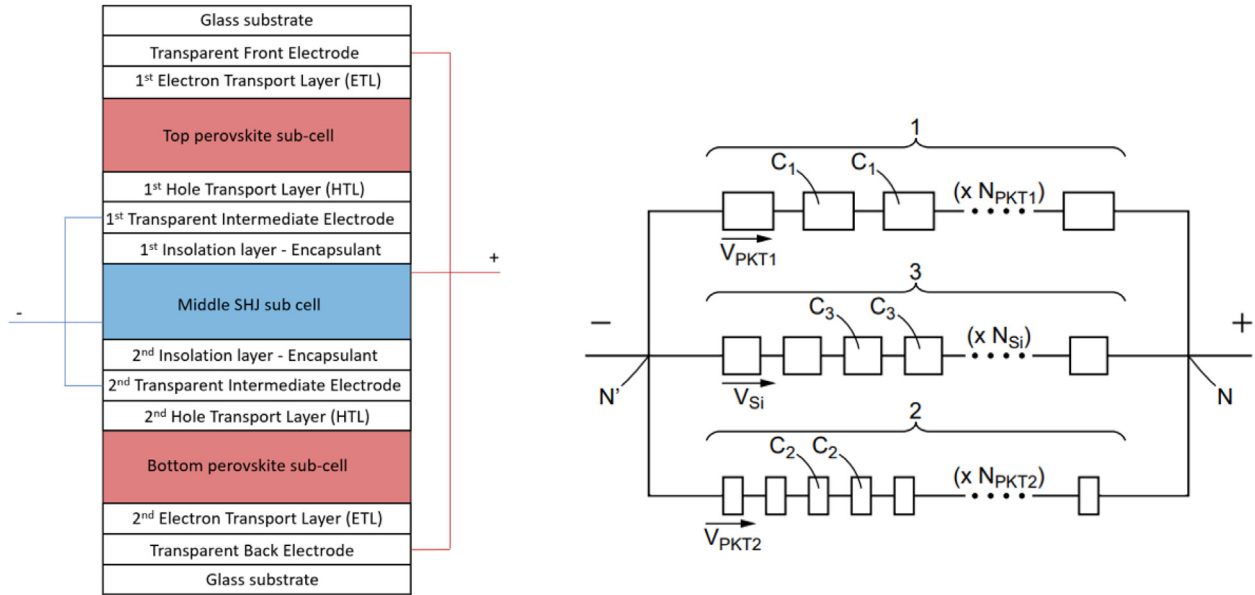


Fig. 2. Cross-section schematic of the triple-junction module (left) and electrical design of the module (right). C1, C2 and C3 denote the front and rear perovskite cells and the Si HJ cell, respectively. N and N' denote the positive and negative electric nodes.

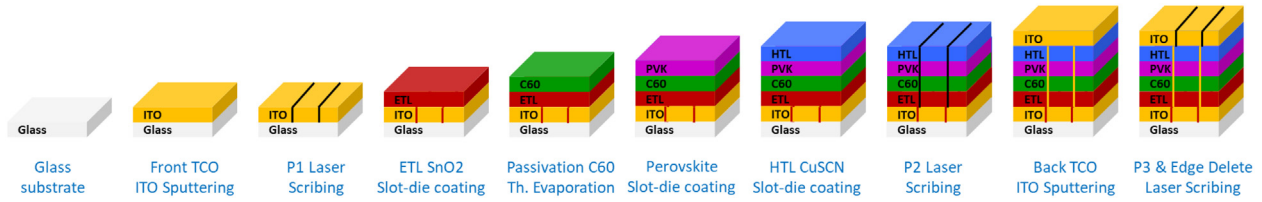


Fig. 3. p-i-n perovskite process flow developed at IPVF for 4-Terminal integration.

concrete application and light conditions but is the same as for the front-side perovskite sub-module. The physical structure is based on a symmetrical stack using the same materials for both Hole Transport Layer (HTL) and Electron Transport Layer (ETL) as shown in Figure 2 (left). The electrical design model to calculate the proper amount of perovskite cells (C_1 , C_2) on front and rear side of the module are described in Figure 2 (right).

In order to evaluate the energy yield and LCOE gains of such a triple-junction structure compared to a single-junction Si HJ module and a tandem perovskite/Si HJ module, a simulation has been performed in PVsyst for single row east-west oriented tilted ground mounted PV plant and vertical PV walls scenarios. The performances of the Si HJ module are based on a certified Si HJ solar cell [15] on which cell to module losses (CTM) have been applied [16] to obtain performances of a 72-cells PV module, while the perovskite module performances have been simulated using an IPVF proprietary software [17]. Both silicon and perovskite sub modules are assumed to have a 0.5%/year degradation rate for a 25 years lifespan. The cost of materials and processes necessary to manufacture a symmetrical triple-junction solar module is based on the process flow developed at IPVF for the manufacturing of a perovskite module as shown in Figure 3.

3 Results and discussions

The evaluation of irradiance potential on the rear side of the PV module has been performed in a standard ground mounted tilted PV module scenario, where the number of perovskite solar cell is higher on the rear side of the module, as well as for vertically mounted PV modules, for which both front and rear perovskite sub-modules are identical, for the locations of Marseille and Marrakech using albedos of 0.8 (white ground), 0.5 (sand) and 0.25 (grass), respectively. Figure 4 gives an example of the differences in the PV module rear side global irradiance of ground mounted PV modules in Marseille at different time of the year, as well as the maximum power point voltage (V_{mpp}) of a perovskite solar module illuminated at irradiances below 100 W/m^2 . It appears that the rear side global irradiance varies from 0 to 120 W/m^2 along the year, involving strong variations of the rear side perovskite module V_{mpp} that will affect the overall efficiency of the triple junction solar module.

As tilted ground mounted applications of the triple junction PV module exhibits difficulties in ensuring the voltage matching along the day and the different times of the year, it requires further investigation in order to determine the proper method to calculate the proper

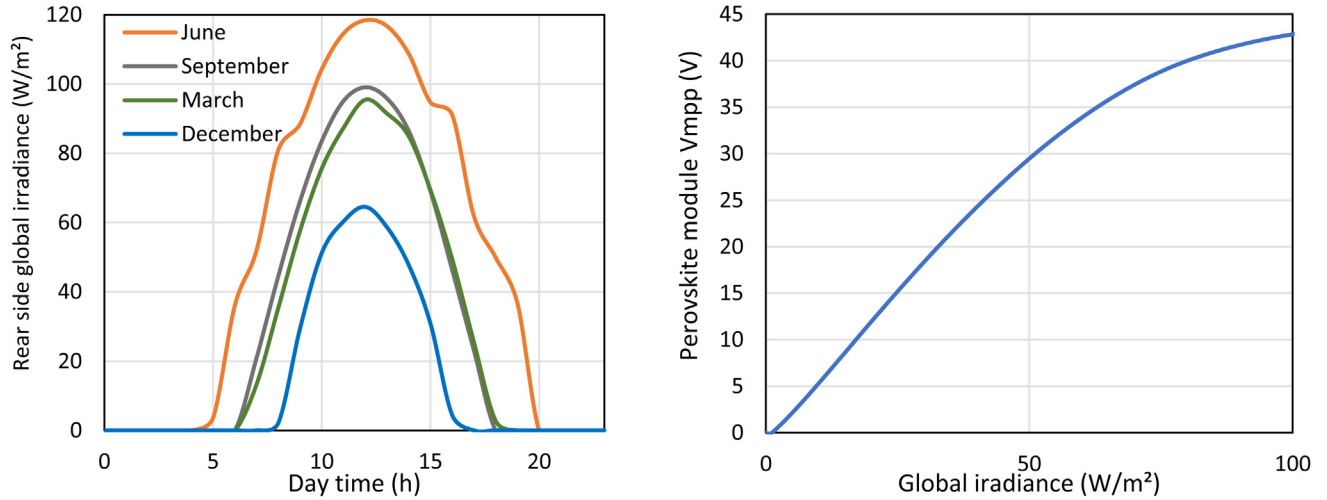


Fig. 4. Rear side global irradiance on a ground mounted PV module in Marseille at different time of the year (left) and perovskite module Vmpp variation in low light irradiance (right).

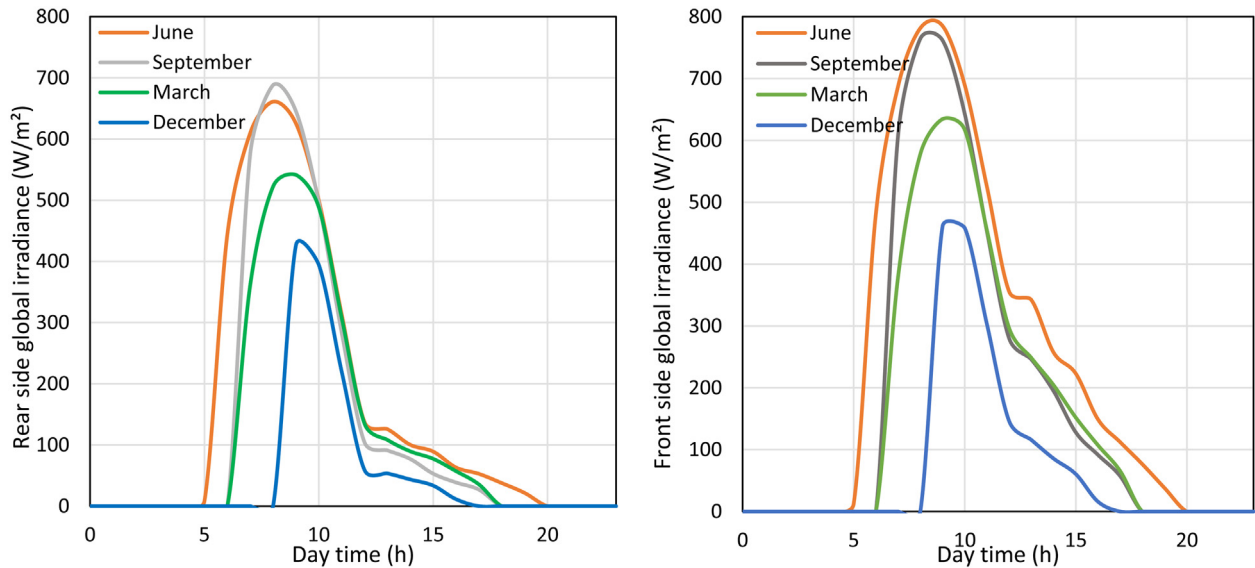


Fig. 5. Front or rear side global irradiance on a vertical PV module in Marseille during the day at different time of the year for a ground albedo of 0.25 (left) and 0.8 (right).

number of cells of the rear-side perovskite sub-module. Figure 5 shows the typical front or rear side global irradiance on a triple junction PV module in Marseille in an east-west oriented vertical configuration at different times of the year and with two different albedos. The global irradiance reaching one side of the module is direct and diffuse irradiance until midday, ensuring a proper voltage matching with the silicon module. The second half of the day provides only reflected and diffuse light to the shadowed side, reducing the irradiance. However, the level of irradiance when one side of the PV module is shadowed is above 100 W/m² in most cases, ensuring a proper voltage matching of the three junctions.

In addition to the irradiance data, the cost of manufacturing of such a symmetrical triple-junction solar module needs to be determined in order to calculate the LCOE of this novel architecture in an actual PV plant.

A breakdown of the Cost Of Ownership (COO) of a perovskite sub-module manufacturing has been performed on the basis of results previously published for the cost assessment of a tandem perovskite/Si module manufacturing process [18]. Figure 6 shows the COO of each process step of a perovskite stack based on a process flow developed at IPVF assuming a 1GW factory.

Based on the manufacturing cost breakdown of a perovskite stack as shown in Figure 6, the cost of silicon cells and the Balance Of Module (BOM) [16], which includes materials/consumables interconnection materials from the ribbons to the junction box, front and back glass, aluminum frame, encapsulant, potting agent and silicon sealant. The COO for a symmetrical triple-junction module is presented in Figure 7. This cost data, in addition to the irradiance and metrological data were then provided as input for LCOE calculations using PVsyst.

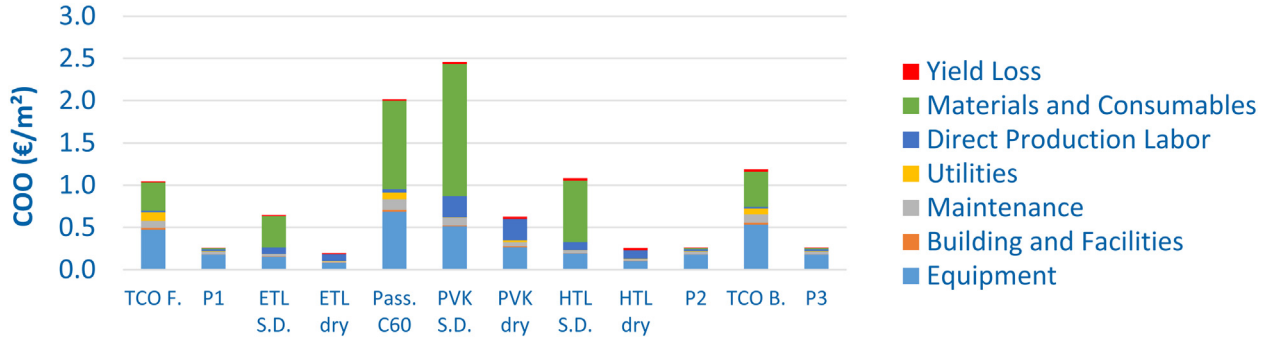


Fig. 6. Cost breakdown of a perovskite stack manufacturing process steps. PVK = perovskite, ETL/HTL = electron/hole transport layer, TCO F./B. = transparent conductive oxide front/back, P1/2/3 = laser scribing steps, S.D. = slot-die coating, pass; = passivation layer.

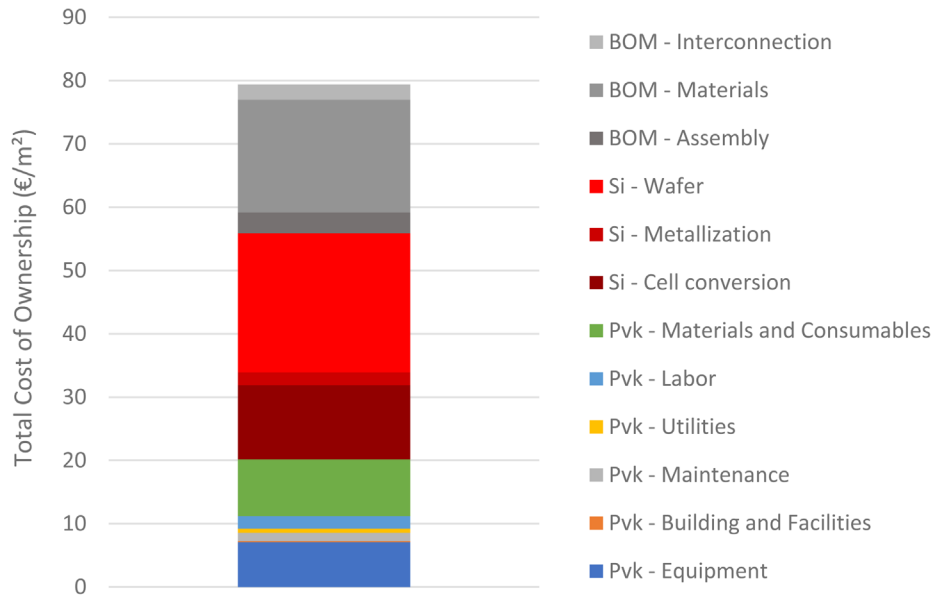


Fig. 7. Breakdown of the total COO of a symmetrical triple-junction perovskite/Si/perovskite module.

The bifaciality factor is defined as the ratio of rear module power conversion efficiency in relation to the front efficiency subject to the same irradiance. In our study we assume a bifaciality factor of 0.9 for the Si HJ [16] solar module, leading to a system production gain of 8.5% compared to a monofacial module based system in the case of Marseille with an albedo of 0.25. This is in good agreement with a study analyzing the energy gain of Si HJ bifacial modules of between 6.5 and 11% [19]. Table 1 summarizes bifaciality factors and cost of Si HJ [16], tandem perovskite/Si HJ [18] and triple-junction perovskite/Si HJ/perovskite modules as used in this study.

PVsyst simulations have been performed for vertical PV systems in Marseille and Marrakech, using Si HJ, perovskite/Si tandem and triple-junction perovskite/Si/perovskite modules-based PV systems. To illustrate the LCOE gains of PV systems using the proposed symmetrical perovskite/Si/perovskite modules with various albedo values, we assume an albedo value of 0.25 (grass), 0.5 (sand) and 0.8 (white floor or snow) for PV plant mounted in Marseille and 0.5 (sand) in Marrakech. The simulation has been performed for the vertical mounting scenario

(90°) which does not require any adaptation and is based on the fully symmetrical structure. Specific yield and LCOE results of these scenarios are summarized in Table 2. The electrical parameters of each module, used as inputs for the PVsyst simulation, are the results of IPVF proprietary software simulations especially designed for perovskite and tandem perovskite/Si electrical performance evaluation.

As an example, the following values have been used for a vertical mounted PV module scenario in Marseille with an albedo of 0.8:

$$Vmpp_{pkt1} = Vmpp_{pkt2} = 0.92 \text{ V}$$

$$Vmpp_{Si} = 0.62 \text{ V.}$$

Following equation (1), the number of perovskite cells should be adapted to match the silicon module voltage:

$$N_{pkt1} = N_{pkt2} = (Vmpp_{Si} \times 72) / Vmpp_{pkt1} = 48.5 \rightarrow 49 \text{ perovskite cells.}$$

In the case of the vertical module the number of perovskite cells on the front and the rear side are equal.

Table 1. Bifaciality factor and cost based on front side efficiency of the three module technologies in this study.

Bifaciality factor (%)	SHJ	90
	Tandem perovskite/SHJ	74
	Triple junction perovskite/SHJ/perovskite	95
Cost (€cent/Wp)	SHJ	27.4
	Tandem perovskite/SHJ	26.9
	Triple junction perovskite/SHJ/perovskite	29.9

Table 2. Summary of system production and LCOE of bifacial silicon heterojunction, tandem perovskite/Si and triple-junction perovskite/Si/perovskite modules-based PV systems in two geographical locations with different albedo values in an east-west vertical configuration for 100 kWp PV systems.

		Vertically mounted PV plant		
		SHJ	Tandem pkt/Si	Triple junction pkt/Si/pkt
Marrakech - Albedo sand 0.5	System production (MWh/year)	171	202	222
	LCOE (€/MWh)	69	63.6	58.8
	LCOE reduction to SHJ		7.8%	14.8%
Marseille - Albedo white floor 0.8	System production (MWh/year)	149	167.8	183.1
	LCOE (€/kMWh)	82	75.7	69.3
	LCOE reduction to SHJ		7.7%	15.5%
Marseille - Albedo sand 0.5	System production (MWh/year)	132	149.5	164.3
	LCOE (€/MWh)	93	85.4	78.6
	LCOE reduction to SHJ		8.2%	15.5%
Marseille - Albedo grass 0.25	System production (MWh/year)	118	141	157
	LCOE (€/MWh)	100	91.2	84.4
	LCOE reduction to SHJ		8.8%	15.6%

4 Conclusion

Our study shows that the concept of a triple-junction perovskite/Si/perovskite module proposed in this paper can decrease the LCOE of a vertical east-west oriented PV installation up to 15.6%, about twice as high as the improvement offered by perovskite/Si tandem modules. However, the use of such triple junction in ground-mounted tilted PV module installations does not seem yet acceptable and requires further analysis due to the very low amount of global rear side irradiance on the module that would create voltage mismatch between the three PV junctions. These results highlight the benefits of such fully symmetrical triple-junction PV modules for vertical mounting applications such as in AgriPV installations.

Author contribution statement

Amaury Martin: Development of the original concept, co-design of the PV module structure (cross-section and electrical scheme) presented in Figure 2, simulation of energy production of the three cases studied here and calculation of the LCOE. Pierre-Philippe Grand: Development of the original concept, the electrical scheme (Fig. 2 right) and the equation to determine the number of cells (Eq. (1)). Matthew Hull: Calculation of production costs (COO) based on IPVF perovskite and tandem perovskite/Si processes. Jean Rousset: Calculation/simulation of perovskite and tandem perovskite/Si module performances. Lars Oberbeck: Development of the original concept and co-design of module of the cross-section presented in Figure 2 (right).

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