Received: 16 August 2022 | Revised: 28 November 2022 | Accepted: 12 February 2023
DOI: 10.1002/pip.3688

REVIEW

PROGRESS IN PHOTOVOLTAICS WILEY

Long-term performance and reliability of silicon heterojunction solar modules

Olatz Arriaga Arruti[1] | **Alessandro Virtuani**[1,2] | **Christophe Ballif**[1,2]

[1]École Polytechnique Fédérale de Lausanne (EPFL), Institute of Electrical and Microengineering (IEM), Photovoltaics and Thin Film Electronics Laboratory (PV-Lab), Neuchâtel, Switzerland

[2]Swiss Center for Electronics and Microtechnology (CSEM), SE-center, Neuchâtel, Switzerland

Correspondence
Olatz Arriaga Arruti, École Polytechnique Fédérale de Lausanne (EPFL), Institute of Electrical and Microengineering (IEM), Photovoltaics and Thin Film Electronics Laboratory (PV-Lab), 2000 Neuchâtel, Switzerland.
Email: olatz.arriagaarruti@epfl.ch

Funding information
GOPV Project, Grant/Award Number: 792059

Abstract

The high-efficiency silicon heterojunction (SHJ) technology is now perceived mature enough to enter the Giga-Watt manufacturing scale with several players around the globe. The growth of the SHJ technology requires confidence from manufacturers, investors, and system developers about its reliability and long-term performance. In this work, we perform a literature survey collecting performance data (and performance loss rates [PLRs]) published for SHJ modules. Publications on this specific subject are still limited; however, enough available data exist to drive some preliminary conclusions. Despite a long list of caveats specific to this type of meta-analysis, when considering all published datasets, we obtain for SHJ modules median and average PLR values of 0.56%/year and 0.70%/year, respectively. These numbers are in line with PLR generally reported for field-deployed crystalline silicon (c-Si modules). We then apply a filtering procedure to distinguish what we perceive to be high-accuracy datasets from less accurate ones. This methodology is understandably arbitrary, but it helps increasing the robustness of the present analysis. Our refined analysis leads us to slightly higher PLR for SHJ modules: 0.80%/year and 0.83%/year for median and average values, respectively. These values fall between previously reported PLR of c-Si and thin-film modules. Additionally, we observe some mild correlations between the PLRs and the climatic conditions of the installation sites, even if we need to stress that for each climate, we find a large variability, including a PLR value as low as 0.29%/year. We complement the survey with information about the main failure modes reported in the literature for this technology and an analysis of the limits and caveats for this type of study. The most significant one is that the reported numbers refer—for the vast majority—to modules from just one manufacturer (i.e., the first company manufacturing and commercializing the SHJ technology). We finally point out that a deep understanding of the potential weaknesses of the technology—collected over the years—has led to several improvements in terms of reliability. A careful material choice and module design may in fact allow the SHJ technology targeting extended service lifetimes of 35+ years.

KEYWORDS
degradation, performance, PLR, reliability, silicon heterojunction

1 | INTRODUCTION

The global solar photovoltaic (PV) industry has been growing exponentially over the last two decades. With a newly installed capacity of ~183 GW last year, the cumulative capacity has approached almost 1 TW worldwide by the first quarter of 2022.[1]

With a market share of approximately 95%, the dominant PV module technology is that based on crystalline silicon (c-Si) cells (with the remaining share covered by thin-film based technologies). Due to several factors, which include efficiency, costs, technology track record, availability of materials, and stability, the dominant role of c-Si solar cells and modules is deemed to continue.[2]

As a result of the relatively young age of existing PV installations, experience about their long-term performance is key to investors, project developers and plant owners. Nowadays, most PV manufacturers guarantee a linear power reduction, with a maximum loss of 16% to 20% after 25 years of operation. Nevertheless, studies have shown that PV modules can suffer from non-linear degradation losses or early life failure modes, such as potential-induced degradation (PID)[3] or other degradation modes. Therefore, a close monitoring of the performance of modules installed in the field is essential in studying their failure modes and, thus, in developing stable modules that can target 35+ years of active service lifetime.

Modules made with conventional c-Si PV cells (i.e., aluminum back-surface field [Al-BSF]) have been in the market for the longest time and have the longest track record. They are currently by far the leading solar cell technology, in terms of cumulative installations, but are about to be completely replaced by more sophisticated technologies, still based on c-Si wafer, that allow targeting higher efficiencies. This is the case of the passivated rear-emitter cell (PERC), which has become in the last 3–4 years the workhorse of the industry (see Figure 1). Other high-efficiency technologies, including silicon heterojunction (SHJ) and tunnel oxide passivated contact (TOPCon) solar cells, will compete in the coming years for increasing their market share. Noticeably with increased efficiency and reliance on surface passivation and higher bulk lifetime, these advanced cell technologies can easily become more prone to degradation.

Developed by Japanese manufacturers in the 1970s, SHJ solar cells are based on an n-type c-Si wafer, with doped amorphous silicon (a-Si:H) layers deposited on the top and bottom surfaces. A transparent conductive oxide (TCO) is used as a transparent electrode.[4] With record efficiencies of large 6″ cells of 26.81%,[5] they offer several advantages over conventional Al-BSF and high-efficiency (e.g., PERC) cells. The main benefits of the industrialization of SHJ solar cells are the shorter processing times and the reduction in the number of manufacturing steps, as well as the possibility to use a lower wafer thickness thanks to the ideally passivated surfaces, thus potentially lowering production costs and material consumption. Additionally, the passivating properties of the a-Si layer allow the achievement of higher open-circuit voltages (V_{OC}) (i.e., 751 mV for the SHJ record cell compared to 650 and 700 mV for Al-BSF and PERC solar cells, respectively[6]), and consequently, lower temperature coefficients of the power, which leads to increased energy yields particularly in hot climates. An additional advantage of using a TCO on both faces is that the cells are "naturally" bifacial, with potential bifaciality factor over 90% (compared to 70% of that of PERC solar cells).[7] This characteristic can potentially allow site-dependent (ground albedo, design of the mounting structures, etc.) energy-yield gains in the range of 10% to 20%.[8,9]

Besides the several advantages, some drawbacks are also associated to the SHJ technology. One of them is related to the string and cell's interconnection processes. The passivating a-Si layer should usually not be heated at temperatures exceeding 200°C to 220°C. Thus, SHJ cells can usually not be stringed using conventional high-temperature soldering, unless the process and soldering materials are adapted. One possible easier approach is to use electrically conductive adhesives (ECA), which have a high silver (Ag) content, to "glue" the ribbons to the cell's busbars. Moreover, the symmetrical stack structure implies printing a Ag grid on both sides of the cell. The consumption of Ag is, thus, higher for SHJ cells than for PERC or other technologies. The industry has been working on finding solutions to reduce Ag consumption by creating alternative interconnecting processes. These include using multi-wire (MWT) or SmartWire technologies (SWCT) or using copper-plated grids.[10] Another potential bottleneck towards a massive deployment of this solar cell technology in the coming decades is related to the availability of some key elements, such as indium (In).[11] Indium tin oxide (ITO) is, in fact, the most widely used and reliable material for TCOs. It is commonly used in the electronic industry, particularly for touch screens and large-area displays. Thus, efforts are also being made to overcome this potential constraint. Some groups use alternative TCOs, such as aluminum-doped zinc oxide (AZO),[12] and transparent conductive layers such as copper or carbon nanotube networks.[13,14] Alternative solutions aim to reduce the thickness of the ITO layer (using some capping layers based on silicon nitride [SiN_x]) or completely get rid of it.[15,16]

Presently, SHJ modules cover ~3% global market share but, thanks to their several advantages, and the number of players entering the market, this number could increase considerably in the coming years (~19% by 2032 [see Figure 1] according to ITRPV[2]). The SHJ solar cell/module technology is not a new one. The first SHJ cell (called HIT: heterojunction with intrinsic thin-layer) was patented by Sanyo (later Panasonic) in 1997.[17] This patent prevented other manufacturers from producing this solar cell structure; hence, its commercialization and deployment was limited to Sanyo/Panasonic for more than a decade. However, the patent that protected the HIT technology expired in 2010, allowing other players to potentially enter the

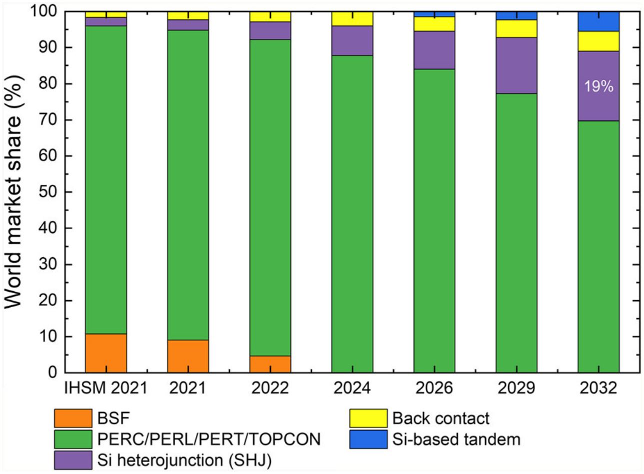

FIGURE 1 Projection of the world market share of different solar cell technologies over the next decade (*Source*: ITRPV2022): back-surface field (BSF), passivated rear-emitter cell (PERC), passivated rear-emitter locally diffused (PERL), passivated rear-emitter totally diffused (PERT), and tunnel oxide passivated contact (TOPCon). [Colour figure can be viewed at wileyonlinelibrary.com]

market and with different manufacturing processes. Consequently, R&D activities for this technology have experienced a significant growth over the last decade, leading to several initiatives of industrial players deciding to invest in it and announcements in 2021 and 2022 of capacity expansions targeting the Giga-Watt scale.

SHJ technology is key to boost the European PV market, and several companies in Europe have decided to proceed on to mass production. With a production capacity of 600 MW in Singapore, the REC Group has announced the addition of 600 MW more to their SHJ production line by the end of 2022.[18] Maxwell is their main equipment supplier for cell lines. Hevel Solar, one of the first companies to enter mass production, currently runs a 340 MW manufacturing line in Russia.[19] Additionally, Meyer Burger, who delivered several production lines, has now moved to solar cells and module production, focusing on SHJ with the SWCT technology in Germany.[20] Production of SHJ modules has started with a capacity of 400 MW per year, now in ramp up to 1.4 GW (with plans to expand to over 5 GW in the coming years). Similarly, 3SUN from Enel Green Power (EGP) has ramped a manufacturing line of SHJ cells/modules in Italy (200 MW) and targets capacity expansion plans to 3 GW of production in the coming years.[21]

Many manufacturers in Asia, particularly in China, have also taken steps to increase their production capacities. Companies such as GS-Solar, Huasun New Energy, and Akcome, with installed capacities of 500–600 MW, have announced expansion plants for the Giga-Watt scale.[22–24] Talesun also announced plans of building a 5 GW factory.[25]

The surge of the SHJ technology in the PV industry requires confidence from manufacturers, investors, and system developers about its reliability and long-term performance. With this aim in mind, in this work, we have been collecting data published over the last two decades (literature reporting degradation rates and performance indicators for SHJ modules). We have also gathered information about failure modes specific to this technology and ways of mitigating/preventing their occurrence.

2 | METHOD AND APPROACH

Recent evidence suggests that properly designed modules can reach service lifetimes of 25–30+ years.[26–28] A frequently used definition of lifetime for modules/systems refers to a threshold (power loss beyond a defined limit) corresponding to 80% of the initial nominal power of the device.

However, the lifetime is expected to depend on the operating conditions. In particular, it is strongly influenced by the general climatic conditions and the type of installation (e.g., open-rack mounting versus full building integration) that may affect the module ventilation and consequently impact the module's operating temperature.

Typical long-term annual degradation rates have been reported (from statistical analyses of data given in the literature) to be in the order of 0.5%/year to 1%/year for conventional c-Si modules and somewhat higher for thin-film modules.[29,30] Additionally, for simplicity, performance losses are generally assumed to follow a linear trajectory, even if this is not the case, particularly when the modules approach their end of life.[26,27] The most relevant ageing and failure mechanisms for c-Si modules that may arise in the early period (so-called "infant-life" failures), during the middle of the operating life, and at the wear out (end of life) include module delamination, glass breakage, encapsulant discoloration (or browning), corrosion of cell interconnects (and of anti-reflective layers), cell or ribbon breakage, and many others.

In addition to impacting the module performance, these failures can, in the worst cases, lead to safety hazards such as the loss of electrical insulation.

Unfortunately, inferring the service lifetime of PV modules exclusively based on stress tests performed in the laboratory is a complex task and often leads to unrealistic estimations. Monitoring and performance data of field-deployed modules (of the same make/typology) extending over a reasonable time horizon (understandably, the longer the extension of the time series, the better) should complement this information in order to get a realistic estimation of the service lifetime of these devices and increase market acceptance of a specific technology.

2.1 | Overview of studies reporting on SHJ technology

In this survey, we collected 54 data points originating from 14 different studies and various climates (see Table 1). Understandably, most entries are relative to the Sanyo/Panasonic's HIT technology, the first company to manufacture and commercialize the technology, and the only one for which a relatively long time series of field-deployed modules have been published. In Table 1, we can observe that most of the installations are less than 10 years old.

TABLE 1 Description of the datasets investigated in the survey: location, climate, installation year, years in operation, manufacturer, module structure (G/BS = glass/backsheet, G/G = glass/glass), and type of structure (BIPV = building integrated PV).

Institute	Location	Köppen climate classification	Installation year	Years in operation	Manufacturer	Module structure	Type of structure
AIST	Tsukuba, Japan[a31]	Cfa—Humid suptropical	2004	3	Sanyo/ Panasonic	G/BS	Ground
	Kyushu, Japan[a32]		2012	4			
ASU	Arizona, USA[33]	Bwh—Hot desert	2010	6	Unknown	-	-
EURAC	Bolzano, Italy[a34]	Cfb—Temperate oceanic	2010	6	Sanyo/ Panasonic	G/BS	Ground
	Nicosia, Cyprus[a34]	Bsh—Hot semi-arid	2006	8			
	Alice Springs, Australia[a34]	Bwh—Hot desert	2008	7			
	Milan, Italy[a34]	Cfa—Humid subtropical	2009	6			
	Catania, Italy[a34]	Csa—Hot-summer Mediterranean	2009	6			
Hevel Solar	Novocheboksarsk, Russia[a35]	Dfb—Warm-summer humid continental	2017	4.5	Hevel Solar	G/BS, G/G	Ground
NISE	Gurgaon, India[a36]	Bsh—Hot semi-arid	2009	2	Sanyo/ Panasonic	G/BS	Ground
	India (multiple locations)[37]	-	-	-	-	-	-
NREL	Colorado, USA[a38]	Bsk—Cold semi-arid	2006	10	Sanyo/ Panasonic	G/BS	Ground
	USA (multiple locations)[39]	-	-	6 (mean)	-	-	-
SERIS	Singapore[a40]	Af—Tropical rainforest	2010	9	Sanyo/ Panasonic	G/BS	Rooftop
SERT	Thailand[a41]	Aw—Tropical savanna	2012	4	Unknown	Unknown	Ground
SUPSI	Lugano, Switzerland[a42]	Cfb—Temperate oceanic	2016	4	Prototype	G/G	Ground and BIPV
TÜV Rheinland	Tempe, USA[a43]	Bwh—Hot desert	2016	2	Unknown	Unknown	Ground
	Chennai, India[a43]	Aw—Tropical savanna					
	Ancona, Italy[a43]	Cfa—Humid subtropical					
	Cologne, Germany[a43]	Cfb—Temperate oceanic					
ZHAW	Dietikon, Zurich, Switzerland[a44]	Cfb—Temperate oceanic	2009	10	Sanyo/ Panasonic	G/BS	Rooftop

Note: Where the symbol (-) is present, the module were installed in several different locations and no direct information is available.
[a]The works considered more accurate.

Several works have been published comparing the performance and performance loss rates (PLRs) of c-Si and thin-film technologies, highlighting the relevance of several factors in this kind of analysis.[30,45,46] A sound methodology is, in fact, a critical aspect in order to obtain reliable results in these types of studies. Each institute/group uses different set-ups and methodologies (including data processing, aggregation, and filtering) to assess the long-term performance of modules or strings. These factors can all play a significant role in the assessment of PLR. As a general rule, we consider current–voltage (*I*–*V*) measurements of individual modules performed regularly over time indoors as a more accurate method for this kind of analysis, compared to data obtained by outdoor monitoring systems (e.g., the performance ratio [PR]). However, for various reasons, including practicality, most of these data are usually obtained by analyzing time series of PR data. Conversely, several methods can be applied to improve the data accuracy and improve the accuracy of outdoor data. In this work, we label as high-accuracy datasets the ones that meet the following criteria:

- Indoor laboratory measurements of modules at Standard Test Conditions (STC):
  - Measurement of modules at STC taken before their installation, rather than using the nameplate rating (i.e., the value provided by the manufacturer) as the initial value, to avoid the underrating or overrating of initial power values.[47]
- In the case of outdoor performance measurements (when reported):
  - Available information on the periodic service and maintenance of the monitoring system (regular calibration and cleaning of radiometric and other sensors);

- Available information on proper data treatment and filtering (generally on the irradiance and module power and removal of outliers);
- The adoption of additional inspection methods, besides the determination of electrical parameters, for example, visual inspection and thermal imaging;
- A well-explained and thorough data treatment methodology.

Jordan et al. reported that degradation rates of modules could vary depending on location and mounting configurations.[30] They showed that modules installed in hotter climates, such as deserts, and those in array configurations leading to higher operating temperatures can suffer higher degradation rates. Temperate climates are generally characterized by more moderate temperature variations, with PV modules not suffering from extreme weather variations, thus subjecting them to lower stress conditions. Figure 2 provides an overview of the publications considered in this survey, granting information about field exposure time, publication year, and the installation location. In this work, the vast majority of the reported degradation rates refer to modules deployed in different countries worldwide (mainly in temperate and arid climates) for more than 4–5 years.

A more exhaustive discussion of the caveats of these types of surveys is performed in the following section.

2.2 | Caveats

As mentioned above, in general, this kind of survey comes with some limitations and caveats, which we briefly recall here.

1. High-accuracy (few) versus low-accuracy (for which no clear information about the methodologies or monitoring systems used is available) datasets are mixed.
2. Usually, module data (i.e., indoor laboratory measurements) are mixed with degradation rates of arrays/systems, for which the reported PLR may be partly due to performance degradation of other non-module components (e.g., inverter, cables, and connectors). Therefore, focusing on the arrays/system level (rather than just on module level) may introduce more significant uncertainty in the analysis, associated with resistive losses in the cables/connections or inverter losses.
3. Climatic conditions may have a substantial impact on PLRs, when the datasets are mixed together.
4. PLRs for the latest technologies are (understandably) not available, as a minimum temporal horizon of at least a few years is required for this kind of analysis.
5. Longer time series, for which it is possible to obtain more accurate and reliable information, may be obtained for older modules/technologies, not necessarily representative of the technologies available on the market today.
6. A linear degradation rate is generally assumed, which may be a good approximation in several cases, but not always. This kind of analysis generally assumes, for simplicity and sometimes as a reasonable approximation, constant degradation rates, corresponding to a linear loss in performance over time. In reality, particularly during the first months of field exposure and approaching end of life, or in the case of modules with serious performance issues due to specific failure modes, performance curves can follow non-linear trajectories.[26,46]

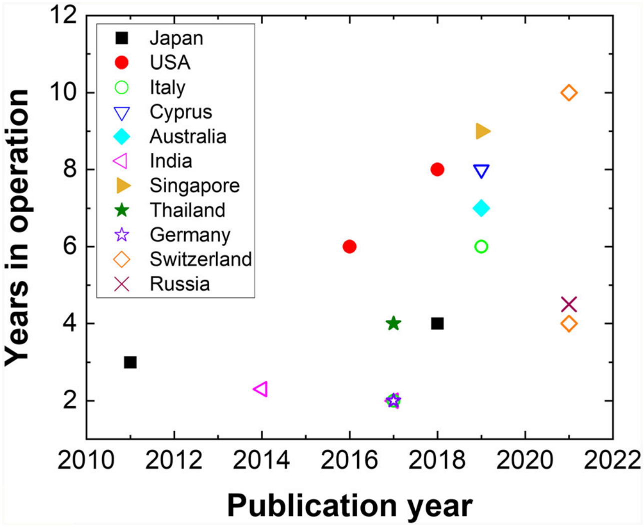

FIGURE 2 Overview of the publications considered in this survey, providing information about field exposure time, publication year, and color coded according to the country of installation. [Colour figure can be viewed at wileyonlinelibrary.com]

Additional caveats are specific to the technology investigated in this work (SHJ cells/modules). These include:

a. The vast majority of the PLR data reported in the literature for SHJ are relative to Sanyo/Panasonic's technology, which may differ in many respects from the technology developed/manufactured today by other SHJ players. These differences may be relative to the cells or the module structure.
   - Many SHJ modules entering the market today have a glass/glass (G/G) structure to benefit from the intrinsic bifaciality of SHJ cells. However, Sanyo/Panasonic modules have a more conventional glass/backsheet (G/BS) structure, even if it is highly probable that this manufacturer adopted—at least for a reasonable timespan—a backsheet containing a metal foil, used as a barrier to water/moisture ingress. Thus, this structure somehow resembles more that of a G/G module rather than that of a conventional G/BS one. Only recently, Panasonic has disclosed the module structure of their later products that are reportedly manufactured with a conventional and breathable backsheet as a rear cover using polyolefin (PO) and ethylene vinyl acetate (EVA), respectively, as the front- and rear-side encapsulants.[48]
   - Additionally, Sanyo/Panasonic has introduced several technological advancements for their cells over the years. Initially, their HIT cells had a front-emitter structure (with the p-doped a-Si:H layer at the front), but they reportedly changed their technology to rear-emitter around 2009.[48] Therefore, the performance of a 10- to 15-year-old module may not be necessarily

representative of a module manufactured today. The advantages of a rear- versus front-emitter structure are briefly recalled in Section 4.1.2.

b. Statistics (i.e., number of published works) and the temporal horizon (maximum 10–15 years) for SHJ devices are still limited. Therefore, the SHJ modules from other players presently entering the market may exhibit different long-term performances (and degradation modes) compared to the Sanyo/Panasonic technology for which most information is available today.

Despite these potential limitations, we believe that this analysis is strongly beneficial to better understand this technology's potential. In parallel, focusing on potential weaknesses and specific failure modes of SHJ modules and understanding the root causes behind, should promote overcoming these potential reliability issues.

3 | LITERATURE SURVEY

3.1 | All datasets

It would be meaningless to assess the degradation rates of SHJ modules without comparing them to technologies with a longer track record in the field. These would correspond to conventional c-Si and thin-film technologies. In 2013, Jordan and Kurtz reported degradation rates of 2000 c-Si modules installed worldwide.[29] They observed a median degradation rate of 0.5%/year for c-Si modules compared to 1.0%/year for thin-film modules. The reported PLRs on thin-film technologies are a mix of several of them (e.g., cadmium telluride [CdTe] and copper indium gallium selenide [CIGS]). Conversely, due to the age of the modules, the PLR for c-Si refer to mainly modules manufactured with conventional c-Si based on Al-BSF. In 2016, this work was further expanded by reporting more than 11,000 datasets on PV modules/systems in different countries.[30] Here, more mainstream technologies, such as PERC solar cells, were considered, SHJ solar cells included. Nevertheless, the mean PLRs for c-Si and thin-film technologies were very similar to the previous ones.

As previously mentioned, in this survey, we analyze 54 datasets from 14 different publications. Figure 3 shows (a) a histogram distribution of PLR (%/year) together with a Lorentz distribution curve and (b) a corresponding Pareto chart for the reviewed degradation rates. These charts provide an overview of all data points, including all climates and levels of dataset accuracy and entries from single modules or string/arrays. The median PLR for all the investigated modules is of 0.56%/year, with an average of 0.70%/year (please note that in our analysis, a positive value corresponds to performance degradation over time).

However, the "reliability" of the different works surveyed may sometimes be questionable. The direct comparison of PLR can be problematic because, as previously pointed out, monitoring equipment and practices and data analysis methodologies may vary considerably between research groups. In Section 2.2, we discuss the issues of considering constant degradation rates. In this literature survey, all analyzed contributions assumed a linear degradation trend. In a paper reporting about a 10-year-old SHJ system in Colorado, USA, the authors observed a non-linear performance loss trend.[38] Nonetheless, they also adopted a linear model to describe the degradation rate of the corresponding modules.

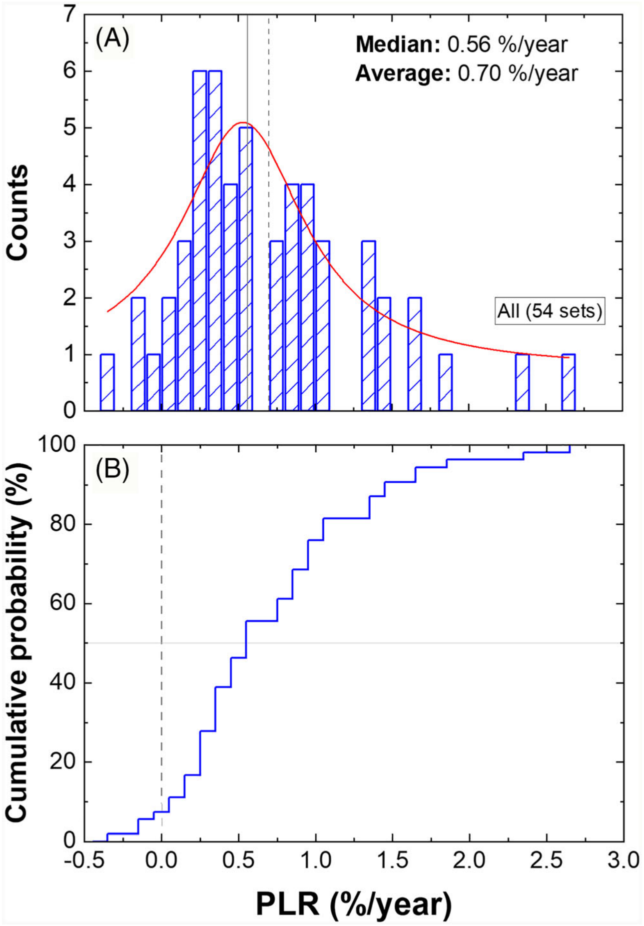

FIGURE 3 (a) Histogram of all 54 datasets investigated in this survey reporting the PLR for SHJ modules, fitted with a Lorentz distribution curve. Solid and dashed lines indicate the median and average values, respectively. (b) The corresponding Pareto chart, with the median PLR defined as 50% of the cumulative probability. In our analysis, a positive PLR corresponds to performance degradation over time. [Colour figure can be viewed at wileyonlinelibrary.com]

3.2 | High-accuracy datasets

In the following, we apply some filters to our analysis, preserving only the datasets that we perceive as more accurate or for which more information is made available by the authors. The applied filtering procedure is understandably arbitrary, but in our view, it helps in increasing the accuracy of the present analysis. The conditions that we apply to filter out what we perceive to be lower accuracy datasets are recalled in Section 2.1. For example, Raupp et al. reported degradation rates of PV systems installed in Arizona and Colorado.[33] However, no clear information about the individual PV systems or the corresponding operation and maintenance (O&M) practices are given. An additional dataset in this review pertains to a PV module reliability survey published in 2016 covering multiple installations in India.[37] Similarly, several degradation rates were reported in 2020 for plants distributed around the United States.[39] A clear description of the monitoring systems and the exact locations of the PV modules/systems studied are lacking in both reports, as well as specific information about the climatic conditions of the installations. Removing these datasets from the survey leads to an increased median and average degradation rates of 0.80%/year and 0.83%/year, respectively, for the SHJ technology. In the US survey, Jordan et al. stated that the low degradation rates with a median of 0.34%/year observed might be correlated to installations in colder climates. Thus, the median and average PLR reported in Figure 3 increase by removing these datasets. As observed in Figure 4, most PLR datasets are distributed in the 0.5%/year to 1.0%/year range.

In the following, focusing on the 19 filtered datasets, we attempt at observing if any particular correlation can be noticed between the absolute values of the PLR and the site-specific climatic conditions.

3.3 | The effect of climate

Several works reported the impact of climate on PLR, with—in general—systems installed in hotter climates experiencing higher degradation rates compared to those installed in temperate climates.[30] Moreover, humid climates may also impact modules' long-term performance by triggering specific degradation modes (e.g., delamination and acetic acid generation if EVA is used as an encapsulant or PID[49]).

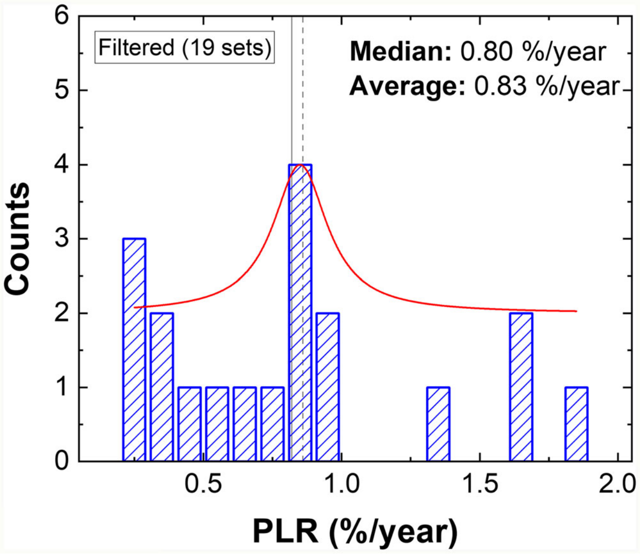

FIGURE 4 Histogram of 19 filtered "high-accuracy" datasets reporting PLR for SHJ solar modules. The filtered datasets discarded did not meet the conditions listed in Section 2.1. A Lorentz distribution curve has been applied to the histogram. Solid and dashed lines indicate the median and average values, respectively. [Colour figure can be viewed at wileyonlinelibrary.com]

The studies analyzed in this meta-analysis report data from a variety of climates. Here, we divide them according to the Köppen–Geiger classification (see Figure 5). A basic Köppen classification is applied in Figure 5a, classifying the different locations as dry, temperate and tropical (i.e., hot and humid) climates. In Figure 5b, more specific Köppen–Geiger sub-classifications are applied. Additionally, due to the specificity of the Mediterranean climate, we add it as a sub-class of the temperate climate.

A large variability is observed for all data groups, regardless of the climate. This may be possibly explained by two factors: the limited amount of data and, in some cases, the relatively short times of operation of the investigated systems. As a first approximation, and surprisingly, modules operating in temperate climates show the most significant median degradation rates of 0.87%/year, followed by arid (0.78%/year) and tropical climates (0.45%/year) and, finally, continental climates with the lowest median PLR of 0.29%/year.

With a median degradation rate of 0.78%/year, arid climates present a lower variability when sub-classified into hot-dry and cold-dry categories. PV systems/modules installed in cold-dry climates have a median degradation rate of 0.91%/year, higher than those in hot-dry climates, with 0.52%/year. Instead, the variability of the former is significantly lower. The performance monitoring of PV modules reported by Schweiger et al. in the dry-hot climate of Tempe (USA) shows a slight reduction in the power of the PV modules in the first 2 years (similarly to the ones observed in other locations), with a degradation rate of 0.35%/year.[43] In agreement with these findings, Sharma et al. reported a 0.36%/year loss for their PV array in India.[36] No visual defects were detected. Conversely, a performance loss of 1.66%/year, attributed to a significant encapsulant browning, was identified in modules installed in Alice Springs (Australia).[34]

Two publications report findings in dry-cold climates. Ingenhoven et al. reported 0.78%/year performance loss in Nicosia (Cyprus), without any apparent defects.[34] Similarly, in 2018 Jordan et al. published an exhaustive work on performance monitoring of a 10-year-old SHJ array in Colorado (USA).[38] A median degradation rate of 0.67%/year was observed, with the authors concluding that the system showed a similar trend to that of conventional c-Si systems. The performance loss was non-linear, but a linear behavior was assumed. In this latter work, the degradation was mainly attributed to a loss in V_{OC}, which may be compatible with a loss of the surface passivation properties of SHJ solar cells.

With a median degradation rate of 0.87%/year, PLR data from modules installed in temperate climates are the more abundant but also affected by the most significant spread. This number barely changes (i.e., to 0.85%/year) when removing the data points from Mediterranean climates. Ishii et al. reported performance monitoring data from SHJ modules installed in two different locations in Japan: Tsukuba[31] and Kyushu.[32] The performance degradation over 3 years of monitoring in the former was systematically lower than that reported for monocrystalline Si technologies, whereas a higher loss, that is, 0.8%/year, was observed in Kyushu compared to other c-Si technologies monitored in parallel. Also, in this work, the authors attributed the higher performance losses to a decrease in V_{OC}. In the

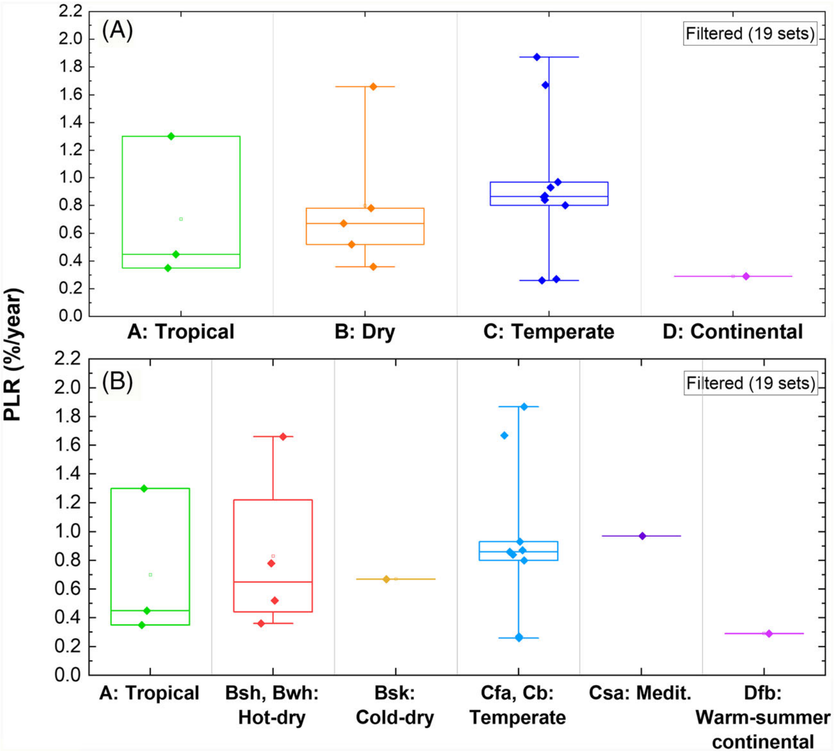

FIGURE 5 Distribution of the degradation rates (from the filtered datasets) by type of climate according to (a) the basic Köppen–Geiger classification (arid, temperate, tropical, and continental climates) and (b) more specific Köppen–Geiger sub-classifications dividing arid climates into hot-dry and cold-dry and general temperate into temperate and Mediterranean. [Colour figure can be viewed at wileyonlinelibrary.com]

survey published by Ingenhoven et al., the SHJ modules installed in temperate climates (Bolzano and Milan in Northern Italy) showed significantly different degradation trends.[34] Modules installed in Bolzano and monitored by EURAC suffered a performance loss of 0.86%/year, more in line with what was reported in other works. However, the modules in Milan showed a significantly higher degradation of 1.67%/year. Similarly to what was observed in Alice Springs, the high degradation rate was attributed to a considerable encapsulant browning. Conversely, performance monitoring of modules located in Cologne reported the same trend as those in Tempe, below 1%/year.[43] The PLRs of two experimental G/G SHJ modules installed in Lugano (Switzerland) showed a large variability.[42] This work reported results about two different mounting configurations: an open-rack and a fully integrated one, mimicking a building integrated PV (BIPV) installation. The PLRs for both G/G modules were significantly different. The module in the open-rack configuration degraded by 0.84%/year, while the BIPV module exhibited a more significant degradation of 1.87%/year over the 4 years of monitoring. Again, this high value was ascribed to a severe browning of the encapsulant material (likely worsened by the higher operating temperatures due to a reduced ventilation) rather than to degradation mechanisms specific to SHJ cells/modules. Finally, in 2021, Carigiet et al. published a study of degradation rates for SHJ modules installed in Zurich (Switzerland).[44] In this case, a detailed methodology was followed where the authors compared indoor measurements of modules to outdoor PR of strings. They reported that the average degradation rate of SHJ modules from indoor laboratory measurements was 0.26%/year, whereas PLR calculated from outdoor data were twice as high (0.52%/year). They attributed this mismatch to resistive losses in the cabling of the modules connected in the string. This showcases the importance of "high-accuracy" monitoring methodologies and the fact that degradation rates of modules or string/arrays may differ due to contributions in assessing the degradation rates from other non-module system components.

SHJ modules installed in hot-summer Mediterranean climates showed consistent degradation rates. In both publications, Ingenhoven et al. and Schweiger et al. reported PLRs just below 1%/year (i.e., 0.97%/year and 0.93%/year, respectively).[34,43] In principle, these PLRs, though limited to just a few entries, position the Mediterranean climate as the statistically most detrimental for the long-term performance of the SHJ modules considered in the study.

Three reported datasets were from modules installed in tropical (i.e., hot and humid) climates. PV modules installed in Thailand showed a degradation rate of 1.3%/year through 4 years of monitoring.[41] Conversely, monitoring modules in Singapore over 9 years lead to observed PLR of 0.45%/year.[40] In this latter case as well, a significant loss in V_{OC} was reported. Finally, Ingenhoven et al. reported a 0.35%/year loss rate in the tropical climate of Chennai (India), driven by a loss in V_{OC}.[34]

Only one dataset was present for a continental climate, coming from the region of Novocheboksarsk, Russia, and reported by Hevel Solar.[35] Two different set of module configurations were monitored: G/G and G/BS. Bifacial SHJ solar cells encapsulated in G/G module structure did not show any signs of degradation after 2 years of operation. Conversely, the same authors reported a median degradation rate of 0.29%/year for the monofacial SHJ G/BS modules. Similarly to other PERC modules being monitored in parallel, the degradation in these SHJ modules was caused by a reduction in short-circuit current (I_{SC}) (not in V_{OC} or FF), showing that a good module design can prevent V_{OC} degradation.

Unfortunately, the limited datasets for the different climatic conditions, often accompanied by the large spread in the data for a specific climate, make it difficult to drive any sharp conclusions looking at a correlation between PLR of SHJ modules and different climatic conditions. The following section further analyzes the failure modes of the PV modules/arrays studied in this survey.

4 | FAILURE MODULES AND POTENTIAL WEAKNESSES REPORTED FOR SHJ CELLS/MODULES

Identifying failure modes and weaknesses in the design of PV modules is critical in improving their reliability/durability and long-term performance. This can be done by carefully selecting the bill-of-material (BOM), reinforcing the packaging structure and optimizing the manufacturing processes and quality controls. Several authors have extensively researched the main failure modes of conventional c-Si modules, including Jordan et al.[46] and the 2015 IEA-PVPS Task 13[3] report. The authors found that, in conventional c-Si modules, one of the main parameters affected in the degradation kinetics is the I_{SC}. The loss in I_{SC} can be caused by several reasons, with one of the most common being a reduction of light absorption due to encapsulant discoloration. This is confirmed by Annigoni et al. reporting a significant encapsulant browning (and a striking correlation between the degree of browning and overall module performance) in a 35-year-old PV installation in Lugano, Switzerland.[27]

4.1 | Outdoor exposure (this survey)

4.1.1 | Encapsulant discoloration

In the articles surveyed in our analysis, several failure modes (specific or not specific to the technology) have been reported for SHJ modules. Ingenhoven et al. observed significant degradation rates (i.e., above 1%/year, higher than the median PLR reported) in SHJ modules installed in Alice Springs and Milan.[34] This was attributed to a significant encapsulant discoloration, causing I_{SC} losses. Similarly, modules installed in a BIPV system in Lugano also suffered from high degradation rates attributable—at least in part—to encapsulant browning. In these cases, the degradation mechanism is most likely related to a poor encapsulant selection rather than to a degradation mechanism peculiar to the SHJ technology. We similarly want to emphasize that the largest degradation rates reported in Figures 3a and 4 are correlated to encapsulant browning.

The very high PLRs might also be related to other degradation mechanisms occurring in parallel to browning. As an example, Wohlgemuth et al. observed delamination between the encapsulant and aluminum backsheet on Sanyo modules installed in the hot-dry climate of Tucson, Arizona.[50] These modules reportedly presented significant power losses, although it was unclear if directly linked to the delamination process.

4.1.2 | Loss of passivation

Conversely, a different degradation mechanism—allegedly specific to the SHJ technology—is reported for other systems and locations. Some authors reported an apparent V_{OC} loss, compatible with a loss of the surface passivation properties in the SHJ cells, as the main cause of degradation in SHJ modules. Luo et al. documented a substantial loss in V_{OC} in modules installed in tropical Singapore,[40] whereas Ishii et al. found similar behavior in the location of Kyushu, Japan.[32] Moreover, Schweiger et al. consistently observed a performance loss in SHJ modules with a continuous degradation in V_{OC} in several different climates.[43] In addition, the authors reported that this decrease did not show any signs of saturation. Jordan et al., finding a non-linear degradation trend for the SHJ modules installed in Colorado, dwelled more into the analysis by performing electroluminescence (EL), photoluminescence (PL), and dark I–V measurements, followed by microscopic analysis.[38,39] The authors found increased saturation currents at the module level, concluding that increased carrier recombination was the cause of the degradation. On the other hand, neither visual defects nor hot spots were observed. Microscopic analysis based on transmission electron microscopy (TEM) and dynamic secondary ion mass spectroscopy (d-SIMS) led them formulate the hypothesis that the passivation loss indicated by the reduction in V_{OC} could be caused by a reduction of the hydrogen content in the a-Si:H layers. Zhang et al. reported additional results obtained on the same samples,[51] attributing the cell degradation to a loss in passivation and to an increased presence of bulk defects. Nevertheless, the authors did not observe any specific indication of a deterioration of the a-Si:H layers.

For older SHJ modules (thus a considerable portion of the modules surveyed here), part of the reported loss of cell passivation properties, however, may be attributed to the use of front-emitter cell structures, a structure which is not allegedly used any longer today by SHJ cell manufacturers. Alternatively TCOs with lower density or active grain boundaries, which should be controlled during cell processing, can lead to enhance diffusion of ions.

In front-emitter cells, Cattin et al. reported the lack of stability (i.e., loss in V_{OC} and FF) when SHJ cells with very thin p-doped a-Si:H were exposed to light.[52] Using thicker (p) a-Si:H layers may overcome the problem, but increasing the absorption of light, thus reducing the overall efficiency of the cell. This p-layer problem is not critical for the rear-emitter cells, which have in fact demonstrated a higher stability in laboratory stress tests.

4.2 | Indoor accelerated ageing testing

Literature on indoor accelerated ageing tests is still limited and in the early stages when referring to SHJ cells and modules. All reported studies highlight the importance of a robust encapsulation and packaging structure to protect the active components of the module against ageing and weathering.

4.2.1 | Water/moisture ingress

In 2019, Park et al. reported the sensitivity to damp heat (DH) exposure of SHJ solar cells encapsulated in a G/G configuration.[53] This depended on the encapsulant used; they reported degradation on cells encapsulated with EVA and polyvinyl butyral (PVB). In both cases, the power loss was mainly driven by a loss in I_{SC}, with a less significant loss in FF and V_{OC} for modules encapsulated with PVB. Conversely, the adoption of polyolefin elastomer (POE) encapsulants, with a lower water vapor transmission rate (WVTR) and a lower water absorption, prevented this degradation from taking place. The observed degradation kinetics was much faster than the one observed in conventional c-Si solar cells encapsulated with EVA.[54,55] Production of acetic acid in PV modules usually takes around 2000–3000 h.[56,57] Therefore, the degradation in these SHJ-based modules is not caused by acetic acid, but it must be rooted by some different degradation mechanism, potentially water ingress.

Recent publications have also reported on DH-induced degradation on Cu-plated SHJ solar cells.[58] As we mentioned previously, the availability and cost of Ag can constitute a bottleneck for the mainstream adoption of SHJ solar cells in the industry. Therefore, this type of technology can be an effective alternative and assist on the efforts of commercializing SHJ-based PV modules. Karas et al. performed DH testing on SHJ solar cells encapsulated with EVA and POE in G/G and G/BS configurations. Similarly to what reported by Park et al., G/G modules encapsulated with EVA degraded the most, whereas the ones encapsulated with POE showed slower degradation kinetics. The degradation was driven by losses in V_{OC}, I_{SC}, and FF, caused by increased recombination and series resistance. The limited moisture ingress provided by the G/G configuration prevented part of the higher degradation observed in G/BS modules, driven by passivation losses. Thus, it emphasizes the sensitivity of SHJ solar cells to moisture ingress and to possible interaction with the encapsulant and other module/cell materials.

The effect of DH on industrial size SHJ solar cells was further studied by Liu et al.[59] The degradation of unencapsulated bare SHJ solar cells exposed to a hot and humid environment was attributed to the susceptibility of the a-Si:H/c-Si interface to moisture. Fourier-transform infrared spectroscopy (FTIR) measurements indicated the formation of silicon–oxygen (Si—O) bonds, suggesting the oxidation of the a-Si:H layers, with an impact on the passivating properties of these layers. In the same work, the authors proposed the application of capping layers made of SiN_x and silicon oxide (SiO_x) to the surface and the edges of the TCO layer, demonstrating the possibility to fabricate unencapsulated DH resistant solar cells.

4.2.2 | PID

Analogously, whereas PID on conventional c-Si cells and thin films is a relatively well-understood phenomenon, SHJ solar cells/modules have been believed for a long time not to suffer from exposure to high potential differences with respect to ground.[49,60] This is because the TCO capping the a-Si layers—generally an ITO layer—does avoid charges to accumulate at the encapsulant/TCO interface; this is an effect generally observed for conventional ARC layers with charges accumulating at the SiN_x layer when this layer is highly resistive. Nevertheless, recent works have reported the possibility of SHJ cells/modules to similarly suffer from PID, despite the kinetics seeming to be slower. Yamaguchi et al. reported PID on SHJ solar cells exposed to dry conditions—differing from the test conditions defined in the IEC 61215-2 standard,[61] that is, 60/85°C and 85% RH—and very high voltages (i.e., −2000 V) encapsulated in a G/BS configuration.[62] A clear two-step degradation mechanism was reported. In the first step, a loss of current due to the degradation of the TCO layer (a tungsten-doped [W-doped] IWO layer) was observed. After 30 days of the test (i.e., more than seven times the test duration defined in the IEC 61215), the reported mechanism changed, and a loss of passivation was also observed. They attributed this to the introduction of sodium ions (Na^+) into the solar cell, disrupting the a-Si:H/c-Si interface.

In more recent works, Arriaga Arruti et al. reported PID degradation in bifacial SHJ G/G mini-modules encapsulated using EVA when negatively biased with respect to the grounded frame.[63,64] The degradation was reportedly driven by a loss of passivation, followed by losses in I_{SC} and FF. The front- and rear-sides showed different degradation mechanisms. The authors performed scanning transmission electron microscopy (STEM) and energy-dispersive X-ray spectroscopy (EDX) on cross-sections of the module[65] and reported a diffusion of Na^+ ions into the ITO/a-Si:H interface. This caused a general passivation loss in the cell, witnessed by a reduction in V_{OC}. Additionally, it caused surface recombination at the front-side and an increased loss in FF at the rear-side, due to an increased recombination at the junction. Moreover, the authors reported solutions to improve reliability of SHJ modules, demonstrating that PID could be prevented using a robust encapsulating structure. This includes (1) the use of a high-volume resistivity encapsulant (e.g., ionomer and POE), which prevents the diffusion of Na^+ from the glass by minimizing leakage currents; alternatively (2) even using EVA (as said a non-optimal encapsulant due to its relatively low volume resistivity), by adopting an edge seal to prevent water ingress from the edges. Therefore, these results remark the great sensitivity of SHJ cells to the combination of moisture and module materials and the need for a robust module design.

4.2.3 | UV exposure

Studies about the impact of UV on the long-term performance of PV modules, particularly on modules encapsulated with EVA, have increased in recent years.[66–68] However, much research needs to be done on the effect of sunlight on novel solar cell architectures, particularly the SHJ technology. In 2020, Sinha et al. reported a higher UV-induced degradation (UV-ID) for high-efficiency technologies.[69] SHJ technologies, in particular, showed high sensitivity to UV-ID, with a higher susceptibility of the rear-side. Losses in FF and V_{OC} drove the degradation. This was attributed to an increased recombination current due to defect generation at the a-Si:H/c-Si interface. In further studies, the previous results were completed by performing X-ray photoelectron spectroscopy (XPS) measurements on the rear-side of the cell.[70] The authors reported a change in chemistry at the rear-side by the diffusion of Si towards the cell's surface and the formation of Si—O_x bonds.

Other works have reportedly attributed this UV-ID to the use of an inappropriately chosen encapsulant. Witteck et al. reported that the use of UV-transparent polymers could result in a module power loss on PERC solar cells (not SHJ cells) after UV irradiation exposure.[71] The effect of this degradation was an increased surface recombination, with a loss of passivating properties. The authors indicated that encapsulants with a UV cut-off of lower than 353 nm could cause Si—H bond breakage, compromising the passivation. Photons below a wavelength of 353 nm would have a high enough energy to break the Si—H bonds of 3.5 eV. Therefore, the authors stressed the fact that encapsulants with a UV cut-off higher than 353 nm (or non-UV-transparent encapsulants) should be used to ensure a good UV stability. Similarly, to protect SHJ cells from UV-ID, we highly suggest avoiding the adoption of UV-transparent polymers to encapsulate these cells. The possible use of down-converters (UV to visible), as reported by CIC and Maxwell, would also be a mitigation strategy against such phenomena.[72]

5 | DISCUSSION: TARGETING SERVICE LIFETIMES OF 35+ YEARS FOR SHJ MODULES

Currently, most manufacturers offer performance warranties of 25 years with a maximum power loss of 20% and a linear degradation over time. However, the industry, as a means of product differentiation, strives to increase the service lifetime of PV modules and systems. Thus, several companies are considering extending performance warranties to 30 or even 35+ years. This can prospectively be done by fully understanding the weaknesses of a specific module configuration and by taking steps towards improving them.

The comparison of the reported PLRs of the different solar cell technologies is presented in Figure 6. As mentioned above, for simplicity, studies reporting degradation rates often assume linear degradation curves. The degradation kinetics of SHJ technology, with median PLRs of 0.56%/year and 0.80%/year for all and for the high-accuracy datasets, respectively, position itself between previously reported degradation rates of conventional c-Si (i.e., 0.5%/year) and that of thin-film (i.e., 1.0%/year) technologies.[29]

A definition of lifetime is arbitrary, depending on the end application and the system used. A frequently used definition of lifetime for modules/systems refers to a threshold (power loss beyond a definite limit) corresponding to 80% of the initial nominal power of the device. Therefore, if we stick to this definition assuming a linear degradation rate and targeting an operational lifetime of 35 years, this would correspond to a maximum allowed degradation rate of 0.57%/year. This trajectory is shown in Figure 6—together with the trajectories for the degradation rates reported above. The mean PLR obtained for SHJ modules in our analysis (all data) is in line with this trajectory, consistent with a lifetime set at 35 years. Conversely, the PLR values (i.e., 0.80%/year) that we obtain when filtering out datasets that we do not perceive as highly accurate are slightly higher. All efforts for an improved SHJ cell and module reliability should be directed to target this goal, which seems to be within reach (particularly if we understand well the root causes of technology-specific failure modes). Understandably, in order to do this, further investigations and R&D activities are needed.

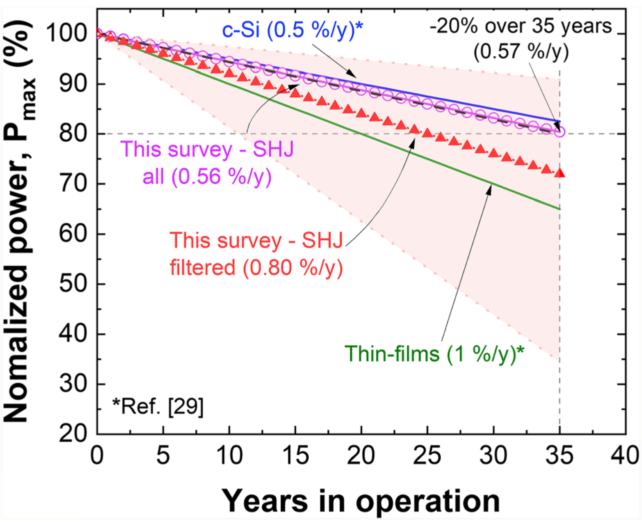

FIGURE 6 Performance loss curves—assuming a linear degradation at constant degradation rate—using the PLRs obtained in the survey for median degradation rates analyzed in this survey, for all datasets (purple) and for the selected ones (red). These trajectories fall in-between the boundaries reported in the literature for more mature solar cell technologies, that is, conventional c-Si (blue solid line) and thin films (green solid line).[29] The performance loss curves corresponding to the maximum and minimum PLRs reported in this survey are indicated in dashed red lines, and the area between them (light red) indicates the variability in degradation rates observed in this meta-analysis. A black dashed line has been added to the chart: This trajectory corresponds to a PLR of 0.57%/year, consistent to a 20% module power loss after 35 years in operation. [Colour figure can be viewed at wileyonlinelibrary.com]

In this work, we have reported the main failure modes observed for SHJ modules. These include, for field-deployed modules, V_{OC} losses ascribed to a loss of the passivating properties of the a-Si layers and I_{SC} degradation from absorption losses due to encapsulant browning.[34,38] On the other hand, indoor accelerated ageing tests highlight the sensitivity of SHJ solar cells to water/moisture ingress, high voltages, and UV exposure. The former can realistically be associated to losses in passivation properties observed in several studies.[58,65] Additionally, we discussed the effect of UV irradiation on the encapsulants and SHJ solar cells. A poor encapsulant selection may result in both polymer discoloration, such as the browning reported in this survey, and degradation of the passivating properties of the SHJ cells if an encapsulant with a low UV cut-off is used.

However, most of these studies suggest ways to reinforce the module structure making SHJ prospectively more reliable and highlighting the importance of understanding the physics behind the observed degradation mode. These strategies include:

a. The adoption of encapsulants with a low WVTR and water absorption (e.g., POs) to minimize water ingress. Alternatively, in G/G structures, the use of an edge seal in combination with a mainstream encapsulant such as EVA has been demonstrated to protect the modules from moisture and to degradation modes associated to water ingress.
b. The adoption of high-volume resistivity encapsulants (such as POs) to prevent diffusion of Na^+ ions (and leakage currents) when a high voltage potential is applied between the SHJ solar cells and the grounded module frame, preventing PID. Additionally, as we have seen that Na^+ migration can also impact on the passivation, we also expect that the nature of the front and back TCOs plays a role in promoting or slowing some of the degradation mechanisms. This can be strongly linked to the materials and processing parameters used in the cell fabrication.
c. UV-ID can be prevented by using encapsulants that are not transparent to UV or polymers with a UV cut-off higher than 353 nm to prevent Si—H bond breakage. The use of down-converters to convert UV to blue/visible light would also be a potentially effective approach to prevent UV-ID.
d. The approach of using a rear-emitter solar cell architecture in place of a front-emitter one, to prevent losses in the cell passivation properties upon exposure to light (when an insufficiently thick front (p) a-Si:H is used).

In conclusion, a deep understanding of the root cause specific to the failure modes of SHJ cells/modules is required to find solutions. Apparently, strategies to overcome these limitations exist and may transform a service lifetime of 35 years for SHJ modules into a realistic target.

6 | CONCLUSIONS

We have performed a literature survey on the reliability and long-term performance of SHJ modules installed in the field. Understandably, most (but not all) of the datasets reviewed in this survey refer to the HIT technology from Sanyo/Panasonic, the first company to manufacture and commercialize this technology. However, accessing statistically reliable data can be a point of concern. We therefore analyze the caveats particular to this type of survey, such as the mix of high- and low-accuracy datasets, the combination of degradation rates for both modules and array/systems others. Further, we highlight the limits of the transferability of the observed results to SHJ modules of other manufacturers with different cell types and module structures (e.g., glass/foil vs. G/G).

From this survey (54 datasets from 14 publications), we obtain for SHJ modules median and average PLR of 0.56%/year and 0.70%/year, respectively. These numbers are absolutely in line with PLR generally reported for field-deployed c-Si modules.

We then filter out datasets that we perceive as less accurate (because of the lack of clear information about the monitoring systems, practices, or methodology used) and obtain slightly higher PLR values for SHJ modules: 0.80%/year and 0.83%/year for median and average values, respectively. As reported by several authors, these numbers fall between PLR of c-Si and thin-film modules.

In addition, some mild correlations of PLR to the different climates of the installations have been noticed, but current available data on outdoor performance of SHJ-based modules is still scarce. We find a considerable variability for each climate, particularly in temperate climates. Not without surprise, we observe that statistically, the highest median PLR corresponds to modules installed in these climates. Surprisingly, data points reported from arid and tropical climates, subjected to harsher environmental conditions, show lower PLR values. Still, these preliminary correlations may be due to the limited numbers of the studies surveyed in this work. Further investigations are therefore required to obtain a higher degree of confidence in the observed correlations.

Moreover, we also report that, conversely to what generally happens to more conventional c-Si technologies deployed in the field for several years, many SHJ modules present performance losses caused by the degradation of the V_{OC}, which can be attributed to a loss in passivating properties of the a-Si layers. Furthermore, the literature survey points out that most of the modules experiencing higher degradation rates (>1%/year) suffered (possibly in combination with other degradation modes) from encapsulant discoloration. Although this failure mode is not intrinsic to the SHJ technology, a correct selection of the encapsulant and its resistance against long-term photo-degradation (induced by combined exposure to UV, humidity, and heat) is critical in guaranteeing the performance of the module over time.

ACKNOWLEDGEMENTS

The authors would like to thank Antonin Faes and Jun Zhao for fruitful discussions. This work was supported by the GOPV Project that has received funding from the European Union's Horizon 2020 research and innovation program under Grant 792059. Open access funding provided by Ecole Polytechnique Federale de Lausanne.

CONFLICT OF INTEREST

There are no conflicts to declare.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID

Alessandro Virtuani https://orcid.org/0000-0001-5523-5200

REFERENCES

1. Weaver JF. World has installed 1TW of solar capacity. *PV Magazine*. March 15, 2022; [Online]. Available: https://www.pv-magazine.com/2022/03/15/humans-have-installed-1-terawatt-of-solar-capacity/#:~:text=The%20world%20has%20very%20recently,at%20the%20end%20of%202020
2. ITRPV. *International Technology Roadmap for Photovoltaic—Results 2021*. ITRPV; 2022.
3. IEA. Review of failures of photovoltaic modules—report IEA-PVPS T13-01: 2014. 2014.

4. Wolf SD, Descoeudres A, Holman ZC, Ballif C. High-efficiency silicon heterojunction solar cells: a review. *Green*. 2012;2(1):7-24. doi:10.1515/green-2011-0018
5. LONGi. At 26.81%, LONGi sets a new world record efficiency for silicon solar cells. 2022. https://www.longi.com/en/news/propelling-the-transformation/
6. Green MA, Dunlop ED, Hohl-Ebinger J, Yoshita M, Kopidakis N, Hao X. Solar cell efficiency tables (Version 58). *Prog Photovolt Res Appl*. 2021;29(7):657-667. doi:10.1002/pip.3444
7. Deline C, Ayala Peláez S, Marion B, Sekulic B, Stein J. Understanding bifacial photovoltaic potential: field performance. Presented at the Taiyang News Webinar. 2019.
8. Yin HP, Zhou YF, Sun SL, et al. Optical enhanced effects on the electrical performance and energy yield of bifacial PV modules. *Sol Energy*. 2021;217:245-252. doi:10.1016/j.solener.2021.02.004
9. Wang L, Tang Y, Zhang S, Wang F, Wang J. Energy yield analysis of different bifacial PV (photovoltaic) technologies: TOPCon, HJT, PERC in Hainan. *Sol Energy*. 2022;238:258-263. doi:10.1016/j.solener.2022.03.038
10. Lachowicz A, Wyss P, Geissbühler J, et al. Review on plating processes for silicon heterojunction cells. Presented at the 8th Workshop on Metallization on Interconnection, Constance. 2019.
11. U.S. Geological Survey. *Mineral Commodity Summaries 2022*. Vol. 2022. U.S. Geological Survey; 2022. doi:10.3133/mcs2022
12. Wu Z, Duan W, Lambertz A, et al. Low-resistivity p-type a-Si:H/AZO hole contact in high-efficiency silicon heterojunction solar cells. *Appl Surf Sci*. 2021;542:148749. doi:10.1016/j.apsusc.2020.148749
13. Won Y, Kim A, Lee D, et al. Annealing-free fabrication of highly oxidation-resistive copper nanowire composite conductors for photovoltaics. *NPG Asia Mater*. 2014;6(6):e105. doi:10.1038/am.2014.36
14. Tune DD, Mallik N, Fornasier H, Flavel BS. Breakthrough carbon nanotube–silicon heterojunction solar cells. *Adv Energy Mater*. 2020;10(1):1903261. doi:10.1002/aenm.201903261
15. Morales-Vilches AB, Cruz A, Pingel S, et al. ITO-free silicon heterojunction solar cells with ZnO:Al/SiO_2 front electrodes reaching a conversion efficiency of 23%. *IEEE J Photovolt*. 2019;9(1):34-39. doi:10.1109/JPHOTOV.2018.2873307
16. Niemelä J-P, Macco B, Barraud L. Rear-emitter silicon heterojunction solar cells with atomic layer deposited ZnO:Al serving as an alternative transparent conducting oxide to In_2O_3:Sn. *Sol Energy Mater Sol Cells*. 2019;200:109953. doi:10.1016/j.solmat.2019.109953
17. Panasonic. *Panasonic HIT Sanyo History*. EU Solar Panasonic. https://eu-solar.panasonic.net/en/panasonic-hit-sanyo-history.htm
18. Scully J. REC group scaling up HJT module production in Singapore with new launch. *PV Tech*. August 6, 2022;
19. Bellini E. Hevel Solar unveils 22.3%-efficient heterojunction BIPV module. *PV Magazine*. April 23, 2022;
20. Jacobo JT. Meyer Burger optimising production expansion to 1.4 GW in Germany to cater for European demand. *PV Tech*. April 29, 2022;
21. Bellini E. Enel, European Commission sign grant agreement for 3 GW Italian module factory. *PV Magazine*. April 1, 2022;
22. Nair M, GS-Solar to build 10 GW HJT production line; 2nd phase of JA Solar 20 GW monocrystal production line begins; DZS & Trina Win China Energy 250 MW PV modules bid; solar, wind and hydro power increase significantly In Oct: NDRC, Taiyang News, November 23, 2020.
23. Bellini E. Huasun achieves 25.26% efficiency for heterojunction solar cell. *PV Magazine*. July 13, 2021;
24. Shaw V, Hall M. Chinese PV Industry Brief: China's NEA predicts 108 GW of solar in 2022. *PV Magazine*. May 31, 2022;
25. Shaw V. Chinese PV Industry Brief: Talesun plans 5GW heterojunction PV module factory. *PV Magazine*. March 25, 2022;
26. Virtuani A, Caccivio M, Annigoni E, et al. 35 years of photovoltaics: Analysis of the TISO-10-kW solar plant, lessons learnt in safety and performance—Part 1. *Prog Photovolt Res Appl*. 2019;27(4):328-339. doi:10.1002/pip.3104
27. Annigoni E, Virtuani A, Caccivio M, Friesen G, Chianese D, Ballif C. 35 years of photovoltaics: Analysis of the TISO-10-kW solar plant, lessons learnt in safety and performance—Part 2. *Prog Photovolt Res Appl*. 2019;27(9):760-778. doi:10.1002/pip.3146
28. Skoczek A, Sample T, Dunlop ED. The results of performance measurements of field-aged crystalline silicon photovoltaic modules. *Prog Photovolt Res Appl*. 2009;17(4):227-240. doi:10.1002/pip.874
29. Jordan DC, Kurtz SR. Photovoltaic Degradation Rates-an Analytical Review. *Prog Photovolt Res Appl*. 2013;21(1):12-29. doi:10.1002/pip.1182
30. Jordan DC, Kurtz SR, VanSant K, Newmiller J. Compendium of photovoltaic degradation rates. *Prog Photovolt Res Appl*. 2016;24(7):978-989. doi:10.1002/pip.2744
31. Ishii T, Takashima T, Otani K. Long-term performance degradation of various kinds of photovoltaic modules under moderate climatic conditions. *Prog. Photovolt. Res. Appl.* 2011;19(2):170-179. doi:10.1002/pip.1005
32. Ishii T, Choi S, Sato R, Chiba Y, Masuda A. Annual degradation rates of recent c-Si PV modules under subtropical coastal climate conditions. In: *2018 IEEE 7th World Conference on Photovoltaic Energy Conversion (WCPEC) (A Joint Conference of 45th IEEE PVSC, 28th PVSEC & 34th EU PVSEC), Waikoloa Village, HI*. IEEE; 2018:705-708. doi:10.1109/PVSC.2018.8548088
33. Raupp C, Libby C, Tatapudi S, et al. Degradation rate evaluation of multiple PV technologies from 59,000 modules representing 252,000 modules in four climatic regions of the United States. In: *2016 IEEE 43rd Photovoltaic Specialists Conference (PVSC), Portland, OR, USA*. IEEE; 2016:0255-0260. doi:10.1109/PVSC.2016.7749590
34. Ingenhoven P, Belluardo G, Makrides G, et al. Analysis of photovoltaic performance loss rates of six module types in five geographical locations. *IEEE J Photovolt*. 2019;9(4):1091-1096. doi:10.1109/JPHOTOV.2019.2913342
35. Hevel Solar. Silicon heterojunction solar modules - field performance and long-term reliability testing. Presented at the 4th International Workshop on Silicon Heterojunction Solar Cells. 2021.
36. Sharma V, Sastry OS, Kumar A, Bora B, Chandel SS. Degradation analysis of a-Si, (HIT) hetro-junction intrinsic thin layer silicon and m-C-Si solar photovoltaic technologies under outdoor conditions. *Energy*. 2014;72:536-546. doi:10.1016/j.energy.2014.05.078
37. National Institute of Solar Energy (NISE). *All-India Survey of Photovoltaic Module Reliability: 2018*. National Centre for Photovoltaic Research and Education (NCPRE); 2019.
38. Jordan DC, Deline C, Johnston S, et al. Silicon heterojunction system field performance. *IEEE J Photovolt*. 2018;8(1):177-182. doi:10.1109/JPHOTOV.2017.2765680
39. Jordan DC, Sulas-Kern DB, Johnston S. High efficiency module degradation—from atoms to systems. In: *37th European Photovoltaic Solar Energy Conference and Exhibition*, Lisbon, Portugal. EU PVSEC Proceedings; 2020:828-833. doi:10.4229/EUPVSEC20202020-4BO.14.2
40. Luo W, Khoo YS, Hacke P, et al. Analysis of the long-term performance degradation of crystalline silicon photovoltaic modules in tropical climates. *IEEE J Photovolt*. 2019;9(1):266-271. doi:10.1109/JPHOTOV.2018.2877007
41. Limmanee A, Songtrai S, Udomdachanut N, et al. Degradation analysis of photovoltaic modules under tropical climatic conditions and its impacts on LCOE. *Renew Energy*. 2017;102:199-204. doi:10.1016/j.renene.2016.10.052
42. Ozkalay E, Friesen G, Caccivio M, et al. Operating temperatures and diurnal temperature variations of modules installed in open-rack and typical BIPV configurations. *IEEE J Photovolt*. 2022;12(1):133-140. doi:10.1109/JPHOTOV.2021.3114988

43. Schweiger M, Bonilla J, Herrmann W, Gerber A, Rau U. Performance stability of photovoltaic modules in different climates. *Prog Photovolt Res Appl*. 2017;25(12):968-981. doi:10.1002/pip.2904
44. Carigiet F, Brabec CJ, Baumgartner FP. Long-term power degradation analysis of crystalline silicon PV modules using indoor and outdoor measurement techniques. *Renew Sustain Energy Rev*. 2021;144:111005. doi:10.1016/j.rser.2021.111005
45. Jordan DC, Silverman TJ, Wohlgemuth JH, Kurtz SR, VanSant KT. Photovoltaic failure and degradation modes. *Prog Photovolt Res Appl*. 2017;25(4):318-326. doi:10.1002/pip.2866
46. Jordan DC, Silverman TJ, Sekulic B, Kurtz SR. PV degradation curves: non-linearities and failure modes. *Prog Photovolt Res Appl*. 2017;25(7):583-591. doi:10.1002/pip.2835
47. Lopez-Garcia J, Sample T. Evolution of measured module characteristics versus labelled module characteristics of crystalline silicon based PV modules. *Sol. Energy*. 2018;160:252-259. doi:10.1016/j.solener.2017.12.018
48. Taguchi M, Irikawa J, Iwata M, Kannou H, Murakami Y, Okamoto S. Approaches to the long-term stability of silicon heterojunction modules. Presented at the 4th International Workshop on Silicon Heterojunction Solar Cells. 2021.
49. Virtuani A, Annigoni E, Ballif C. One-type-fits-all-systems: strategies for preventing potential-induced degradation in crystalline silicon solar photovoltaic modules. *Prog Photovolt Res Appl*. 2019;27(1):13-21. doi:10.1002/pip.3066
50. Wohlgemuth JH, Hacke P, Bosco N, Miller DC, Kempe MD, Kurtz SR. Assessing the causes of encapsulant delamination in PV modules. In: *2016 IEEE 43rd Photovoltaic Specialists Conference (PVSC), Portland, OR, USA*. IEEE; 2016:0248-0254. doi:10.1109/PVSC.2016.7749589
51. Zhang SM, Sulas-Kern DB, Chin RL, et al. Investigation of SHJ module degradation: a post-mortem approach. In: *2020 47th IEEE Photovoltaic Specialists Conference (PVSC), Calgary, AB, Canada*. IEEE; 2020:0814-0817. doi:10.1109/PVSC45281.2020.9300728
52. Cattin J, Senaud LL, Haschke J, et al. Influence of light soaking on silicon heterojunction solar cells with various architectures. *IEEE J Photovolt*. 2021;11(3):575-583. doi:10.1109/JPHOTOV.2021.3065537
53. Park H, Jeong J, Shin E, Kim S, Yi J. A reliability study of silicon heterojunction photovoltaic modules exposed to damp heat testing. *Microelectron Eng*. 2019;216:111081. doi:10.1016/j.mee.2019.111081
54. Wohlgemuth JH, Kempe MD. Equating damp heat testing with field failures of PV modules. In: *2013 IEEE 39th Photovoltaic Specialists Conference (PVSC), Tampa, FL, USA*. IEEE; 2013:0126-0131. doi:10.1109/PVSC.2013.6744113
55. Zhu J, Koehl M, Hoffmann S, et al. Changes of solar cell parameters during damp-heat exposure. *Prog Photovolt Res Appl*. 2016;24(10):1346-1358. doi:10.1002/pip.2793
56. Zhu J, Montiel-Chicharro D, Betts TR, Gottschalg R. Correlation of degree of EVA crosslinking with formation and discharge of acetic acid in PV modules. In: *33rd European Photovoltaic Solar Energy Conference and Exhibition*, Amsterdam, The Netherlands. WIP; 2017:1795-1798. doi:10.4229/EUPVSEC20172017-5DV.3.21
57. Masuda A, Uchiyama N, Hara Y. Degradation by acetic acid for crystalline Si photovoltaic modules. *Jpn J Appl Phys*. 2015;54(4S):04DR04. doi:10.7567/jjap.54.04dr04
58. Karas J, Sinha A, Buddha VSP, et al. Damp heat induced degradation of silicon heterojunction solar cells with Cu-plated contacts. *IEEE J Photovolt*. 2020;10(1):153-158. doi:10.1109/JPHOTOV.2019.2941693
59. Liu W, Zhang L, Yang X, et al. Damp-heat-stable, high-efficiency, industrial-size silicon heterojunction solar cells. *Joule*. 2020;4(4):913-927. doi:10.1016/j.joule.2020.03.003
60. Luo W, Khoo YS, Hacke P, et al. Potential-induced degradation in photovoltaic modules: a critical review. *Energ Environ Sci*. 2017;10(1):43-68. doi:10.1039/C6EE02271E
61. International Electrotechnical Commission. *IEC 61215-2: Terrestrial Photovoltaic (PV) Modules—Design Qualification and Type Approval—Part 2: Test Procedures*. International Electrotechnical Commission; 2021.
62. Yamaguchi S, Yamamoto C, Ohshita Y, Ohdaira K, Masuda A. Influence of emitter position of silicon heterojunction photovoltaic solar cell modules on their potential-induced degradation behaviors. *Sol Energy Mater Sol Cells*. 2020;216:110716. doi:10.1016/j.solmat.2020.110716
63. Arriaga Arruti O, Gnocchi L, Lisco F, Virtuani A, Ballif C. Optimized module packaging for silicon heterojunction solar cells and increased PID resistance. In: *37th European Photovoltaic Solar Energy Conference and Exhibition*, Lisbon, Portugal. EU PVSEC Proceedings; 2020:789-791. doi:10.4229/EUPVSEC20202020-4BO.12.2
64. Arriaga Arruti O, Gnocchi L, Virtuani A, Ballif C. Encapsulant selection for PID resistant modules made with heterojunction solar cells. In: *37th European Photovoltaic Solar Energy Conference and Exhibition*, Lisbon, Portugal. EU PVSEC Proceedings; 2020:974-977. doi:10.4229/EUPVSEC20202020-4AV.1.8
65. Arriaga Arruti O, Gnocchi L, Jeangros Q, Virtuani A, Ballif C. Potential induced degradation mechanism in rear-emitter bifacial silicon heterojunction solar cells encapsulated in different module structures. In: *2021 IEEE 48th Photovoltaic Specialists Conference (PVSC), Fort Lauderdale, FL, USA*. IEEE; Jun. 2021:2032-2036. doi:10.1109/PVSC43889.2021.9518967
66. Barretta C, Oreski G, Feldbacher S, Resch-Fauster K, Pantani R. Comparison of degradation behavior of newly developed encapsulation materials for photovoltaic applications under different artificial ageing tests. *Polymers*. 2021;13(2):271. doi:10.3390/polym13020271
67. Sharma BK, Desai U, Singh A, Singh A. Effect of vinyl acetate content on the photovoltaic-encapsulation performance of ethylene vinyl acetate under accelerated ultra-violet aging. *J Appl Polym Sci*. 2020;137(2):48268. doi:10.1002/app.48268
68. Jentsch A, Eichhorn K-J, Voit B. Influence of typical stabilizers on the aging behavior of EVA foils for photovoltaic applications during artificial UV-weathering. *Polym Test*. 2015;44:242-247. doi:10.1016/j.polymertesting.2015.03.022
69. Sinha A, Qian J, Hurst K, et al. UV-induced degradation of high-efficiency solar cells with different architectures. In: *2020 47th IEEE Photovoltaic Specialists Conference (PVSC), Calgary, AB, Canada*. IEEE; 2020:1990-1991. doi:10.1109/PVSC45281.2020.9300993
70. Sinha A, Hurst K, Ulicna S, Schelhas LT, Miller DC, Hacke P. Assessing UV-induced degradation in bifacial modules of different cell technologies. In: *2021 IEEE 48th Photovoltaic Specialists Conference (PVSC), Fort Lauderdale, FL, USA*. IEEE; 2021:0767-0770. doi:10.1109/PVSC43889.2021.9518728
71. Witteck R, Veith-Wolf B, Schulte-Huxel H, et al. UV-induced degradation of PERC solar modules with UV-transparent encapsulation materials. *Prog Photovolt Res Appl*. 2017;25(6):409-416. doi:10.1002/pip.2861
72. Scully J. Maxwell, Cybrid use light conversion film to boost HJT module power output. *PV Tech*. April 20, 2022;

How to cite this article: Arriaga Arruti O, Virtuani A, Ballif C. Long-term performance and reliability of silicon heterojunction solar modules. *Prog Photovolt Res Appl*. 2023;1-14. doi:10.1002/pip.3688