Technological Feasibility Indicator Of Photovoltaic Cells For Tropical Climates: An Analysis Applied To The Brazilian Solar Belt

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Abstract

This paper presents an updated study on the technological feasibility of different photovoltaic cells in tropical climates, focusing on the Brazilian Solar Belt, a high-irradiance region. A multicriteria indicator based on Hierarchical Process Analysis (HPA) was developed to evaluate technologies under high temperature, humidity, and irradiation. Crystalline silicon cells (PERC, TOPCon, HJT, IBC), thin films (CdTe, CIGS), and emerging cells (organic, perovskites and tandem) were assessed for efficiency, cost, climate resistance, and degradation. Real climate data and Brazilian field evidence calibrated the model. This work fills a gap in the literature by integrating economic and degradation data into a decision tool focused on Brazil. Cost per watt installed (≈29%) and conversion efficiency (≈18 %) dominated the weights, whereas PID and damp-heat resistance accounted for less than 3%. The final ranking showed TOPCon as the preferred technology followed by IBC and HJT; PERC, Perovskite and OPVs occupied intermediate positions, while CdTe and CIGS ranked lowest. The results highlight the trade-off between performance and reliability in hot–humid climates and the need for region-specific technology choice.

Keywords: Photovoltaic technologies, crystalline silicon cells, Hierarchical Process Analysis (HPA), Brazilian Solar Belt, Technology Performance Matrix

1. Introduction

The construction of a photovoltaic (PV) module involves a certain level of complexity, as it consists of a variety of materials and interfaces that operate under diverse environmental conditions (Filho *et al*., 2022). However, PV generation is strongly influenced by environmental variables. Factors such as dust, snow, temperature, humidity, and storms can lead to different types of defects, including discoloration, glass breakage and cracking, hot spots, and corrosion, all of which can compromise the module's performance (Fazal and Rubaiee, 2023). Brazil, for instance, has regions with wide climatic variations. In tropical regions, particularly in the so-called Brazilian "Solar Belt" (Pereira *et al*., 2017), an area with the highest solar irradiation index, PV arrays operate under a unique combination of high temperature, elevated relative humidity, and intense ultraviolet (UV) exposure. These stressors accelerate thermo-mechanical fatigue, moisture ingress, corrosion, light-induced degradation (LID), and light- and elevated-temperature-induced degradation (LeTID), ultimately reducing power output and shortening service life (da Silva *et al*., 2021).

As Brazil surpassed 53 GW of installed solar capacity (Hein, 2025), selecting robust cell technologies has become essential for industry decision-makers. Commercial PV cells include first-generation crystalline silicon (c-Si) architectures such as PERC (Passivated Emitter and Rear Cell), TOPCon (Tunnel Oxide Passivated Contact), HJT (Heterojunction), and IBC (Interdigitated Back-Contact), as well as thin-film CdTe (Cadmium Telluride), CIGS (Copper-Indium-Gallium-Selenium), and emerging perovskite (PVK) or tandem stacks. Each architecture exhibits a distinct profile of efficiency, cost (USD W^{-1}), temperature coefficient (γ), annual power-degradation rate (PDR), and qualitative resistance to moisture, temperature, and irradiance (Fazal and Rubaiee, 2023). These variations increase the complexity of technology selection when the objective is to maximize energy yield over a 25-year period in hot-humid climates.

Given the wide range of technologies and the variables associated with them, selecting the most suitable architecture for a specific system is not straightforward. It requires multiple layers of analysis, encompassing both technical and subjective criteria that depend on the decision-maker's priorities. In this context, the use of indicators is a valuable tool for identifying the technology that best fits a particular application, whether prioritizing cost, efficiency, or performance under the environmental conditions to which the PV system is exposed. This process enables the selection of the most appropriate technology for deployment in the Brazilian Solar Belt region.

In this context, this work presents a structured Hierarchical Process Analysis (HPA), ranking nine PV technologies, involving mainstream, thin film and emerging technologies, across ten criteria: conversion efficiency, cost, temperature coefficient, resistance to temperature, moisture, and high irradiance, bifaciality, besides initial and annual degradation. Pairwise-comparison were based on peer-reviewed laboratory and field data; the overall consistency ratio confirms judgement reliability (Saaty, 2008).

10.18086/swc.2025.03.74 Available at http://proceedings.ises.org

From an industrial perspective, this study seeks to translate laboratory and field data into a decision-making tool capable of guiding investors and manufacturers toward the most cost-effective and climate-resilient PV technologies for Brazil's high-irradiance regions.

2. Environmental and Performance Factors

To assess the most suitable technologies for operation under adverse climatic conditions, the evaluation of several aspects is recommended. For instance, analyzing the cell temperature coefficients (Tempco) and the degradation factors to which each technology is more susceptible. Resistance to humidity, temperature, and irradiance are also critical parameters to be considered, in addition to the cost and efficiency values of each technology.

A PV module is expected to have an operational lifetime of 20 to 30 years. Within this period, certain acceptable power limits are considered, such as a maximum reduction of 10% of its initial power after the first 10 years of operation. After 25 years, this limit increases to 20%. The quantification of this power decline over time is expressed by the PDR, which can be useful to estimate the impact of degradation on energy cost, thereby influencing the system's economic viability (da Silva *et al*., 2021).

LID and LeTID are common phenomena that affect the stability and performance of PV modules. The former occurs when the module is exposed to sunlight, while the latter arises under simultaneous exposure to light and high temperatures, both resulting in decreased module performance (Yeo *et al.,* 2022). Their effects can be mitigated by replacing boron with gallium as the dopant in the silicon wafer (Köntges *et al*., 2025).

Moisture in the air can diffuse through the polymeric structure of the encapsulant and reach the solar cell, leading to delamination, which facilitates further ingress of moisture and air into the module, weakens its passivation, and deteriorates its performance (Ren *et al*., 2024). Temperature also has a major impact on solar cell efficiency. High temperatures can reduce cell performance by decreasing efficiency. The percentage loss in efficiency due to an increase in module surface temperature is expressed by the Tempco. This parameter depends on the cell material used, while the module temperature is influenced by climate, location, and solar radiation (Fazal and Rubaiee, 2023).

UV radiation can cause damage to the backsheet surface, encapsulant, cell surface, and even the interface between the silicon and the passivation layers of the photovoltaic cell, contributing to the degradation of module efficiency and lifetime (Adothu *et al*., 2025). Moreover, this factor can significantly influence the occurrence of Potential-Induced Degradation (PID). This degradation mechanism is caused by high system voltage, involving charge transfer through the PV module's encapsulant either from or to the cell, leading to reduced module performance (Köntges *et al*., 2025).

3. Technological Overview of Photovoltaic Technologies

This section evaluates several PV cell technologies from the first (crystalline silicon), second (thin-film), and third (emerging) generations considered in this study. The technical characteristics of each technology are analyzed based on the indicators defined for this research.

1.1. First-Generation Technologies

PERC, TOPCon, HJT, and IBC cells are silicon-based technologies. They represent the most widespread type of PV cell, dominating the market due to their reliability, scalability, cost-effectiveness, and durability (Oni *et al.,* 2024). PERC (p-type) has led the market in recent years as a well-established technology. PERC cells were developed to incorporate additional passivation contacts to reduce optical, transmission, and charge recombination losses, compared to Aluminum Back Surface Field (Al-BSF) solar cells. The inclusion of a rear passivation layer increases efficiency by providing an additional opportunity for photon absorption. The presence of anti-reflective coating further reduces incident light reflection, enhancing light capture (Kashyap *et al*., 2020). However, in hot and high-irradiance climates, this cell design is more prone to LeTID degradation (Köntges *et al*., 2025). In humid environments, PERC modules are also susceptible to accelerated degradation of encapsulant and passivation layers (Kyranaki *et al*., 2022).

Recently, TOPCon (n-type) modules have emerged as a more competitive technology, replacing PERC as the market leader since 2024. TOPCon cells can achieve higher efficiencies than PERC, in addition to exhibiting a lower temperature coefficient and lower annual degradation rate (Kivambe *et al*., 2025). The TOPCon architecture replaced boron with phosphorus as the silicon wafer dopant, reducing susceptibility to LeTID and consequently lowering the annual degradation rate compared to PERC (PV Magazine, 2023). Its front surface is similar to PERC, while the rear side features an enhanced passivation structure (Liu *et al*., 2025). This more robust passivation, combined with the longer carrier lifetime, contributes to greater bifaciality and higher power output (Jang *et al*., 2024). Figure 1a presents a typical structure of a TOPCon solar cell.

HJT cells exhibit higher efficiency than PERC and TOPCon cells (Green et al., 2024). They feature a heterojunction structure, symmetric on both sides, consisting of a Transparent Conductive Oxide (TCO) layer and an amorphous silicon layer deposited on n-type silicon, providing a double passivation effect (Liu et al., 2025). Among silicon-based technologies, HJT has the lowest temperature coefficient, indicating reduced power loss during temperature cycles (Fazal and Rubaiee, 2023). However, its manufacturing process is more complex and costly, hindering the transition from PERC to HJT technology (Kivambe et al., 2025). Moisture penetration into the module can affect the cell's TCO layers, compromising their transparency and conductivity (Ren et al., 2024).

IBC technology also demonstrates high efficiency (Green et al., 2024). In its architecture (Figure 1a), the metallic contacts are arranged in an interdigitated pattern on the rear side of the cell, thereby eliminating shading losses caused by front-side metallization and resulting in higher efficiency values (Oni et al., 2024). IBC modules exhibit lower degradation under UV exposure compared with HJT, PERC, and TOPCon technologies. Among these, TOPCon modules showed the highest level of UV-induced degradation, followed by PERC and HJT (Adothu et al., 2025).

1.2 Second-Generation Technologies

Second-generation technologies include thin-film cells such as CdTe and CIGS. These technologies are manufactured through physical and chemical vapor deposition processes, enabling the production of lighter, more flexible, and versatile modules. However, they typically offer lower efficiency than first-generation cells. This type of technology is generally applied as a thin layer on glass, polymer, or metal substrates, being versatile for curved surfaces, Building Integrated Photovoltaic (BIPV) systems, and portable devices (Oni et al., 2024). The schematic view of CdTe and CIGS solar cell is presented on Figure 1b.

The CdTe cell is composed of cadmium and tellurium. It exhibits one of the highest efficiencies in this category, with competitive potential against silicon cells, and can be produced using various methods. However, environmental concerns exist due to the toxicity of cadmium. Its metallic contacts are made of copper, which provides resistance to water-induced corrosion (Efaz et al., 2021).

CIGS ($Cu(In,Ga)Se_2$) technology has a high absorption coefficient ($>10^5$ cm^{-1}), allowing the fabrication of thin, flexible cells with reduced raw material consumption. Moisture is identified as one of the main causes of power loss in these cells (Debono et al., 2024). Additionally, this type of cell faces other challenges, such as limited indium reserves and cadmium toxicity, similar to CdTe cells (Efaz et al., 2021).

1.3. Emerging Technologies

Emerging technologies include organic photovoltaic (OPV), Perovskite, and Tandem cells. These technologies are still under intensive research and development due to the wide range of materials and design characteristics available for cell fabrication. OPVs offer advantages such as low cost, semitransparency, flexibility, and ease of manufacturing; however, their efficiency remains lower compared with other technologies (Fazal and Rubaiee, 2023).

Perovskites are a promising technology due to their remarkable electronic properties and simple production process, making them one of the most studied materials for PV cell applications. It has shown rapid development, notable efficiency gains, and low manufacturing costs. However, challenges remain for commercial application, including low stability, as perovskites are susceptible to degradation when exposed to humidity, UV radiation, oxygen, and high temperatures, as well as difficulties related to scalability (Al-Ali et al., 2025; Ahmed et al., 2025).

Tandem cells are multijunction devices, such as Perovskite/Silicon, which can achieve efficiencies around 34%. Despite their high efficiency, transitioning from laboratory to industrial scale is necessary. Furthermore, for this technology to become viable, stability issues must be addressed, and its field performance should be examined more thoroughly (Yang et al., 2025). The typical structure of Perovskite and Tandem solar cell is provided on Figure 1c.

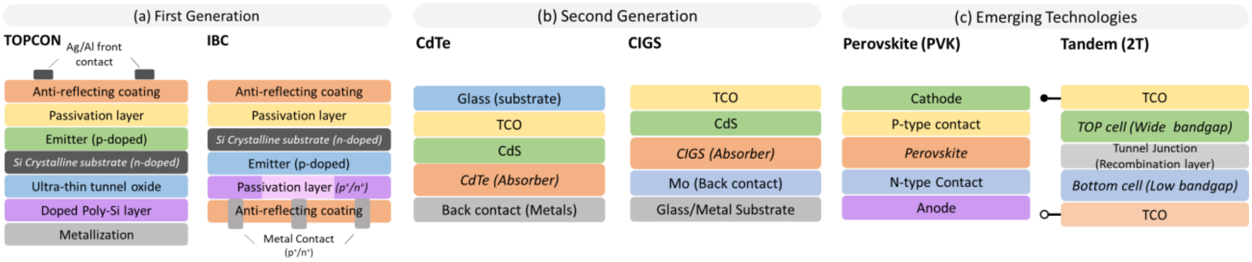

Figure 1 - Schematic view of (a) First generation (TOPCon, IBC), (b) Second generation (CdTe, CIGS) and (c) Emerging (PVK, tandem -2T) solar cells. Adapted from: Hollemann *et al*. 2020, Fazal and Rubaiee, 2023 and Pereira *et al*, 2024 .

4. Methodology

The study considered nine PV cell or technology alternatives included in the final decision matrix: PERC, TOPCon, HJT, IBC, OPV(s), CIGS, CdTe, Perovskite, and tandem. These technologies represent the evolution of crystalline silicon, heterojunction, and passivated contact cells, as well as thin-film devices and emerging perovskite and organic architectures. Each alternative was evaluated according to ten parameters representing performance, degradation, bifaciality, cost, and robustness. A summary of the main studies addressing this topic is presented in Table 1.

Table 1. Parameters by technology and units.

PARAMETER	PERC	TOPCon	HJT	IBC	CIGS	CdTe	OPVs	Tandem	PVK
Efficiency (%)	21.72[a]	24.80[b]	24.00[c]	24.80[d]	23.60[e]	23.08[f]	19.20[g]	34.95[h]	26.95[i]
Tempco (Pmax,%/°C)	-0.35[j]	-0.26[k]	-0.24[l]	-0.26[m]	-0.31[n]	-0.32[o]	0[p]	-0.21[q]	-0.25[r]
Initial degradation (%)	-1[s]	-1[t]	-1[u]	-1[v]	-0.26[w]	-2[x]	-1[y]	-20[z]	-2[aa]
Bifaciality (%)	74.10[ab]	85[ac]	90[ad]	75[ae]	3[af]	15[ag]	99.10[ah]	74[ai]	95[aj]
Cost (US$/Wp)	0.094[ak]	0.088[al]	0.1[am]	0.095[an]	0.4[ao]	0.29[ap]	0.75[aq]	0.428[ar]	0.57[as]
Degradation (%/ano)	-0.45[at]	-0.35[au]	-0.30[av]	-0.35[aw]	-1.55[ax]	-0.30[ay]	-0.90[az]	-21[ba]	-27[bb]
Damp heat (ΔPmax%)	-2.32[bc]	-1.31[bd]	-1.40[be]	-1.21[bf]	-17[bg]	-1.70[bh]	-41[bi]	-13[bj]	-8.50[bk]
PID(ΔPmax%)	-1.74[bl]	-1.03[bm]	-1.60[bn]	-0.92[bo]	-50[bp]	-5.50[bq]	-23[br]	-50[bs]	-24[bt]
Thermal Cycling	-2.22[bu]	-2.08[bv]	-0.67[bw]	-0.53[bx]	-10[by]	-25.13[bz]	-8[ca]	-1.20[cb]	-5[cc]
UV Stability (ΔPmax%)	-2.2[cd]	-3.2[ce]	-1.1[cf]	-0.7[cg]	-1.0[ch]	-0.6[ci]	-10.0[cj]	-2.0[ck]	-6.0[cl]

[a]LV *et al*. (2020), [b]Jinko Solar (2025), [c]Risen (2025), [d]Aiko (2025), [e,f,g,h,i]NREL (n.d.), [j]Jang *et al*. (2024), [k] Jinko Solar (2025), [l]Risen (2025), [m]Aiko (2025), [n]Bamisile *et al*. (2025), [o]First Solar (2024), [p]Heliatek (2025), [q]Babics *et al*. (2023a), [r]Halal and Plesz (2024), [s]Deline *et al*. (2024), [t]Jinko Solar (2025), [u]Risen (2025), [v]Aiko (2025), [w]Cantürk *et al*. (2024), [x] First Solar (2024), [y]Luo *et al*. (2024), [z]Babics *et al*. (2023b), [aa]Yan *et al*. (2025), [ab]Jang *et al*. (2024), [ac]Jinko Solar (2025), [ad]Risen (2025), [ae]Aiko (2025), [af]Ahmad *et al*. (2024), [ag]Zhang *et al*. (2024), [ah]Liu *et al*. (2024), [ai]Martin *et al*. (2023), [aj]Rabhi *et al*.(2025), [ak]Vikranth (2025), [al, am]Infolink Consulting (2025), [an]Longi (2025), [ao]Kumar *et al*.(2024), [ap]Meagley *et al*. (2025), [aq]Shielden (2024), [ar]Cordell et al. (2025), [as]Liu, Y. *et al*. (2025), [at]Deline *et al*. (2024), [au]Jinko Solar (2025), [av] Risen (2025), [aw]Aiko (2025), [ax]Straub-Mück *et al*. (2025), [ay]First Solar (2024), [az]Chen *et al*. (2025), [ba, bb]Zwaal (2024), [bc]Jinko Solar (2023a), [bd]Longi (2025), [be]Wu *et al*. (2025), [bf]Longi (2025), [bg]Lee *et al*. (2015), [bh]Wallén (2024), [bi]Wachsmuth *et al*. (2023), [bj]Khan *et al*.(2022), [bk]Mavlonov *et al*. (2025), [bl, bm]Jinko Solar (2023a), [bn]Wallén (2024), [bo]Longi (2025), [bp]Yilmaz *et al* (2022), [bq]Raza *et al*. (2023), [br]Akcaoğlu *et al*. (2019), [bs]Xu *et al*. (2022), [bt]Breugelmans *et al*. (2024), [bu]Jinko Solar (2023a), [bv]Jinko Solar (2023b), [bw]Risen (2023), [bx]Longi (2025), [by]Lee *et al*. (2015), [bz]Zeng *et al*. (2019), [ca]Cai *et al*. (2021), [cb]Wang *et al*. (2023), [cc]Wang, T. *et al*. (2023), [cd, ce, cf, cg]Adothu *et al*. (2025), [ch]Münch *et al*. (2012), [ci]Sample *et al*. (2009), [cj]Patel *et al*. (2019), [ck]Jung *et al*. (2023), [cl]Jiang *et al*. (2023).

To capture climatic particularities, annual averages of meteorological variables were used for three macro-regions of the Solar Belt: semi-arid Northeast, transitional North, and Midwest. Figure 2 illustrates the geographical boundaries of these macro-regions within Brazilian territory, highlighting the latitudinal extent of the so-called Solar Belt and its correspondence with major biomes and associated climatic zones, which support the comparative analyses of PV performance.

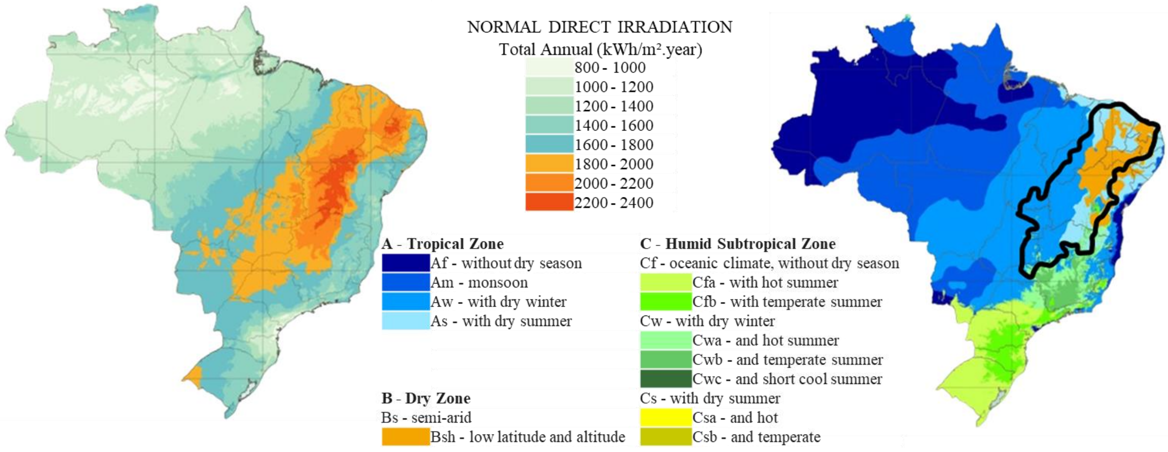

Figure 2 - Macro-regions of the Solar Belt. Adapted from Pereira *et al*., 2017.

Mean air temperature (23.5–25.5 °C), daily maximum (32.5–34.5 °C) and minimum (16–19 °C) temperatures, as well as mean relative humidity (62–73 %), were derived primarily from the Brazilian Atlas of Solar Energy (Pereira *et al*., 2017) and historical series from the NASA POWER Project (NASA POWER Project, n.d.). Annual precipitation is about 650 mm in the semi-arid Northeast and reaches 1,350 mm in the transitional and Midwest regions. The annual frequency of fog and dew ranges from 3.8 days year^{-1} in the Northeast to 22.2 days year^{-1} in the transitional zone, with intermediate values (15 days year^{-1}) in the Midwest. Global horizontal irradiance (GHI) ranges between 5.2 and 5.8 kWh m^{-2} day^{-1}, while diffuse horizontal irradiance (DHI) reaches 1.7 kWh m^{-2} day^{-1} in the Cerrado–Amazon transition. The diffuse fraction (DHI/GHI) is approximately 0.4, indicating the predominance of the direct component in all regions. The key parameters reported in the reviewed literature are summarized in Table 2.

Table 2. Climatic statistics by macro-region.

Variable	Mean	Semi-arid Northeast	Transitional North	Midwest
Mean temperature (°C)	24.50	25.5[a]	24.5[b]	23.5[c]
Maximum temperature (°C)	33.50	34.5[d]	33.5[e]	32.5[f]
Minimum temperature (°C)	17.67	18[g]	19[h]	16[i]
Relative humidity (%)	67.48	62.47[j]	72.74[k]	67.22[l]
Annual precipitation (mm year^{-1})	1116	650[m]	1350[n]	1350[o]
Fog/dew (days year^{-1})	13.77	3.8[p]	22.2[q]	15.3[r]
GHI (kWh m^{-2} day^{-1})	5.43	5.73[s]	5.20[t]	5.35[u]
DNI (kWh m^{-2} day^{-1})	5.38	5.88[v]	5.00[w]	5.25[x]
DHI (kWh m^{-2} day^{-1})	1.63	1.718[y]	1.560[z]	1.605[aa]
Diffuse fraction (%)	0.40	0.400[ab]	0.400[ac]	0.400[ad]
GTI (kWh m^{-2} day^{-1})	5.54	5.80[ae]	5.35[af]	5.48[ag]
UV index (IU)	2.29	2.37[ah]	2.25[ai]	2.24[aj]
Land cover		Grassland[ak]	Forest[al]	Agricultural[am]
Chlorides (Cl^-) (mg m^{-2} day^{-1})	2.25	1.4[an]	3.1[ao]	2.25[ap]
Altitude (m)	550	600[aq]	375[ar]	675[as]
Climate classification		Hot semi-arid[at]	Tropical with dry winter[au]	Tropical with dry winter[av]
Annual PV yield (kWh kWp^{-1} year^{-1})	1658	1750[aw]	1625[ax]	1600[ay]

[a, b, c, d, e, f, g, h, i, m, n, o, s, t, u, v, w, x, ae, af, ag, ao, ap, aq, ar, as, at, au, av, aw] *Pereira et al. (2017);* [j, k, l, ah, ai, aj] *NASA POWER Project (n.d.);* [p, q, r] *da Silva (2018);* [y, z, aa, ab, ac, ad] *de Souza et al. (2023);* [ak, al] *IBGE (2020);* [am] *Valporto (2023);* [an, ax, ay] *Lyon (2020).*

The hierarchical structure of the adopted AHP consists of three levels: (i) the goal of selecting the most suitable PV technology, (ii) ten evaluation criteria, and (iii) nine technological alternatives. The criteria are: conversion efficiency, power temperature coefficient, annual degradation, initial degradation, bifaciality, cost per installed watt, damp heat robustness, PID susceptibility, stability under thermal cycling, and UV radiation stability. Criteria such as efficiency and bifaciality are of the benefit type (the higher, the better), whereas temperature coefficient and degradation rates (annual and initial) are of the cost type (lower absolute values are desirable). Environmental data from the Brazilian Solar Belt informed the weights assigned to each desired technology attribute. Given the region's high irradiance, UV-resistant technologies were prioritized. The pronounced thermal variability further favored options that maintain performance after the Thermal Cycling test. The pairwise comparison matrix between criteria was developed by solar industry's persona (SIP) and is presented in the weighting spreadsheet (Table 3); the principal eigenvector method was used to extract the normalized weights. Consistency was verified using the Saaty consistency ratio (Saaty, 2008), maintaining acceptable values (CR < 0.1).

Table 3. Weights assigned to PV cell technology criteria.

Criterion	Weight
Conversion efficiency (%)	0.18
Temperature coefficient (Pmax, % °C^{-1})	0.09
Annual degradation (% year^{-1})	0.10
Initial degradation (%)	0.14
Bifaciality (%)	0.06
Cost per installed watt (US$ Wp^{-1})	0.29
Damp heat robustness (ΔPmax %)	0.03
PID (ΔPmax %)	0.02
Thermal cycling	0.05
UV stability (ΔPmax %)	0.04

5. Results

The most influential criterion was the cost per installed watt, reflecting the need for competitive technologies in large-scale scenarios. According to market indices, PERC module costs are approximately 0.09 US$ Wp^{-1}, while TOPCon shows slightly lower values (0.088 US$ Wp^{-1}) and HJT around 0.10 US$ Wp^{-1}; emerging technologies such as OPVs and perovskites present significantly higher costs (0.57–0.75 US$ Wp^{-1}). Conversion efficiency ranked as the second most important criterion; data reported in the literature and technical reports indicate efficiencies of 21.7% for PERC, 24.8% for TOPCon, 24% for HJT, and up to 34.95% for perovskite/silicon tandem cells. Initial degradation and annual degradation were highly valued due to their influence on lifetime energy yield; field measurements report annual degradation rates between 0.35% and 0.45% year^{-1} for TOPCon and PERC modules. The temperature coefficient quantifies the sensitivity of power to temperature increase; HJT (–0.24% °C^{-1}) and TOPCon (–0.26% °C^{-1}) technologies have advantages in hot environments compared with PERC, reducing thermal losses. Bifaciality benefits from reflective surfaces and high diffuse radiation fractions, such as in the Cerrado–Amazon transition region where the diffuse fraction is 0.4; HJT and TOPCon modules exhibit bifaciality factors of 0.85–0.9, while OPVs reach values close to 0.99. Reliability criteria (DH, PID, thermal cycling, UV) reflect resistance to humidity, corrosion, and photodegradation; industrial reports indicate power losses below 2% in damp-heat tests for PERC and TOPCon, but above 10% for CIGS, CdTe, and OPVs.

The final scores of each technology are presented in Table 4. TOPCon achieved the highest score (0.169), standing out for its balance between high efficiency, moderate temperature coefficient, and competitive cost. IBC ranked second (0.142), benefiting from high efficiency and good stability, although with higher cost. HJT took third place (0.137), showing excellent thermal behavior but still elevated cost. The perovskite/silicon tandem cell obtained an intermediate score (0.116); its very high efficiency was offset by high costs and significant initial degradation. PERC cells (0.103) ranked in the middle of the distribution, reflecting their balance between cost and performance. Perovskite (0.092) and OPV (0.086) technologies showed moderate scores, penalized by stability issues. Thin-film options CdTe (0.079) and CIGS (0.076) occupied the last positions due to lower efficiency and higher cost per watt. The results highlight a trade-off between high performance and feasibility. TOPCon led the ranking due to its combination of nearly 25% efficiency, relatively low cost, and good bifaciality. However, recent reports indicate specific failure modes (cracking and passivation loss) in humid environments (Hasan *et al*., 2025; Zeng *et al*., 2024), requiring improvements in PV module manufacturing processes and encapsulant selection. IBC technology exhibits high performance, but its cost and manufacturing complexity limit broader adoption. HJT combines excellent thermal stability and high bifaciality. PERC remains a mature, low-cost solution, yet its unfavorable temperature coefficient and initial degradation demand careful system design in hot climates. Perovskite and tandem-based technologies achieve record efficiencies; however, their accelerated degradation (up to 20% $year^{-1}$) and lifetime below ten years hinder immediate commercial deployment. OPVs benefit from flexible mechanical properties and high bifaciality but suffer from chemical degradation under environmental stresses such as humidity, UV radiation, and thermal cycling (Choi *et al*., 2025). Finally, thin-film CIGS and CdTe offer tolerance to shading and high temperatures, but lower efficiency and sensitivity to PID and DH reduced their scores.

Table 4. Final scores by technology and ranking

Technology	Decision
TOPCon	16.9%
IBC	14.2%
HJT	13.7%
Tandem	11.6%
PERC	10.3%
Perovskite	9.2%
OPVs	8.6%
CdTe	7.9%
CIGS	7.6%

The decision matrix aggregates weighted technical criteria, with each weight reflecting its perceived importance: the cost per installed watt accounted for 29.3% of the total weight, followed by conversion efficiency (18.5%), initial degradation (14.3%), and annual degradation (9.8%). The temperature coefficient contributed 9%, and bifaciality 5.7%. Criteria related to environmental reliability, including thermal cycling, UV stability, damp heat resistance, and PID susceptibility, together representing 13% of the weights, highlight the need for suitability across diverse solar belt environments. TOPCon, IBC, and HJT technologies exhibit conversion efficiencies of 24–25%, with temperature coefficients ranging from −0.24% $°C^{-1}$ to −0.26% $°C^{-1}$.

These modules are able to maintain power output under intense heat, an important advantage in the semi-arid Northeast, where maximum temperatures can exceed 35.9 °C in inland municipalities and the average annual humidity is around 50%. In contrast, PERC modules have lower efficiency (21.7%) and a more negative temperature coefficient; although they offer low cost, their performance declines when ambient temperature exceeds 25 °C. Perovskite/silicon tandem cells achieve laboratory efficiencies above 34%, but their thermal gain (coefficient of –0.21% $°C^{-1}$) does not offset their high cost and instability. The high average temperatures in the northern transition zone (30.7–34.1 °C) and the strong heat waves in the Midwest highlight the importance of this criterion, as technologies with less negative coefficients, such as HJT and TOPCon, minimize daily losses. This factor explains why TOPCon and IBC occupy the top positions in the ranking, even though competitors such as CdTe show similar efficiencies but poorer temperature coefficients.

In tropical regions, accelerated aging can compromise energy generation throughout the service life (Islam *et al*., 2024). Initial and annual degradation together accounted for nearly one quarter of the decision weight. PERC, TOPCon, HJT, and IBC exhibit initial degradation of approximately 1%, while emerging technologies (perovskite, tandem) suffer initial losses between 2% and 20%. Annual degradation ranges from 0.3% to 0.6% for silicon technologies but can reach 20% $year^{-1}$ in perovskite devices. This vulnerability becomes critical in the hot and humid northern transition environments, where relative humidity remains high for much of the year, exacerbating ion diffusion and oxidation (Thornton *et al*., 2022; INMET, 2025). In the semi-arid region, the low atmospheric humidity reduces corrosion risk, but intense radiation and large day–night temperature variations can amplify fatigue mechanisms (da Silva *et al*., 2021; Han, 2023). The relatively high weight assigned to initial and annual degradation favors oxide-passivated or heterojunction technologies (TOPCon, IBC, HJT), which exhibit slower aging, and penalizes perovskite and tandem technologies, resulting in their lower scores.

Bifaciality received a moderate weight (5.7%) because its benefit depends on the environment. TOPCon and HJT exhibit bifaciality indices above 0.85, allowing them to capture radiation reflected from the ground. This advantage is significant in regions with a high diffuse irradiance fraction (≈40%), such as the northern transition zone, and in high-albedo areas in the Midwest. In contrast, CIGS and CdTe show bifaciality below 0.15 and, although some have favorable thermal coefficients, they do not benefit from diffuse light, which contributes to their position at the bottom of the ranking. OPVs exhibit a theoretical bifaciality of 0.991, but their very low power density (79 Wp m^{-2}) would require larger installation areas, making them unsuitable for centralized power plants. This contrast justifies the relatively low weight assigned to bifaciality in the final decision and explains why the additional gains of bifacial technologies were insufficient to overcome deficiencies in cost or reliability.

The 29% weight assigned to cost reflects the SIP economic priority for large-scale deployment. PERC remains the competitive technology (0.094 US$ Wp^{-1}), but its low efficiency and weak thermal performance limit its position (5th in the ranking). TOPCon combines cheapest cost (0.088 US$ Wp^{-1}) with high efficiency, enabling greater energy yield per area; this balance explains its leading position. IBC and HJT, although slightly more expensive (0.095–0.10 US$ Wp^{-1}), maintain high rankings due to their advantages in efficiency, temperature behavior, and durability. In contrast, thin-film technologies (CdTe, CIGS) and emerging devices (perovskite, tandem) exhibit much higher costs (0.29–0.75 US$ Wp^{-1}), excluding them from the top positions regardless of other strengths. In economically vulnerable regions such as the semi-arid Northeast, where rural economies still face negative water balances, high costs can make projects unfeasible; this reality justifies the SIP emphasis on the economic criterion.

The four environmental reliability criteria account for just over 13% of the total weight but are decisive for real-climate performance. Damp-heat tests (85 °C/85% RH) show that TOPCon, IBC, and HJT modules lose less than 2% of their power after 1000 h, while thin-film technologies can lose more than 10%. This aspect is critical in the northern transition region, where projected temperature anomalies reach 1.5–2.5 °C above average and the rainy season is intense. Susceptibility to PID can be controlled in silicon modules through doping and encapsulant selection; values from −0.009% (IBC) to −0.017% (PERC) contrast with losses of −0.23% in OPVs or −0.50% in CIGS. Thermal-cycling tests strongly penalize CdTe (−25.13%), making it less suitable for the Midwest, where occasional cold fronts can cause abrupt temperature drops. Finally, UV stability is particularly important in the semi-arid region, which combines clear skies with a high mean UV index (≈2.3). Silicon devices lose less than 2% under accelerated UV exposure, whereas perovskite and OPV devices can lose up to 10%. Thus, although these criteria carry less individual weight, they reinforce the advantages of silicon technologies and justify the lower ranking of emerging options.

The convergence between the weight of the criteria, the intrinsic properties of the cells, and the climatic requirement of the solar belt explains the final score distribution. TOPCon leads by combining low cost and high efficiency with controlled temperature coefficient and degradation, qualities essential to maximize return in hot, dry, or humid environments. IBC ranks second because, although slightly more expensive, it offers superior robustness under thermal cycling and UV exposure, valuable characteristics in the Midwest and semi-arid regions. HJT takes third place; its high performance is offset by cost, but this effect is mitigated in locations with a high diffuse fraction and strong bifaciality. The fourth-place position of tandem cells reflects their exceptional efficiency, but the combined weight of high cost and elevated annual degradation prevents them from competing with more mature technologies. PERC remains fifth because its low cost does not outweigh the combined disadvantages in efficiency, temperature behavior, and degradation. Perovskite and OPV technologies, despite their promising innovations, are relegated to lower positions due to high cost, short lifetime, and severe degradation under humid tropical conditions. CIGS and CdTe close the ranking because of their high cost, low bifaciality, and vulnerability to PID and thermal cycling, which are critical limitations in regions with alternating dry and wet seasons.

By correlating the decision matrix with the climatic profiles of the macro-regions, it becomes clear that the superiority of passivated and heterojunction silicon technologies stems not only from their efficiency but also from their ability to maintain stable performance under the extreme conditions of the solar belt. The combination of high temperatures, strong solar radiation, and pronounced contrasts in humidity and seasonality demands modules with slightly negative temperature coefficients, slow aging rates, and robust encapsulation. The SIP prioritization of cost and efficiency reflects budget constraints and the need to maximize energy generation in areas with negative water balances and limited infrastructure. Thus, the final hierarchy composed of TOPCon, IBC, HJT, tandem, PERC, perovskite, OPV, CdTe, and CIGS represents a synthesis of the economic and environmental demands of the Brazilian solar belt, demonstrating that the ideal technological choice must balance price, performance, and climatic robustness to ensure long-term viability.

6. Conclusion

This study applied the Analytic Hierarchy Process (AHP) to integrate SIP preferences with measured evidence of performance, cost, and reliability, aiming to rank PV technologies for the Brazilian Solar Belt. The goal was achieved by translating the objective–criteria–alternatives hierarchy into comparable scores, allowing the ranking to be interpreted considering dominant physical and environmental mechanisms. The weighting structure explained the outcome: cost per installed watt played the most significant role, followed by efficiency and initial degradation, while temperature coefficient, bifaciality, and environmental robustness metrics acted as modulators under hot, humid, and diffuse-radiation conditions. The combination of competitive price, high efficiency, and lower thermal sensitivity placed TOPCon in the lead, followed by IBC and HJT. PERC remained competitive due to its low cost but lost position when initial stability and thermal performance became more relevant. Perovskite, tandem, CdTe, and CIGS ranked lower due to cost, maturity, and vulnerability to environmental stresses, given the established priorities.

The results have direct practical implications for climate- and cost-oriented technology selection in large-scale power plants across the analyzed macro-regions. The conclusions are contingent upon the elicited preferences and the database used, which suggests periodic reviews of the weighting factors and the inclusion of sensitivity analyses and higher-resolution local climate scenarios. Future work should explore region-specific normalizations, test hybrid combinations of multi-criteria methods, and continuously update cost and reliability inputs for emerging technologies. In summary, the optimal decision results from the consistent alignment between decision priorities, intrinsic cell properties, and local climatic signature, providing a transparent and replicable framework for technology planning in the Solar Belt. It is worth noting that one limitation of the method is that parameter weights are not initially determined analytically but rather defined through SIP judgment and experience. Moreover, an excessive number of evaluation factors may compromise the consistency ratio (C.R), and only essential parameters should be selected. Nevertheless, the method remains an effective tool for comparative assessment.

7. Acknowledgments

The authors gratefully acknowledge of the Tangipar Group and Sengi Solar for their institutional, technical, and strategic support that made this work possible, as well as to the Ministry of Science, Technology and Innovation (MCTI) of the Federal Government of Brazil, whose commitment to innovation and national technological development was essential to the advancement of this research.

8. References

Adothu, B., *et al*., 2025. UV-Induced Degradation of New Generation Bifacial HJT, IBC, PERC, and TOPCON PV Modules. doi:10.1109/PVSC59419.2025.11133194

Ahmad, F., Monk, P. B., and Lakhtakia, A., 2024. Bifacial flexible CIGS thin-film solar cells with nonlinearly graded-bandgap photon-absorbing layers. J. Phys. Energy 6 025012. doi:10.1088/2515-7655/ad29fd

Ahmed, S., Ali, A., Ansari, J. A., Qadir, S. A., and Kumar, L., 2025. Comprehensive Review of Solar Photovoltaic Systems: Scope, Technologies, Applications, Progress, Challenges, and Recommendations. IEEE Access.

Aiko, 2025. Neostar 3P+54 Dual-Glass Module 465W-495W. Avaiable at: https://aikosolar.com/static/pdfjs/web/viewer.html?file=/wp-content/uploads/2025/08/Neostar-3PPlus54_AIKO-A-MCE54Dw_465-495W-1762%C3%971134%C3%9730_DsDr_EN.pdf. Accessed on: September 29, 2025

Akcaoğlu, S., Martinopoulos, G., Koidis, C., Kiymaz, D., and Zafer, C., 2019. Investigation of cell-level potential-induced degradation mechanisms on perovskite, dye-sensitized and organic photovoltaics. Solar Energy. doi:https://doi.org/10.1016/j.solener.2019.08.031

Al-Ali, S., Olabi, A. G., and Mahmoud, M., 2025. A review of solar photovoltaic technologies: developments, challenges, and future perspectives. Energy Conversion and Management: X. doi: https://doi.org/10.1016/j.ecmx.2025.101057.

Babics, M., *et al.*, 2023a. Temperature Coefficients of Perovskite/Silicon Tandem Solar Cells. ACS Energy Letters. doi: https://doi.org/10.1021/acsenergylett.3c00930

Babics, M., *et al*., 2023b. One-year outdoor operation of monolithic perovskite/silicon tandem solar cells. Cell Reports Physical Science. doi:https://doi.org/10.1016/j.xcrp.2023.101280

Bamisile, O., Acen, C., Cai, D., Huang, Q., and Staffell, I., 2025. The environmental factors affecting solar photovoltaic output. Renewable and Sustainable Energy Reviews. doi:https://doi.org/10.1016/j.rser.2024.115073

Breugelmans, R., *et al*., 2024. Method to Study Potential-Induced Degradation of Perovskite Solar Cells and Modules in an Inert Environment. Sol. RRL, 8: 2400046. doi:https://doi.org/10.1002/solr.202400046

Cai, P., *et al*., 2021. Cross-Linkable and Alcohol-Soluble Pyridine-Incorporated Polyfluorene Derivative as a Cathode Interface Layer for High-Efficiency and Stable Organic Solar Cells. ACS Applied Materials & Interfaces. doi:10.1021/acsami.1c00350

Cantürk, Z., ÖZDEN, T., and Akınoğlu, B. G., 2024. Outdoor degradation analyses of six different aged photovoltaic module technologies under the arid-steppe climate condition. Isi Bilimi Ve Teknigi Dergisi/ Journal of Thermal Science and Technology, 44(1), 103–115.

Chen, K., Zuo, J., and Chang, R., 2025. Compendium of degradation rates of global photovoltaic (PV) technology: insights from technology, climate and geography. Solar Energy Materials and Solar Cells. doi:https://doi.org/10.1016/j.solmat.2025.113839

Choi, Y., *et al*., 2025. Stability of Organic Photovoltaics: From Root Causes to Advanced Analytical Techniques. Adv. Energy Mater. doi:https://doi.org/10.1002/aenm.202501340

Chunduri, S., 2024. Monthly TaiyangNews Update On Commercially Available High Efficiency Solar Modules. Retrieved from Taiyang News: https://taiyangnews.info/top-solar-modules-listing-february-2024/. Accessed on: March 28, 2025.

Cordell, J. J., Woodhouse, M., and Warren, E. L., 2025. Technoeconomic analysis of perovskite/silicon tandem solar modules. Joule. doi:https://doi.org/10.1016/j.joule.2024.10.013

da Silva, A. O., 2018. Nevoeiro e Nuvem Estratos no Brasil: Observação, Sensoriamento Remoto e Simulação Numérica. Tese (Doutorado em Ciências Atmosféricas) — Universidade de São Paulo, IAG/USP, São Paulo. Avaiable at: https://www.iag.usp.br/sites/default/files/2023-05/t_aliton_o_silva_original.pdf. Accessed on: Oct. 17. 2025.

da Silva, M. K., Gul, M. S., and Chaudhry, H., 2021. Review on the Sources of Power Loss in Monofacial and Bifacial Photovoltaic Technologies. Energies. doi: https://doi.org/10.3390/en14237935

Debono, A., *et al*., 2024. Synergistic effect between molybdenum back contact and CIGS absorber in the degradation of solar cells. Progress in photovoltaics, pp. 137-155.

Deline, C., *et al*., 2024. PV Lifetime Project – 2024 NREL Annual Report. Retrieved from NREL: https://docs.nrel.gov/docs/fy24osti/90651.pdf

de Souza, A. P., et al., 2023. Diurnal Evolution and Estimates of Hourly Diffuse Radiation Based on Horizontal

Global Radiation, in Cerrado-Amazon Transition, Brazil. Atmosphere, 14(8), 1289. Disponível em: https://www.mdpi.com/2073-4433/14/8/1289. Acesso em: 17 out. 2025. https://doi.org/10.3390/atmos14081289

Efaz, E. T., 2021. A review of primary technologies of thin-film solar cells. Engineering Research Express 3 032001. doi: 10.1088/2631-8695/ac2353

Fazal, M., and Rubaiee, S., 2023. Progress of pv cell technology: Feasibility of building materials, cost, performance, and stability. Solar Energy. doi: https://doi.org/10.1016/j.solener.2023.04.066

Filho, N. M., *et al.*, 2022. Snail trails on PV modules in Brazil's tropical climate: Detection, chemical Properties, bubble formation, and performance effects. Sustainable Energy Technologies and Assessments. doi: https://doi.org/10.1016/j.seta.2022.102808

First Solar, 2024. Series 7 TR1 525-550W Thin Film Solar Module. Avaiable at: https://www.firstsolar.com/-/media/First-Solar/Technical-Documents/Series-7/Series-7-TR1-High-Bin-Datasheet.ashx?la=es-CSA. Accessed on: September 30, 2025.

Green MA, Dunlop ED, Yoshita M, *et al*, 2024. Solar cell efficiency tables (Version 64). Prog Photovolt Res Appl.; 32(7): 425-441. Doi:10.1002/pip.3831.

Halal, A., and Plesz, B., 2024. A Comprehensive Study on the Thermal Behavior of Perovskite Solar Cell. EEE Transactions on Components, Packaging and Manufacturing Technology. doi:10.1109/TCPMT.2024.3430220

Han, C., 2023. Simulation of Series Resistance Increase through Solder Layer Cracking in Si Solar Cells under Thermal Cycling. Energies 16. doi:https://doi.org/10.3390/en16062524

Hasan, A. A., *et al*., 2025. A review on silicon photovoltaic module degradations and recent identification techniques. Solar Energy. doi:https://doi.org/10.1016/j.solener.2025.113288

Hein, H., 2025. Energia solar atinge 53 GW de capacidade instalada no Brasil. Canal Solar. Avaiable at: https://canalsolar.com.br/energia-solar-capacidade-instalada-brasil-4/. Accessed on: March 24, 2025

Heliatek, 2025. HeliaSol 436-2000-CFF Avaiable at: https://www.heliatek.com/fileadmin /user_upload/pdf_documents/Datasheet_HeliaSol_436-2000_Website_EN.pdf. Accessed on: September 30, 2025

Hollemann, C. *et al*., 2020. Separating the two polarities of the POLO contacts of an 26.1%-efficient IBC solar cell. Scientific Reports. doi: 10.1038/s41598-019-57310-0

IBGE. 2020. IBGE retrata cobertura natural dos biomas do país de 2000 a 2018. Agência de Notícias IBGE, 24 set. 2020. Avaiable at: https://agenciadenoticias.ibge.gov.br/agencia-sala-de-imprensa/2013-agencia-de-noticias/

releases/28943-ibge-retrata-cobertura-natural-dos-biomas-do-pais-de-2000-a-2018. Accessed on: Oct. 17. 2025.

Infolink Consulting. 2025. Spot Price: N Type Cell. Retrieved from Infolink: Avaiable at: https://www.infolink-group.com/spot-price/. Accessed on: September 30, 2025

INMET. 2025. Junho: como será o clima no Brasil? Retrieved from Ministério da Agricultura e Pecuária: Avaiable at: https://portal.inmet.gov.br/uploads/Previsao_INMET_Junho_2025.pdf. Accessed on: September 17, 2025.

Islam, M. I., Jadin, M. S., Mansur, A. A., and Alharbi, T., 2024. Electrical Performance and Degradation Analysis of Field-Aged PV Modules in Tropical Climates: A Comparative Experimental Study. Energy Conversion and Management: X. doi:https://doi.org/10.1016/j.ecmx.2024.100719

Jang, H., *et al*., 2024. Comparative Study on Energy Yield of Tunnel Oxide Passivated Contact (TOPCon) and Passivated Emitter and Rear Contact (PERC) Solar Cells and Analysis of Optimal Installation Method for Vertical Photovoltaics. Process Integration and Optimization for Sustainability.

Jiang, Q., *et a*l., 2023. Towards linking lab and field lifetimes of perovskite solar cells. Nature 623, 313–318. doi:https://doi.org/10.1038/s41586-023-06610-7

Jinko Solar. 2023a. The "Low Degradation" Performance of N-type Module——Based on the Reliability Tests Conducted by TÜV NORD. TÜV NORD Test Result of N-type TOPCon Module. Retrieved from Avaiable at: https://www.jinkosolar.com/2023/PDF/072501.pdf. Accessed on: September 9, 2025

Jinko Solar. 2023b. JinkoSolar N-type TOPCon Module Outperforms in PVEL Test in Every Category. PVEL Test Result of N-type TOPCon Module. Retrieved from https://www.jinkosolar.com/2023/PDF/PVEL.pdf

Jinko Solar, 2025. Tiger Neo III 66QL6-BDV. Avaiable at: https://jinkosolarcdn.shwebspace.com/themes/ basicen/skin/pdf/JKM650-670N-66QL6-BDV-D1(P8)%20CC-EN.pdf. Accessed on: September 29, 2025.

Jung, E. D., *et al*., 2023. Aesthetic and efficient perovskite/Si tandem solar cells using luminescent down-shifting textured anti-reflection films. EcoMat. doi:10.1002/eom2.12399

Kashyap, S., Madan, J., Pandey, R., and Sharma, R., 2020. Comprehensive Study on the Recent Development of PERC Solar Cell. 47th IEEE Photovoltaic Specialists Conference (PVSC), pp. 2542-2546.

Kivambe, M., *et al*., 2025. Comprehensive assessment of performance and reliability of PERC, TOPCon and SHJ modules in desert climates. Solar Energy. doi: https://doi.org/10.1016/j.solener.2025.113555

Köntges, M., *et al*., 2025. Degradation and failure modes in new photovoltaic cell and module technologies. IEA PVPS Task 13-30:2025.

Kumar, A., Giripunje, S. M., Patel, A. K., and Gohri, S., 2024. Designing and simulating of new highly efficient ultra-thin CIGS solar cell device structure: Plan to minimize cost per watt price. Journal of Physics and Chemistry of Solids. doi:https://doi.org/10.1016/j.jpcs.2024.112194

Kyranaki, N., *et al*., 2022. Damp-heat induced degradation in photovoltaic modules manufactured with passivated emitter and rear contact solar cells. Progress in Photovoltaics: Research and Applications. doi: https://doi.org/10.1002/pip.3556

Lee, D., *et al*., 2015. Damp heat and thermal cycling-induced degradation mechanism of AZO and CIGS films in Cu(In,Ga)Se2 photovoltaic modules. Current Applied Physics. doi:https://doi.org/10.1016/j.cap.2014.12.023

Liu, L., *et al*., 2025. Numerical and experimental investigation on solar photovoltaic-thermal assisted heat pump systems using different kinds of solar cells. Renewable Energy. doi: https://doi.org/10.1016/j.renene.2025.123319

Liu, X., *et al*., 2024. A semitransparent organic solar cell with a bifacial factor of 99.1%. Materials Today Energy. doi:https://doi.org/10.1016/j.mtener.2024.101614

Liu, Y., Zhang, Z., and Wu, T., 2025. Cost Effectivities Analysis of Perovskite Solar Cells: Will it Outperform Crystalline Silicon Ones? Nano-Micro Lett. 17, 219. doi:https://doi.org/10.1007/s40820-025-01744-x

Longi. 2025. Back Contact (BC) Solar Technology Development: White Paper. Retrieved from Longi: Avaiable at: https://static.longi.com/Back_Contact_BC_Solar_Technology_Development_White_Paper_ff1a12170f.pdf. Accessed on: September 30, 2025

Luo, W., *et al*., 2024. Long-term outdoor study of an organic photovoltaic module for building integration. Prog Photovolt Res Appl. doi:10.1002/pip.3791

Lv, Y., *et al*., 2020. Towards high-efficiency industrial p-type mono-like Si PERC solar cells. Solar Energy Materials and Solar Cells. doi: https://doi.org/10.1016/j.solmat.2019.110202

Lyon, S., 2020. Atmospheric Corrosion. Guides to Good Practice in Corrosion Control No. 12. Teddington: National Physical Laboratory. Avaiable at: NPL Publications. Accessed on: Oct. 17. 2025.

Ma, S., *et al*., 2025. Light and elevated temperature induced degradation (LeTID) of N-type TOPCon solar cells. Solar Energy. doi: https://doi.org/10.1016/j.solener.2025.113573

Martin, A., Grand, P.-P., Hull, M., Rousset, J., and Oberbeck, L., 2023. Architecture of symmetrical bifacial perovskite/Si/perovskite PV modules and LCOE comparison in bifacial applications. EPJ Photovolt. doi:10.1051/epjpv/2023025

Mavlonov, A., *et al*., 2025. Perovskite solar cell modules: Understanding the device degradation via damp heat testing. Solar Energy. doi:https://doi.org/10.1016/j.solener.2024.113174

Meagley, R., *et al*., 2025. Cadmium Telluride Photovoltaics Perspective Paper. Retrieved from U.S. Department of Energy: Avaiable at: https://www.energy.gov/sites/default/files/2025-01/DOE%20SETO%20CdTe%20 Photovoltaics%20Perspective %20Paper.pdf. Accessed on: September 15, 2025.

Münch, M., *et al*., 2012. Flexible CIGS modules – selected aspects for achieving long-term reliable products. Photovoltaics International. Avaiable at: https://www.pv-tech.org/wp-content/uploads/legacy-publication-pdfs/6dbfb00bff-flexible-cigs-modules-selected-aspects-for-achieving-longterm-reliable-products.pdf. Accessed on: September 15, 2025.

NASA Prediction Of Worldwide Energy Resources (POWER) Project (s.d.). Climatology API Documentation. NASA/LaRC. Avaiable at: https://power.larc.nasa.gov/docs/services/api/temporal/climatology/. Accessed on: Oct. 17. 2025.

NREL, n.d. Interactive Best Research-Cell Efficiency Chart. Avaiable at: https://www.nrel.gov/pv/cell-efficiency. Accessed on: September 30, 2025.

Oni, A. M., Mohsin, A. S., Rahman, M. M., and Belal, M., 2024. A comprehensive evaluation of solar cell technologies, associated loss mechanisms, and efficiency enhancement strategies for photovoltaic cells. Energy Reports. doi: https://doi.org/10.1016/j.egyr.2024.03.007

Patel, J. B., *et al*., 2019. Effect of Ultraviolet Radiation on Organic Photovoltaic Materials and Devices. ACS Applied Materials & Interfaces. doi:10.1021/acsami.9b04828

Pereira, E. B., *et al*., 2017. Atlas brasileiro de energia solar (2. ed ed.). São José dos Campos: INPE. Avaiable at: https://labren.ccst.inpe.br/atlas_2017.html. Accessed on: September 10, 2025

Pereira, G. N., *et al*., 2024. Tecnologias de células fotovoltaicas utilizadas em módulos comerciais e suas principais características: uma revisão. Anais Congresso Brasileiro De Energia Solar - CBENS. https://doi.org/10.59627/cbens.2024.2379

PV Magazine, 2023. Why TOPCon cells will not be deteriorated by light-induced degradation. Avaiable at: https://www.pv-magazine.com/press-releases/why-topcon-cells-will-not-be-deteriorated-by-light-induced-degradation/. Accessed on: September 16, 2025.

Rabhi, S., Hafaifa, L., Alsalmi, O. H., and Alali, A. S., 2025. Boosting bifacial efficiency in inverted perovskite solar cells: 95% bifaciality and 28% PCE through materials and device engineering. New J. Chem. doi:10.1039/D5NJ02604K

Raza, H. A., Mahmood, F. I., and TamizhMani, G., 2023. Use of non-contact voltmeter to quantify potential induced degradation in CdTe modules. Solar Energy. doi:https://doi.org/10.1016/j.solener.2023.02.002

Ren, J., *et al*., 2024. Predicting the lifetime of HJT modules towards the outdoor real-world environment. Solar Energy Materials and Solar Cells.

Risen. 2023. White paper of HJT Hyper-ion products of Risen Energy: development and applications of low-silver metallization paste. Avaiable at: https://en.risenenergy.com/uploads/20230828/77456af7682eb30d9b8f409bc2da4c59.pdf. Accessed on: Sep. 18, 2025

Risen, 2025. Hyper-ion Pro: Heterojunction Hyper-ion Series Bifacial Module (RSM132-8-720-745BHDG). Avaiable at: https://en.risen.com/uploads/20250702/298ba122d54ed2c06ea8a700c196c17f.pdf. Accessed on: September 29, 2025.

Saaty, T.L., 2008. Decision making with the analytic hierarchy process. Int. J. Services Sciences, Vol. 1, N°. 1, pp.83–98

Sample, T., *et al.*, 2009. Accelerated Ageing of Seven Different Thin-Film Module Types by Sequential Exposure to Damp Heat or Damp Heat with either Additional Applied Voltage or Ultraviolet Light. Proceedings of the 24th European Photovoltaic Solar Energy Conference. WIP-Renewable Energies

Shielden. 2024. Exploring Organic Solar Cells: The Frontier of Future Photovoltaic Technology. Avaiable at: https://www.shieldenchannel.com/blogs/solar-panels/organic-solar-cells?srsltid=AfmBOooSzrZw16YSQS qHOa70vrLTEXP-Rhe0Zd4bXyKd7i3YVxan84FL. Accessed on: Sep. 13, 2025

Straub-Mück, M., *et al.*., 2025. Determinants of the long-term degradation rate of photovoltaic modules: A meta-analysis. Renewable and Sustainable Energy Reviews. doi:https://doi.org/10.1016/j.rser.2025.115697

Thornton, P., Moffitt, S. L., Schelhas, L. T., and Dauskardt, R. H., 2022. Dependence of adhesion on degradation mechanisms of ethylene co-vinyl acetate encapsulants over the lifetime of photovoltaic modules. Solar Energy Materials and Solar Cells. doi:https://doi.org/10.1016/j.solmat.2022.111818

Valporto, O., 2023. Agro avança e já toma metade das áreas do Cerrado. Projeto Colabora, 31 ago. 2023. Avaiable at: https://projetocolabora.com.br/ods15/agro-avanca-e-ja-toma-metade-das-areas-do-cerrado/. Accessed on: Oct. 17. 2025.

Vikranth. 2025. TaiyangNews PV Price Index – 2025 - CW36. Retrieved from Taiyang News: Avaiable at: https://taiyangnews.info/price-index/taiyangnews-pv-price-index-2025-cw36. Accessed on: September 30, 2025

Wachsmuth, J., *et al*., 2023. Overcoming Moisture-Induced Degradation in Organic Solar Cells. Adv. Eng. Mater., 25: 2300595. doi:https://doi.org/10.1002/adem.202300595

Wallén, A. 2024. PV module type qualification – A review of different technologies from a reliability perspective. Master Thesis. Department of Energy Sciences. LUND University. Retrieved from http://lup.lub.lu.se/student-papers/record/9151164

Wang, G., *et al*., 2023. Molecular engineering of hole-selective layer for high band gap perovskites for highly efficient and stable perovskite-silicon tandem solar cells. Joule. doi:https://doi.org/10.1016/j.joule.2023.09.007

Wang, T., Yang, J., and Cao, Q., 2023. Room temperature nondestructive encapsulation via self-crosslinked fluorosilicone polymer enables damp heat-stable sustainable perovskite solar cells. Nat Commun 14, 1342. doi:https://doi.org/10.1038/s41467-023-36918-x

Wu, X., *et al*., 2025. Unveiling the degradation mechanisms in silicon heterojunction solar cells under accelerated damp-heat testing. Solar Energy Materials and Solar Cells. doi:https://doi.org/10.1016/j.solmat.2024.113325

Xu, L., *et al*., 2022. Potential-induced degradation in perovskite/silicon tandem photovoltaic modules. Cell Reports Physical Science. doi:https://doi.org/10.1016/j.xcrp.2022.101026

Yan, B., *et al*., 2025. 3D laminar flow–assisted crystallization of perovskites for square meter–sized solar modules. Science. doi:10.1126/science.adt5001

Yang, G., *et al*., 2025. Towards efficient, scalable and stable perovskite/silicon tandem solar cells. Nature Photonics 19, pages 913–924. doi: https://doi.org/10.1038/s41566-025-01732-y

Yeo, Z. Y., Ling, Z., Ho, J., Lim, Q. X., and So, Y., 2022. Status review and future perspectives on mitigating light-induced degradation on silicon-based solar cells. Renewable and Sustainable Energy Reviews. doi: https://doi.org/10.1016/j.rser.2022.112223

Yilmaz, P., *et al*., 2022. Post-mortem analysis of a commercial Copper Indium Gallium Diselenide (CIGS) photovoltaic module after potential induced degradation. Prog Photovolt Res Appl. doi:10.1002/pip.3538

Zeng, F., *et al*., 2024. Accelerated degradation of PET-based photovoltaic backsheets under UV and acetic acid exposure. Polymer. doi:https://doi.org/10.1016/j.polymer.2024.127671

Zeng, G., *et al*., 2019. Study on the Stability of Unpackaged CdS/CdTe Solar Cells with Different Structures. International Journal of Photoenergy. doi:https://doi.org/10.1155/2019/3579587

Zhang, J., *et al*., 2024. High-performance bifacial perovskite solar cells enabled by single-walled carbon nanotubes. Nat Commun 15, 2245 . doi:https://doi.org/10.1038/s41467-024-46620-1

Zwaal, D. 2024. The effect of degradation on the lifetime energy yield of crystalline-silicon/perovskite tandems. Master Thesis. Electrical Engineering, Mathematics and Computer Science. Delft University of Technology.