

# IPVF's PV technology vision for 2030

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## Abstract

Current single-junction crystalline silicon (c-Si) solar cells are approaching their power conversion efficiency (PCE) limit. Tandem solar cells are expected to overcome such efficiency limit, with perovskite on c-Si tandems being a promising candidate for commercialization over the next years. This work aims at describing the conditions that tandem cells and modules need to fulfill to successfully enter the market in 2030. We first estimate that industrial c-Si photovoltaic modules may reach a price level of about 15 c\$/W in 2030 at a PCE of 22–24%, with an expected lifetime of 30 years and an annual degradation of 0.5%. For commercial relevance, we anticipate that tandem module efficiencies need to be increased to reach around 30%, while matching lifetime and degradation rate of c-Si modules. Provided these conditions, we find that these tandem modules could then have a cost bonus of around 5–10 c\$/W compared to c-Si modules for reaching equal levelized cost of energy values.

## KEYWORDS

levelized cost of energy (LCOE), perovskites, power conversion efficiency (PCE), tandem

## 1 | INTRODUCTION

Photovoltaic (PV) energy generation systems have reached annual installation volumes of >100 GW and a cumulative installation volume of >500 GW at the end of 2018. The market is dominated by crystalline silicon (c-Si) technologies that have seen a tremendous cost reduction in recent years and a significant increase in power conversion efficiency (PCE), making the technology competitive in terms of levelized cost of energy (LCOE) in many regions of the world. However, the PCE of single-junction c-Si PV is approaching its perceived practical limit, driving the attention towards new technologies that will enable PCEs higher than 30% while reducing the cost of PV systems.

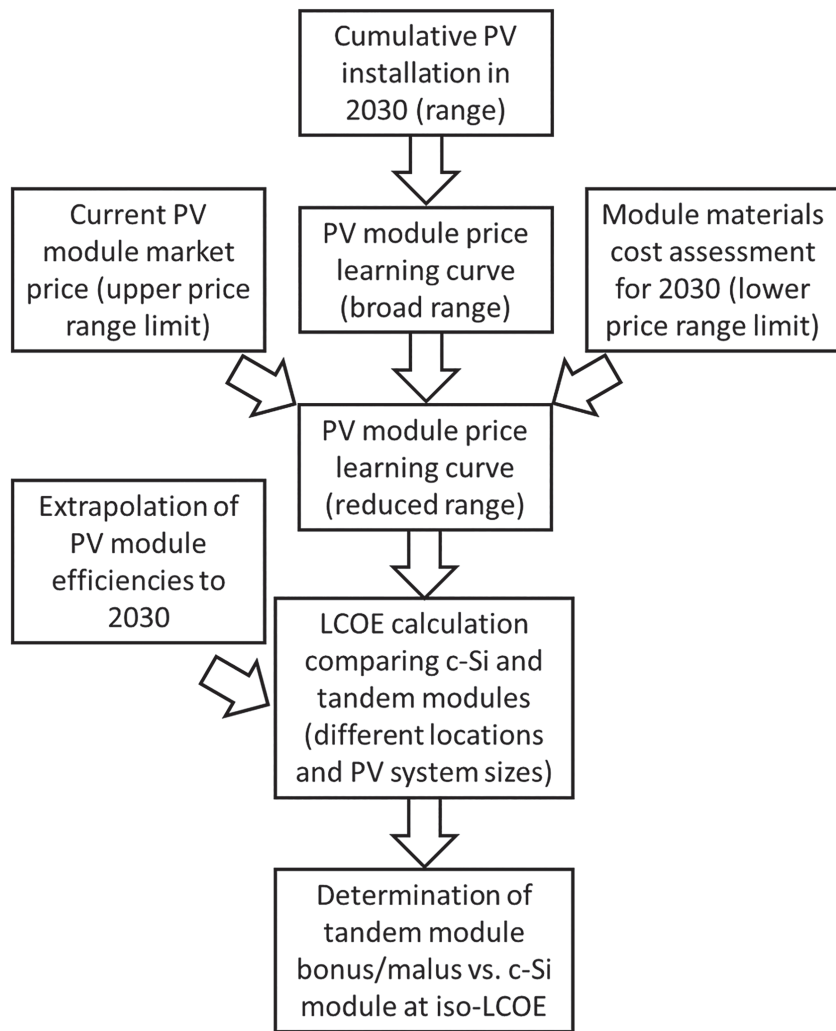
At the COP21 climate change conference in Paris in 2015, the Institut Photovoltaïque d'Ile-de-France (IPVF) published a position paper on efforts required in PV to fight climate change and gave itself an objective of "30–30–30": PV module efficiency of >30% at a price of <30 c\$/W by 2030, to be achieved using tandem PV modules, with the support of 10 representatives of major international PV research

centers.<sup>1</sup> Four years later, in this paper we review our PV market vision for the year 2030 and our strategic view on the tandem PV module technologies and their market introduction. We review existing PV technologies, markets and costs and outline boundary conditions under which tandem PV modules could successfully be introduced in the market.

To assess the competitiveness of tandem PV modules vs. c-Si modules in 2030, we use an iso-LCOE approach, i.e. we determine the price difference between tandem and c-Si modules that results in the same LCOE value, dependent on the lifetime, degradation, financing conditions etc. of tandem modules. Figure 1 outlines the approach: from the expected cumulative PV installation in 2030, we determine a possible c-Si module price range from the learning curve. As this range will be rather broad, also depending on the learning rate used for the extrapolation, we use a comparison with module materials cost data for 2030 and current module market prices to eliminate the very low and high price ranges (i.e. below materials cost or above current market price). This c-Si module price

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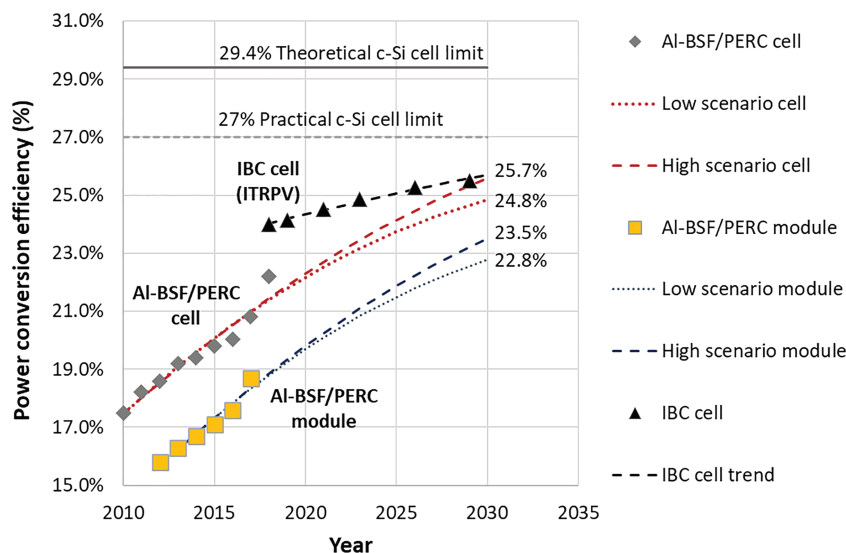


**FIGURE 1** Approach used to determine the cost bonus or malus (i.e. competitiveness) of tandem vs. c-Si PV modules at iso-LCOE for 2030

value is then used together with the extrapolated module efficiency to 2030 in an LCOE calculation for two different PV system sizes and locations to determine the cost bonus/malus of tandem vs. c-Si modules, as an indicator of the competitiveness of tandem modules in the PV market in 2030.

## 2 | CURRENT PV TECHNOLOGIES

The PV module market is dominated by c-Si technology with a market share of about 95%, whereas thin-film technology, mainly cadmium telluride (CdTe) and copper indium gallium selenide (CIGS), has a



**FIGURE 2** Historical evolution of mainstream (Al-BSF/PERC) industrial crystalline silicon solar cell and module power conversion efficiencies (from refs. [6, 8, 10] As well as internal data) and extrapolation towards 2030, using the Pearl-Reed function<sup>9</sup> to take the practical efficiency limit of c-Si solar cells of 27% (low scenario) and the theoretical limit of 29.4% (high scenario), respectively, into account. ITRPV expectations for IBC cells are shown for comparison<sup>11</sup>

market share of about 5%.<sup>2</sup> While the theoretical PCE limit of c-Si solar cells is 29.4%,<sup>3</sup> the record c-Si solar cell efficiency to date was achieved by Kaneka for an Interdigitated Back-Contact Silicon Heterojunction (IBC-SHJ) solar cell with 26.7%.<sup>4</sup> Best production cell efficiencies are reached by SunPower with about 25% for IBC technology<sup>5</sup> and mainstream c-Si Passivated Emitter and Rear Cell (PERC) in production reaches ca. 22.2%.<sup>6</sup>

However, c-Si solar cells are approaching the practical PCE limit which is thought to be in the 27% efficiency range (see e.g.<sup>4,7</sup>). Average industrial solar cell and module efficiencies have increased over the last years by 0.4–0.6% abs. per year.<sup>6,8</sup> Figure 2 shows historical industrial mainstream Aluminum Back-Surface-Field (Al-BSF) and PERC cell and module efficiency data extrapolated towards 2030, applying the Pearl-Reed function<sup>9</sup> and their respective upper solar cell efficiency limits of 27% and 29.4%. The Pearl-Reed curve (Equation 1) presents an s-shaped form that describes an accelerated growth at the beginning, followed by a slowing down after reaching half of the possible improvement:

$$n(t) = \frac{L}{1 + ae^{-bt}} \quad (1)$$

with  $n(t)$  = time-dependent efficiency,  $L$  = upper limit of  $n(t)$ ,  $a$  = location coefficient and  $b$  = shape coefficient.

Module power conversion efficiencies were calculated from the respective cell efficiencies, using cell-to-module (CTM) power ratios from the International Technology Roadmap for Photovoltaic (ITRPV).<sup>11</sup> In 2025, average industrial cell efficiencies of ca. 24% can be expected, and in 2030 values of ca. 25%. Average module efficiencies of around 22% can be anticipated for 2025, further increasing in 2030 to around 23%, approaching the practical efficiency limit. For comparison, we also show IBC cell efficiencies that will reach approximately 26% in 2030, according to expectations from ITRPV.<sup>11</sup>

Besides efficiency, the lifetime of c-Si PV modules is a critical parameter. Manufacturers today typically give a performance warranty with a specified power output value after 25 years for glass-backsheet modules and 30 years for glass-glass modules. The module power warranty has increased over time from originally 5 years in the 1980 s<sup>12</sup> and is expected to reach 30 years in general from 2022 onwards.<sup>11</sup>

At the end of their life (or after early failures), it is mandatory in the European Union<sup>13</sup> (and increasingly required in other regions of the world as well) that PV modules are recycled. Due to small volumes, dedicated PV recycling is almost non-existent as of today, but these modules are being processed on existing recycling lines for other consumer products. While today, mainly for c-Si modules, only aluminum frames and glass are re-used and encapsulants and silicon cells are incinerated, it can be expected that in the future more advanced recycling schemes will be implemented that maximize the value of recycled material and minimize the ecological footprint of the PV modules. For an overview of PV module recycling see e.g. ref. [14].

### 3 | MULTIJUNCTION PV CELLS AND MODULES

In order to further increase cell and module efficiencies and thereby leveraging balance of system (BOS) costs, tandem solar cells and modules are expected to be introduced in the market from around 2023 onwards.<sup>11</sup> Such tandem solar cells have a theoretical efficiency limit of >40%.<sup>15</sup> Various materials combinations for tandem cells are currently under investigation, the most prominent being perovskites on c-Si,<sup>16</sup> III-V on c-Si,<sup>17</sup> III-V on III-V,<sup>18</sup> perovskite on perovskite,<sup>19</sup> perovskite on CIGS<sup>20</sup> and CIGS on Si<sup>21</sup> in 2-terminal (2 T), 3 T or 4 T configurations. Both 2 T and 4 T configurations show advantages and disadvantages: 2 T tandem cells benefit from easier, less costly module integration using established production technologies, whereas 4 T cells maximize power output without the need of current matching between the two sub-cells, but require non-standard module integration of the top and bottom cells. Differences in power output between 2 T and 4 T tandem cells have been investigated by various authors and are expected to be between 1–2%<sup>22</sup> and around 15%<sup>23</sup> depending on mounting conditions and location.

In the case of III-V, single-junction solar cells achieve high efficiencies of currently up to 29.1%<sup>24</sup> and tandem cells achieve 32.8% (GaInAsP/GaAs, 2 T),<sup>25</sup> and 32.8% for GaAs on c-Si (4 T).<sup>17</sup> However, there is a critical cost issue with III-V materials that is being currently addressed e.g. by developing lower-cost deposition methods such as hydride vapor phase epitaxy (HVPE).<sup>17</sup>

On the other hand, being at a lower level of maturity, perovskite tandem solar cells have already reached a PCE of 28.0% in a 2 T configuration,<sup>26</sup> thereby surpassing all single-junction c-Si solar cells, with the potential of having low costs.<sup>27</sup> For a 4 T configuration, a practical implementation of combining a bifacial c-Si bottom cell with a perovskite top cell has recently been shown by ECN/Solliance with a cell efficiency of 30.2%.<sup>28</sup> Note however that this is the so-called “bifacial-equivalent efficiency” that assumes 20% of standard irradiance also impinging onto the rear side of the bifacial cell and that must not be confused with the power conversion efficiency PCE. The PCE of this cell is in the 26% range. While upscaling and stability issues of perovskites are still challenging, continuous progress is under way.

Bifacial solar cells and modules can increase the power output by up to 30% in an ideal case compared to monofacial cells and modules,<sup>29</sup> but performance strongly depends on the albedo and use case. Three-terminal and 4 T tandem modules can benefit from bifacial bottom solar cells, whereas bifacial 2 T tandems are less favorable due to current matching issues associated with varying current generation in bifacial bottom cells from varying rear-side illumination conditions.

The requirement for recycling of PV modules, as mentioned in the previous section, also holds for novel technologies that are introduced in the market. Recycling studies are therefore needed to follow the development of multijunction cells and modules. In the case of perovskite on c-Si tandem modules, first investigations on the recycling of perovskite thin-film test cells have been carried out with the intention

of re-using the transparent conductive oxide coated glass (as the highest cost component) and recycling the Pb-containing perovskite layer, see e.g. refs. [30, 31]. These studies seem to bode well for the future recycling of commercial perovskite on c-Si tandem modules.

#### 4 | PV MARKET DEVELOPMENT AND PRICE EVOLUTION BASED ON THE PV MODULE LEARNING CURVE

Addressing the evolution of the PV market, it is obvious that historically the market growth has repeatedly been underestimated so far, see e.g. ref. [32]. Recent estimates predict a cumulative installed PV capacity in 2030 ranging from 1.29 TW<sup>33</sup> to 5.01 TW,<sup>34</sup> see Table 1.

Applying IEA current policies and the Shell sky scenario as the lower and upper estimates for cumulative shipments, we use the learning curve of PV modules to extract a target range of PV module prices that can be expected in 2030, see Figure 3. The learning curve can be expressed as

$$C(q_t) = C(q_0) * \left(\frac{q_t}{q_0}\right)^{-b} \quad (2)$$

with  $C(q_t)$  = quantity-dependent module price,  $q_0$  = accumulated module shipments in year 0,  $t$  = time,  $q_t$  = accumulated shipments in year  $t$  and  $b$  = constant.<sup>37</sup> The learning rate (LR) which describes the price change with a doubling of cumulative shipments is<sup>37</sup>

$$LR = 1 - 2^{-b} \quad (3)$$

The learning curve describes the price reduction per watt peak of PV modules with increasing cumulative shipments. This price reduction mainly results from economy of scale and only to a smaller extent from an increase in the PCE.<sup>11</sup> Historically, the learning rate is about 24% for the years of 1976 to 2018. Considering specifically recent years when mass production of PV modules started, the authors

find for the period from 2008 to 2018 a learning rate of 38.6%. At the beginning of 2019, average c-Si PV module spot market prices were around \$0.21/W to \$0.27/W, depending on the technology and region.<sup>38</sup>

From the extrapolation of the learning and PV module efficiency curves, we conclude that c-Si modules may reach a price range of \$0.06/W to \$0.34/W in 2030, depending on cumulative shipments and learning rate, with industry average module PCEs of about 23%. The lower limit of the price range results from applying the high LR of 38.6% from 2008 onwards, while the higher limit is determined by the extrapolation of historical data with a LR of 24%. The application of the historical LR of 24% to the 2018 module price data point gives values of \$0.11/W to \$0.19/W in 2030, depending on the cumulative PV installation scenario. While there is good reason to assume that a module price of \$0.34/W is too high, given that 2019 values are already significantly lower, it is desirable to further narrow down the broad range by estimating the material costs of a PV module in 2030 as a lower limit to the module price. Note that for the PV industry to be financially self-sustaining, the long-term operating profit margin should be around 15%, see e.g. ref. [39], i.e. a module price of 15 c\$/W would correspond to a cost of ca. 13 c\$/W.

#### 5 | PV MODULE MATERIALS COST ESTIMATE

We perform a bottom-up module materials cost assessment for a 60-cell glass-backsheet monocrystalline Si PERC module that can be used as a lower boundary for module prices in 2030. We use a detailed PV module cost model that has been developed within Total for this simplified calculation that takes into account wafer costs, costs of silver and aluminum metallization pastes and of screens used in screen-printing metallization as well as module material costs. Labor costs, depreciation and other costs are not considered. As materials represent about 80% of the module and cell conversion costs, this leads us to a reasonable assumption for a lower limit to future PV module costs.

Key assumptions: (based on internal data, ITRPV<sup>11</sup> and PV Pulse<sup>40</sup>)

- For Q4/2018: 175  $\mu\text{m}$  wafer thickness, 88  $\mu\text{m}$  kerf loss; 22% cell efficiency; Ag (130 mg per cell), Al paste (950 mg per cell) and screen costs
- For 2030 moderate scenario: 120  $\mu\text{m}$  wafer thickness, 60  $\mu\text{m}$  kerf loss; 24% cell efficiency; Ag (70 mg per cell), Al paste (700 mg per cell) and screen costs; 4.6% module materials cost reduction per year (calculated from ref. [40])
- For 2030 aggressive scenario: 100  $\mu\text{m}$  wafer thickness, 50  $\mu\text{m}$  kerf loss; 27% cell efficiency; Ag (55 mg per cell), Al paste (600 mg per cell) and screen costs; 4.6% module materials cost reduction per year, add. -20% backsheet and frame costs

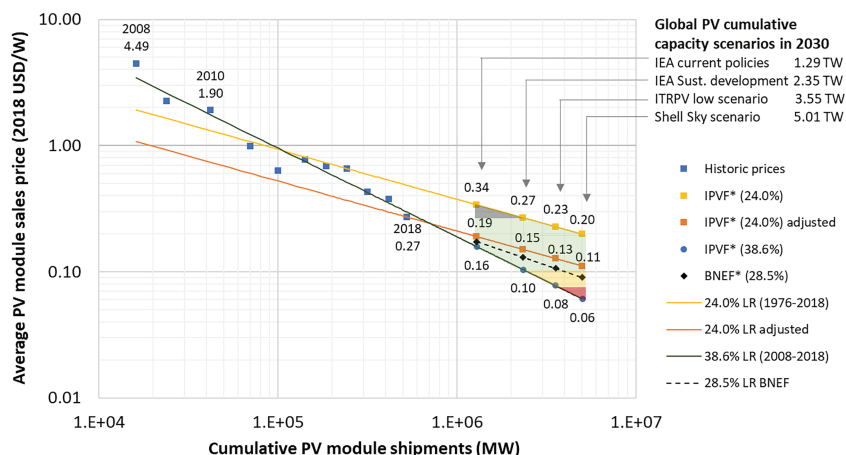
As shown in Table 2, we consider two scenarios for 2030, a moderate and an aggressive cost scenario which differ in cell efficiency, wafer thickness and kerf loss as well as paste consumption. The

**TABLE 1** Cumulative PV module installation volumes in 2030 from various sources

Source/scenario	Cumulative installation in 2030 [TW]
IEA current policies <sup>33</sup>	1.29
IEA new policies <sup>33</sup>	1.59
IRENA 2017 <sup>35</sup>	1.76
BNEF <sup>36</sup>	2.14
IEA sustainable development <sup>33</sup>	2.35
ITRPV low <sup>11</sup>	3.55
ITRPV high <sup>11</sup>	4.74
Shell sky scenario <sup>34</sup>	5.01

**Abbreviation:** BNEF, Bloomberg New Energy Finance; IEA, International Energy Agency; IRENA, International Renewable Energy Agency.

**FIGURE 3** Learning curve of average PV module price as a function of cumulative shipments, incl. extrapolation to expected cumulative shipment values in 2030 from various sources (see Table 1) using different learning rates: IPVF extrapolation of PV learning rates – historical (1976 to 2018: 24%) and recent trend (2008 to 2018: 38.6%). The colored areas indicate the likelihood of achieving respective price values from a bottom-up materials cost estimate (see following section) and the grey area marks module prices that are higher than today's values



applied values are variations of the expectations in ITRPV's roadmap.<sup>11</sup> Note that a 24% cell efficiency in 2030 should be at the lower end of future industrial solar cell PCEs and is expected to be achieved by improved PERC solar cells, whereas an efficiency of 27% would require a high-end single junction c-Si solar cell which, from today's perspective, could be realized by IBC-SHJ technology. We estimated that the module materials cost value in 2030 is driven by the rate of cost reduction of module materials such as glass, encapsulant, backsheet etc. We assume this annual cost reduction to be 4.6%, based on calculations from PV Pulse data for recent years.<sup>40</sup> The module materials cost value for Q4/2018 is shown for comparison and as a sanity check for our cost model and assumptions. Given current average monocrystalline silicon PERC module prices of around 27 c\$/W displayed at PVinsights,<sup>38</sup> our value of 18.9 c\$/W for module material costs seems appropriate.

For the year 2030, our bottom-up module material costs assessment results in 10.3 and 8.0 c\$/W for the moderate and aggressive scenario, respectively. Therefore, we have color-coded in Figure 3 the range of PV module prices and cumulative shipment values that could be expected in 2030 depending on the likelihood of occurrence: the range of module prices below 8 c\$/W is shown in red, since we assume that they are unlikely to be achieved with current module technologies. The range above 10.3 c\$/W is colored in green, indicating that these values are more likely to be achieved given our materials costs assessment. The range in-between is shown in yellow to indicate an intermediate likelihood of being realized. Note that our cost assessment assumes that current module technology for glass-backsheet modules with encapsulants and tabbing/stringing will continue to be used. The development of novel module technologies,

e.g. encapsulant-free modules,<sup>41</sup> could help in further reducing manufacturing cost, increasing energy yield over module lifetime and facilitating recycling.

## 6 | LEVELIZED COST OF ENERGY

Based on our expectations for module efficiency and cost in 2030, we calculate technical LCOE values (without taxes) for two locations, Southern France with an energy yield of 1,575 kWh/kWp/a and Northern Europe with 1,025 kWh/kWp/a,<sup>42</sup> see Table 3. For the calculation of LCOE for new plants, we use the net present value method to arrive at the ratio of the discounted lifecycle costs over the discounted lifetime energy generation of the plant.<sup>43</sup> We find ranges of LCOE values for both large- (1 MWp) and small-scale (100 kWp) PV installations, resulting from the different module cost and PCE input data as well as ranges of BOS costs that we obtain by applying a cost reduction methodology to 2050 as described in ref. [37]. The resulting CAPEX (i.e. sum of module and BOS costs) is found to be in close agreement to the estimated CAPEX in 2030 by IHS Markit.<sup>44</sup> A comparison with LCOE values from IHS Markit<sup>44</sup> shows good robustness of the results, given the difference in tax consideration. Note that the assumed module efficiencies of 22.2% and 25.2% correspond to cell efficiencies of 24 and 27%, respectively, based on CTM assumptions by ITRPV.<sup>11</sup>

Our main objective in calculating LCOE values is to determine the additional cost that can be allowed for 30% efficient tandem modules, compared to c-Si modules with efficiencies of 22.2% and 25.2%. For this, we use varied scenarios for obtaining the same LCOE values than

**TABLE 2** Bottom-up materials cost estimation for a 60-cell glass-backsheet monocrystalline silicon PERC module. Cost modelling is based on a Total-internal cost model as well as material costs data from PV Pulse<sup>40</sup>

	Q4/2018	2030 moderate scenario	2030 aggressive scenario
Wafer (2019 c\$/W)	7.0	4.2	2.9
Cell materials (2019 c\$/W)	2.7	1.5	1.1
Module materials (2019 c\$/W)	9.2	4.7	3.9
Total cost of materials (2019 c\$/W)	18.9	10.3	8.0



**TABLE 3** Expected technical (without taxes) LCOE values in 2030 for small- and large-scale PV systems in two different locations using an LCOE model developed within IPVF<sup>45</sup> and comparison with literature data (ref. [44], incl. taxes). WACC: Weighted average cost of capital. Key assumptions: Annual degradation 0.5%, lifetime 30 years

	Small-scale PV (size: 100kWp)	Large-scale PV (size: 1 MWp)
LCOE southern France 1,575 kWh/kWp/a (c\$/kWh)	10.4–11.1 (comparison value: 12.9, <sup>44</sup> )	2.8–3.3 (comparison value: 4.1, <sup>44</sup> )
LCOE northern Europe 1,025 kWh/kWp/a (c\$/kWh)	16.0–17.1 (comparison value: 16.2, <sup>44</sup> )	4.7–5.4 (comparison value: 7.1, <sup>44</sup> )
Module cost (c\$/W)	10/15	10/15
Module PCE (%)	22.2/25.2	22.2/25.2
WACC (real in %) <sup>44</sup>	6	4/5 (France/Sweden)
CAPEXcalculated (\$/kW)	1,590–1,690	500–580
OPEX (as % of CAPEX) <sup>43</sup>	2.5	2.5

c-Si modules in 2030 with a lifetime of 30 years and an annual degradation of 0.5%, values in accordance to those from ITRPV.<sup>11</sup> We investigate the influence of higher WACC rates, shorter lifetime and higher annual degradation rates of the tandem module on the tandem module cost bonus. Results for small- and large-scale systems located in outhern France are shown in Figure 4. Due to the higher relative BOS costs, effects on the tandem module costs are more pronounced for small-scale applications.

As a result, a cost bonus of up to 12c\$/W can be observed if the tandem module matches the c-Si module's lifetime and degradation rate, i.e. the tandem module cost can be 12 c\$/W higher than the cost of the 22.2% efficient c-Si module for achieving the same LCOE value. Naturally, this cost bonus decreases (and can also turn into a cost malus) with decreasing lifetime and increasing annual efficiency degradation of the system. The situation is generally worsened for large-scale PV installations with lower relative BOS costs and compared against a higher reference module efficiency of 25.2%.

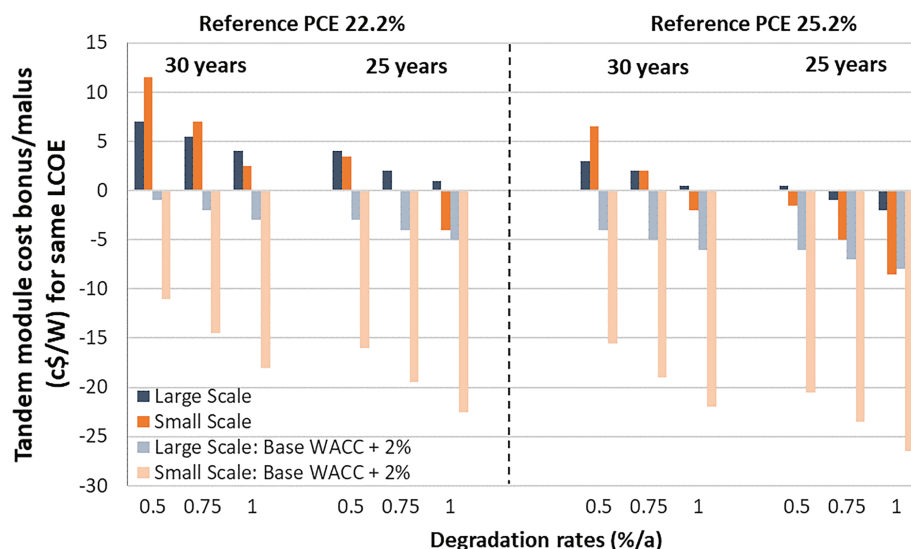
Our calculations emphasize as well the importance of achieving a high reliability of the tandem PV module: for a 30-year lifetime and low to moderate degradation rates of 0.5 or 0.75%/a, tandem modules have a cost bonus of 2 to 12 c\$/W, whereas for a reduced

lifetime of 25 years and a higher annual degradation of 1%, a malus of up to 9 c\$/W can be observed, i.e. such less reliable tandem module would need to have 9 c\$/W lower cost to achieve the same LCOE as the reference c-Si PV module.

Project financing, represented by the WACC rates, has an even more pronounced influence on the financial viability of using tandem modules, see Figure 4: At a WACC of +2% abs. compared to the calculation for c-Si modules, the tandem module cost bonus previously obtained using the same WACC turns into a malus, both for small- and large-scale PV projects and across all degradation rates. Thus, obtaining the same financing conditions for PV projects with tandem modules as for projects applying standard modules is therefore of utmost importance, highlighting the need for high lifetime and reliability of tandem modules in order to gain the same level of bankability as for c-Si modules.

## 7 | DISCUSSION AND CONCLUSIONS

Our results show that c-Si modules may reach a price of ca. 15 c\$/W or less in 2030, agreeing with expectations of other authors.<sup>36</sup> At that



**FIGURE 4** The tandem module cost that results in the same LCOE value that is achieved using a c-Si reference module depends both on the lifetime (30 vs. 25 years) and the annual PCE degradation (0.5%/a, 0.75%/a, 1%/a) of the system using tandem modules, as well as the reference module PCE (22.2% vs. 25.2%), but also strongly on the financing costs (WACC). Large- and small-scale PV installations differ in BOS costs and WACC rates. The lifetime of the reference module is 30 years, the annual system degradation 0.5%, the efficiency of the tandem module is 30% and the location southern France. Further details can be found in Table 3

time, module PCEs of 22–24% are expected to be standard in industrial production, possibly a maximum of ca. 25% if IBC-SHJ solar cells can be industrialized. Such modules are expected to have a lifetime of 30 years at an annual PCE degradation of 0.5%. Further efficiency increases of single-junction c-Si solar cells seem unlikely given their theoretical efficiency limit of 29.4%.

However, further cost reduction might be possible if novel module concepts with a different bill of materials (BOM) were introduced. To overcome the PCE limit of c-Si modules in production, perovskite on c-Si tandem modules currently seem to be the most promising candidate. For commercial relevance, it is expected that tandem cell and module efficiencies will need to be further increased to reach ca. 30% module PCE, and that such modules need to match lifetime and degradation rate of c-Si modules in order to gain bankability. These tandem modules could then have a cost bonus of around 5–10 c\$/W compared to c-Si modules in our example for an installation in Southern France in 2030 to reach equal LCOE values, i.e. the tandem module price could be around 20–25 c\$/W. If bankability remains lower than for standard modules, project financing conditions are not expected to be in favor of tandem modules which would have a cost malus in LCOE calculations, meaning that they would need to have even lower costs than c-Si modules.

For a market introduction of tandem PV modules, we can distinguish between two different cases: small-scale PV applications, in particular residential, and large-scale PV applications. The criteria that need to be met for a successful market introduction are different for the two cases. For residential applications, higher module efficiencies at comparable or better PV module lifetime and degradation rates are key, qualifying the tandem module as a premium product. Here, experience with current high-efficiency c-Si IBC and SHJ modules shows that customers may pay a “high-efficiency premium” module price that goes beyond the benefits of high-efficiency modules in LCOE calculations. For large-scale PV applications, bankability and LCOE advantage (which takes e.g. cost, efficiency, degradation and lifetime of the module into account) are the most important criteria. In both cases, tandem modules should come as a “plug-in” solution for conventional modules, i.e. they should not require modifications of existing BOS components. Note that module recyclability or other measures for waste reduction are mandatory requirements for all cases.

We anticipate that perovskite on c-Si tandem modules, which can build upon a > 100 GW c-Si module production base, might first be deployed in constrained area markets as a premium product, competing with SHJ and IBC premium c-Si modules. Such an introduction of the novel material perovskite in the PV market could then help in decreasing the hurdles for bankability associated with technology risks of novel materials. Note that there can also be specific incentives for the market introduction of a novel high-efficiency technology (such as China's Top Runner program currently<sup>46</sup>) that can facilitate gaining extended field experience to demonstrate module performance, and in particular reliability, for subsequent large-scale deployment.

Current and future work at IPVF therefore focuses on the development of low-cost, high-efficiency tandem modules mainly using perovskite on c-Si, but also alternative technologies based on

combinations with III-V materials.<sup>47</sup> While we have achieved first promising results for perovskite on c-Si tandem cells,<sup>48</sup> we are committed to demonstrate a tandem cell with a PCE of >30% that can be commercialized before 2030, with the help of national and international academic and industrial collaborations.

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## CONFLICT OF INTEREST

There are no conflicts to declare.

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