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THE TECHNOLOGICAL FRONTIER OF COMMERCIAL PHOTOVOLTAICS: CURRENT STATUS AND FUTURE DIRECTIONS FOR SILICON AND THIN-FILM TECHNOLOGIES

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Abstract: This review sheds light on the photovoltaic technologies' evolving progress, a technology involving light conversion into electricity via the photovoltaic effect. While with main focus on the first and second generation photovoltaic technologies, the scope of this review covers three generations of solar cell materials, examining the triumphs and challenges of the most representative and leading materials for each, in order to delineate the state of the art in the area. The technologies covered include: first-generation crystalline silicon (c-Si), second-generation commercial thin-film technologies such as cadmium telluride (CdTe) and copper indium gallium diselenide (CIGS), and third-generation emerging cells like perovskites. While c-Si is the leading PV technology due to its high maturity, high efficiency, and reliable large-scale manufacturing, its efficiency is limited theoretically. Thin-film technologies offer lower manufacturing costs, but rely on pricier encapsulation and scarce materials. Emerging technologies sit at the research frontier and can potentially surpass the efficiencies of the first and second generations, but lack demonstrated module-scale systems, and, in the case of the most efficient perovskites, face moisture-induced degradation and toxicity concerns. The conclusion is that as dominant technologies reach plateaus of performance improvement, future development focus must shift toward interface-oriented strategies, innovative architectures like the cross-fertilizing tandem cells, and solutions for material and environmental sustainability to continue advancing the field.

Keywords: Crystalline silicon; Cadmium telluride; Copper indium gallium diselenide; Hydrogenated amorphous silicon; Photovoltaics; Perovskite solar cells

1 INTRODUCTION

Solar energy stands out as one of the rare low-carbon renewable resources that possess the technological readiness and expansion potential in addressing the rising global need for electricity [1], and solar photovoltaics (PV) have achieved the widest application among all solar-based energy systems [2]. In 1954, the first generation of modern solar cells was developed, and it was later deployed in 1958 aboard a U.S. satellite. Globally, solar energy now ranks as the third-largest renewable electricity source [3]. Since 2000, the global PV installation capacity has maintained a 43% compound annual growth rate. Today, solar PV technology expands at the most rapid rate worldwide and brings the prospect of achieving zero-carbon terawatt-scale electricity production by mid-century. Since PV cells are light-driven and run at roughly ambient temperatures, not only do they not contain any mechanical components, they also support deployment at any scale without harming efficiency — in theory, a 10 m^2 PV array can achieve the same efficiency per unit area as a 10 km^2 PV array, outperforming wind turbines and thermal generators, as their efficiency declines with smaller scale [4]. This paper examines the first to third generation PV technologies, discusses the triumphs and limitations of specific materials that fall under each generation — for instance, the first-generation crystalline silicon (c-Si) technologies dominate the global PV deployment for numerous reasons such as high efficiency, verified manufacturability, and abundance in material, yet it is also constrained by many shortcomings. Ultimately, this paper comes up with a conclusion and an outlook on future research directions and the challenges and opportunities of PVs.

2 THE PHOTOELECTRIC EFFECT

The photoelectric effect, a quantum phenomenon, happens when incident electromagnetic radiation transfers energy to bound electrons in a material. The electron will be emitted from the surface of the material when the energy of the photon exceeds the work function of that material. The frequency of the incident radiation determines the maximum kinetic energy of the emitted electron according to $K_{max} = \hbar v - \phi$ [5]. The intensity of the incident radiation affects the number of electrons ejected, if the frequency is above threshold, instead of their individual energy. This effect proved that light comes in discrete packets, laid quantum mechanics' foundation, and Einstein's explanation using Planck's quantum hypothesis earned him the Nobel Prize in Physics [6].

3 FROM PHOTOELECTRIC EFFECT TO PHOTOVOLTAIC EFFECT

The photovoltaic effect is similar to the photoelectric effect in the sense that it also involves absorbing light—bundles of electromagnetic radiation—and exciting a charge carrier to a state with higher energy. Specifically, for the photovoltaic effect, the energy of the incident electromagnetic radiation is lower than the energy required for a low-energy charge carrier to escape into the vacuum; therefore, it is still bound to the atomic nuclei by attractive forces, meaning it's still contained within the material instead of out into the vacuum, and has an increased potential energy. This effect occurs in solar cells composed of a p-type semiconductor and an n-type semiconductor joined together as a p-n junction, forming a built-in electric field [1]. When photons excite electrons and holes, this internal field drives the negatively charged electrons and positively charged holes toward their respective ohmic contacts, allowing them to flow through an external circuit, thereby generating electrical power in a solar cell [4] (However, it is worth noting that the development in organic polymer PVs, dye-sensitive solar cells, and quantum dot PVs does not rely on a classical bulk p-n junction to achieve charge separation) [1].

4 SOLAR CELLS

The individual solar cells act as the fundamental units and are assembled into PV modules, which are then deployed in series and/or parallel to form PV arrays. The arrays interface with balance-of-system hardware components (which convert the low-voltage direct current from the PV modules into high-voltage alternating current suitable for grid integration through components like the transformers, combiners, and inverters). As a result, the array delivers a net voltage and a net voltage from the modules engenders a net current under constant illumination, with an output power density given by: $\frac{P_{out}}{area} = \frac{I}{area} \cdot V = J \cdot V\ [A/m^2] \cdot [V] = [W/m^2]$ [7]. Although PV offers clean and renewable energy sources, has low operational costs, is highly scalable from small installations to large plants, it is also challenged by highly variable solar energy and high initial installation costs [1]. Based on the type of materials and fabrication technologies employed, solar cells can be categorized into three generations: the commercially dominant first and second, and the emerging third (early stage of commercialization), see Table 1.

Table 1 Comparison of First and Second Generation PV Technologies

Generation	First	Second	Second	Second
Technology	Crystalline Silicon (c-Si)	Cadmium Telluride (CdTe)	Copper Indium Gallium Diselenide (CIGS)	Hydrogenated Amorphous Silicon (a-Si:H)
Film/Wafer Thickness (μm)	mc-Si: 180-200 μm [8] sc-Si: 150-180 μm [4]	0.1-10 μm [1]	0.1-10 μm [1]	0.3 μm [1] ****
Cell PCE Record	mc-Si: 20.8% sc-Si: 25.6% [4]	21% [4]	21.7% [4]	13.4% for triple-junction cell [4]
Module PCE Record	mc-Si: 18.5% sc-Si: 22.4% [4]	17.5% [4]	17.5% [4]	12.2% for dual-junction module [4]
Materials Utilization	N/A**	90-99% [11]	60-80% [11]	15-70% [11]
PV Market Share	mc-Si: ~55% sc-Si: ~35% [9]	5% [4]	2% [4]	2% [4]
Resource Abundancy	Silicon: abundant [4]	Telluride: scarce [4]	Indium: scarce [4]	Silicon: abundant [4]
Cost Per Watt	$0.25-0.27/W [10]*	$0.28/W [10]	$0.48/W [10]	N/A***
Toxicity	Non-toxic [4]	Cadmium: toxic [4]	Low toxicity [12]	Non-toxic [4]

Note: This table summarizes the main parameters of the first and second generation PV technologies covered later in this review for reference.

*The costs listed for c-Si, CdTe, and CIGS are their minimum sustainable prices (MSP), which is derived from a bottom-up manufacturing cost analysis. This price includes a 15% gross margin to account for the minimum rate of return required for long-term business viability [10].

**The materials utilization mentioned stands for the proportion of the raw material successfully manufactured into the final PV module. However, that for c-Si is not specified due to the limited data available.

***The cost listed for a-Si:H is N/A since this technology has lost ground in recent years, displaced by more competitive mc-Si, sc-Si, and CdTe technologies [13].

****The film thickness listed for a-Si:H can absorb close to 85% of photons exceeding the bandgap in one passage [1].

5 COMMERCIAL PHOTOVOLTAICS

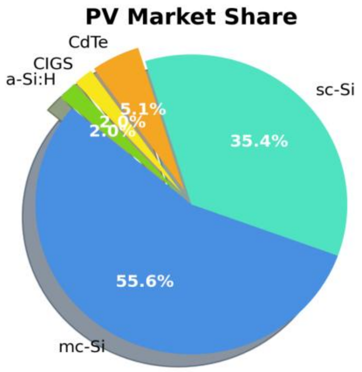

Figure 1 PV Market Share of First-and Second-Generation PV Technologies

Commercial photovoltaic technologies are mainly made up of the first-generation wafer-based crystalline silicon (single-crystalline [sc-Si] and multicrystalline [mc-Si]) and the second-generation thin-film technologies (copper indium gallium diselenide [CIGS], cadmium telluride [CdTe], and hydrogenated amorphous silicon [a-Si:H]), each with its respective PV market share shown in Figure 1 above.

5.1 First Generation — Crystalline Silicon

Categorized as the first generation PV technology, the conventional wafer-based PV cells are built on semiconducting wafers and do not require additional substrate for handling, though glass is usually added at the final modules to ensure durability and protection. This generation PV technology took up the vast majority of the global PV market, is the most mature, and is typically made from either single-crystalline silicon (sc-Si), with market shares of ~35%, or multicrystalline (mc-Si), with market shares of ~55%, as shown in Figure 1. These two types of crystalline silicon PV make up about 90% of worldwide commercial PV module manufacturing due to the long research history in semiconductors, their high efficiency, and non-toxicity [1,4]. A typical photovoltaic module's glass surface contributes to roughly 75% of the total weight, with silicon taking up only 5% [14]. The contact lines and interconnectors are even lighter in proportion, with silver <0.1% and copper 1% [8]. Additionally, after more than 60 years of development, crystalline silicon and multicrystalline silicon offer the most reliable large-scale manufacturing among all solar cells [1], from lab prototypes to real commercial modules with only 3-4% efficiency lost [15].

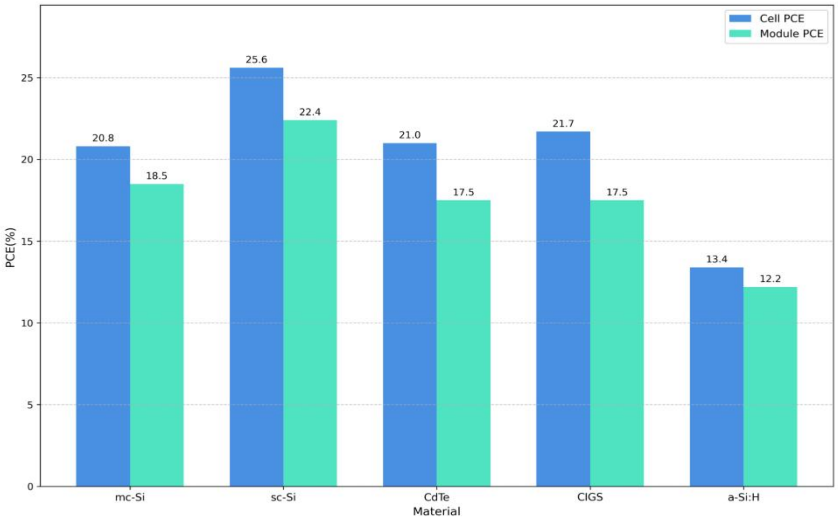

Figure 2 Power Conversion Efficiency of First-and Second-Generation PV Technologies

Multicrystalline cells are made from casting molten silicon into blocks [16], and have roughly 1 cm^2 grains randomly oriented, which, though easier to produce, those grain boundaries reduces the charge extraction efficiency, with a cell efficiency record at 20.8% and a large-format PV module record at 18.5%, shown in Figure 2. Yet the indirect bandgap of crystalline silicon results in poor light absorption, meaning that absorption needs more material, which entails brittle, rigid, impurity-free, and thicker wafers (180-200 μm) [4,8] for high efficiency, costly for sure. In contrast, single-crystalline silicons, mostly with cylindrical ingots grown by the Czochralski (CZ) or float-zone (FZ) methods [17,18] and sliced into very thin wafers, 150-180 μm, consist of a single silicon crystal. The improved crystal quality in single-crystalline cells boosts both charge extraction and power conversion efficiency (25.6% cell efficiency record and 22.4% large-format PV module record, see Figure 2), saving space and functioning well in dim light conditions, though it requires more expensive wafers (20% to 30% more costly, shown in Figure 2) [8]. A top-performing variant, the HIT design (heterojunction with intrinsic thin layer) reduces interfacial carrier recombination by joining the n-type single-crystal silicon with a thin amorphous silicon layer, and thus boosting the open-circuit voltage (5-10%) [4]. Nevertheless, the significant material volume and long lifetime for silicon's charge carriers substantially increased the effect of minor defects on particular losses caused by non-radiative recombination mechanisms such as Auger recombination [15,9]. As a result, these intrinsic properties, along with the Shockley–Queisser limit, greatly limit the performance of crystalline silicon-based cells, with a maximum achievable power conversion efficiency (PCE) of 29.4% [15]. Moreover, the high material use, high requirement for material purity, the slow production rate from batch processing, substantial waste output in production [4,16], and limited flexibility in module form are also challenges faced by crystalline silicon PVs [1,4,8].

5.2 Second Generation — Commercial Thin-Film

Thin-film technology solar cells, classified as the second generation PV technology and made from thin-film semiconductors, are commercially established, widely utilized, and now account for roughly 10% of the world's photovoltaic module production. Thin film solar cells are produced by applying a thin photoactive layer onto a transparent substrate, typically glass or a transparent film, and this single-process manufacture greatly diminishes production costs [8]. Primarily represented by copper indium gallium diselenide (CIGS), cadmium telluride (CdTe), and hydrogenated amorphous silicon (a-Si:H)*, thin-film photoactive materials have 10-100 times higher light absorption efficiency than silicon, and only a few microns of film are needed [4]. Therefore, low demand for raw materials (often 99% less than crystalline solar cells) offers significant advantages to this technology, and they are often regarded as cost-efficient [1]. Additionally, thin-film modules can be fabricated in advanced facilities with a high degree of automation and optimized workflow [4].

The Cadmium telluride (CdTe) modules currently dominate global thin-film PV installations, take up 56% of the thin-film market share (and about 5% share in the global PV market, shown in Figure 1), and are the most cost-efficient PV technology on the market. The CdTe has a cell efficiency record of 21% and a module efficiency record of 17.5%, as shown in Figure 2, making it a high-performance thin-film cell technology, and it is still improving. Moreover, CdTe features a direct bandgap of 1.45 eV, ideal for solar energy conversion, and exhibits a strong absorption over a wide range of the solar spectrum. Despite the high processing temperature of around 500 degrees Celsius needed, CdTe manufacturing uses high-throughput deposition methods, making the module cost the lowest among all photovoltaic technologies by contributing to simplicity and scalability. Yet the scarcity of tellurium is a significant bottleneck [4,8], and at current production rates, achieving 25 TW_p installations would require the amount of tellurium as much as 1,500 years of global production. However, although toxicity issues and ecological barriers associated with cadmium are another limiting factor that restricts its usage [4], there have been safe methods for producing, installation, and recycling, after 15 years of focused development on CdTe. Additionally, CdTe's extremely poor solubility in aqueous environments reduces the risk of groundwater contamination [15].

Copper indium gallium diselenide (CIGS) takes up approximately 22% of the thin-film market share (and 2% share in the global PV market, shown in Figure 1), less widespread than CdTe. It is also a high-performance technology, which has nearly the same PCE records as CdTe, see Figure 2. As shown by Figure 3, these cells are typically built on soda-lime glass, then coated with molybdenum back contact. The active absorber layer is manufactured by co-evaporation or sputtering of copper, gallium, selenium, and indium, then annealed in a selenium-rich atmosphere, a stage known as chalcogenization that promotes CIGS formation. The layers above are to improve light transmission and strengthen conductivity, consisting of undoped ZnO and aluminum-doped ZnO [8].

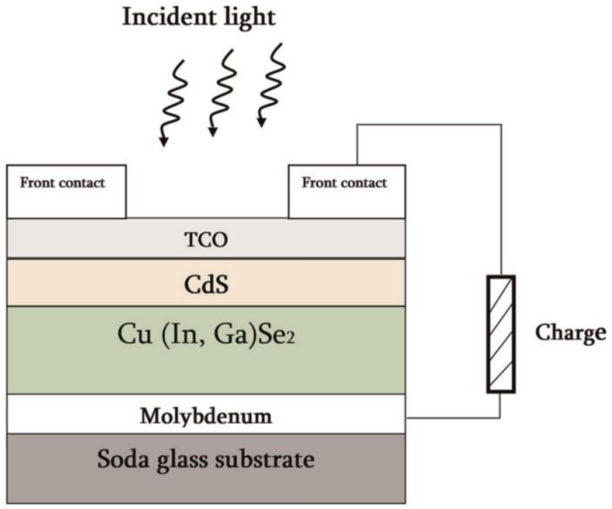

Figure 3 Structure of a Solar Cell based on CIGS [19]
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CIGS thin-films are well-suited for building-integrated and other nontraditional photovoltaic applications, since they can be applied to flexible substrates, but likely, the scarcity of indium could inhibit their scalability [1]. As a compound semiconductor, CIGS has a direct bandgap between 1.1 and 1.2 eV, favorable for photovoltaics, and also demonstrates high resistance to radiation, enabling space applications [4]. Moreover, the toxicity of the elements composing CIGS is low [12]. However, CIGS is facing six major hurdles: limited abundance of indium, large inconsistencies in the film's chemical composition and material properties, making it difficult for industrial mass production; unclear understanding of the impact of grain boundaries on performance, restricting optimization; reduced open-circuit voltage induced by material and electronic inhomogeneity; difficulty of engineering wider-bandgap alloys required for multijunction devices without sacrificing performance; photocurrent losses due to the transparent conductive oxide layer on the top [4].

Hydrogenated amorphous silicon (a-Si:H) has a market share of 2% worldwide and 22% in the thin-film market, as shown in Figure 1. As a non-crystalline form of silicon that has more effective light absorption compared to crystalline silicon, it benefits from the low cost, abundance, and non-toxicity of its base material. It can be deposited by PECVD at temperatures as low as 150-300 degrees Celsius, with a thin 300 nm film capable of absorbing about 90% of photons above the bandgap, enabling PV modules to be lightweight with flexible integration options. Additionally, it is usually used in multijunction cells with nc-Si or a-SiGe without being constrained by lattice-matching [4]. Yet, its performance stability is limited by light-induced degradation—known as the Staebler–Wronski effect— due to the intrinsic unstable nature of a-Si:H [1]. Its bandgap width of roughly 1.7-1.8 eV, compared to 1.12 eV for crystalline silicon, also limits its spectral matching, and results in comparatively lower efficiency relative to its competing thin-film technologies — with a multijunction device record at only 12.2% for a dual-junction module and 13.4% for a triple-junction cell, shown in Figure 2. Furthermore, a-Si:H technology has seen little to no progress in PCE over the past decade due to the inherent material flaws of static disorder in the absorber layer. Intrinsic flaws in the material contribute to the highest operational losses among the thin-film materials evaluated, and the voltage loss caused by the tail states in an amorphous absorber poses an even greater challenge to commercialization than the well-studied Staebler-Wronski degradation effect mentioned previously [15]. Furthermore, it has already lost its once noticeable share of the PV market due to failing to keep pace with the cost reduction of c-Si and the efficiency improvements seen in CdTe and CIGS [13].

Notably, recent progress in single-crystalline silicon and polycrystalline CIGS and CdTe cells mostly arises from modifying interfaces or device structures, suggesting that the absorber materials of the technologies are reaching a performance plateau. Commercial thin-film modules often underperform in power conversion efficiency, generally falling between 12% and 15%, in contrast to first-generation crystalline silicon cells' 15-21% (Even so, in the past 5 years, cell efficiencies in CdTe and CIGS have been significantly increased) [15]. Despite the smaller material footprint of thin-film solar cells than that of crystalline silicon cells, the electronic waste caused by the inappropriate disposal of end-of-life panels poses concerning environmental threats [8]. In addition, some thin-film technologies, such as the CIGS and CdTe, rely on rare and harmful elements, thereby limiting the deployment on a large scale and decreasing sustainability [1,15]. Another major limitation to commercial thin-film PV is its sensitivity to moisture and oxygen, demanding pricier airtight encapsulation to guarantee 25 years of reliability [4].

6 EMERGING PHOTOVOLTAICS — THIRD/NEXT GENERATION

The third generation of PV cells falls under the category of "most recent and most advanced" technology [8], nanoengineered rationally to reach the potential to surpass the PCE of both crystalline silicon and thin-film technologies [1], and points to strong potential for scaling up manufacturing and deployment [4]. These materials refer to emerging photovoltaic technologies beyond first-generation traditional crystalline silicon and second-generation thin-film cells, with industrial development primarily centered on perovskite solar cells (PSCs), organic photovoltaics (OPVs), and Colloidal Quantum Dot Photovoltaics (QDPV). Moreover, third-generation materials aim at diminishing manufacturing costs, simplifying fabrication processes for large-scale production, reaching visible transparency, unconventional shapes and formats [1], minimizing material consumption, and relying more on earth-abundant materials [4]. Even though the third-generation photovoltaics involve more complex chemistries, they are usually suitable for rapid thin-film deposition after synthesis. Their architectures typically enable thinner absorber layers, lighter devices, and integration with flexible substrates, which increases the power-to-weight ratio. In addition, their structure allows the existence of greater material impurity than most first-and second-generation PV technologies.

Perovskite solar cells (PSCs) have quickly become a leading contender among third-generation thin-film PV technologies, with record PCE soaring from 10.9% to 20.1% in less than three years. "Perovskite" refers to the specific crystal structure of the film absorbing light — hybrid organic-inorganic lead halides. This class of material has several benefits: charge carriers can diffuse over long distances, minimal recombination losses, cheap production costs, and the flexibility in adjusting bandgap through cation/anion substitution. Moreover, it reached notably high open-circuit voltages of roughly 1.1 V in the early version of perovskite cells, reaching one of the hardest-to-achieve performance metrics for solar technologies. Major technological obstacles exist, such as more precise control of film structure and material properties, preventing moisture degradation, verifying long-term stability, and reducing the reliance on toxic lead [1].

Organic PVs (OPVs)'s light absorption process utilizes organic small molecules or polymers that are made from primarily earth-abundant elements, and the thin-films are manufactured using large-area, high-throughput deposition methods. OPVs boast certified lab PCEs of up to 11.1% and real deployment module PCEs of up to 8.7%. Additionally, it has the strengths of compatibility with scalable deposition methods, multijunction architecture potential, low-cost material and manufacture, and high defect tolerance property, which facilitates easy fabrication. However, OPVs remain limited by inefficiency in charge carriers transport, poor long-term durability, low yield during large-panel thin-film deposition, and modest PCE ceilings [4].

Colloidal Quantum Dot Photovoltaics (QDPV) rely on quantum dots, solution-processed metal chalcogenide nanocrystals, to absorb light, and they enable precise tuning of the light wavelength being absorbed, thereby allowing the absorption of near-infrared light as well as multijunction architectures of the same material. Nowadays, this technology has seen a gradual increase in PCE, with recent lab-scale cells reaching 9.2%. Despite the simplicity in manufacturing and reasonable stability against moisture and oxygen, QDPV is facing the bottlenecks of unclear understanding of quantum dot surface stoichiometry, limited mobility of charged carriers, and low open-circuit voltages that possibly originated from mid-gap traps or disordered structure inherent to quantum dot films [1].

Despite all the edge-cutting advancements, emerging solar cells face numerous challenges, such as economic practicality, attributing to low PCE, lack of demonstrated module-scale systems, and limited material stability. Therefore, a major focus going forward is on enhancing both power conversion efficiency and long-term stability of next-generation semiconductor materials so they can be innovated and widely deployed [1].

7 CONCLUSION

This review examines the development process of commercial photovoltaic technologies from the first generation to the third generation, whose evolution process is closely tied to market trade-offs. The first-generation technology is dominated by crystalline silicon, accounting for about 90% of worldwide commercial PV module manufacturing, and has achieved considerable technological maturity. Yet, its PCE has approached its theoretical limit of 29.4%, signifying little to no room for improvement, as well as the limitations of high material consumption, low tolerance to material impurity, and the slow production rate. As a result, the second generation commercial PV technology — thin-film technologies emerged. Although it successfully diminishes material cost by achieving 10-100 times higher absorption efficiency than crystalline silicon, its PCE is generally significantly lower, and faces serious concerns about the scarcity and toxicity of materials such as tellurium and indium, and their susceptibility to moisture and oxygen in ambient conditions. Thus, the third generation, emerging technologies, were introduced. Despite the great potential to surpass the PCE of the first and second generation technologies with materials such as PSCs and the utilization of earth-abundant materials, this generation of technology faces the bottleneck of the absence of proven module-scale systems, low PCE, and poor material stability. This development pathway for PV technologies reflects the ongoing effort in photovoltaics to balance between efficiency, cost, stability, and sustainability.

As the performance of dominant technologies such as CIGS and CdTe is experiencing a considerable slowdown, the focus of future research should shift from bulk material advancements into more refined, interface-oriented strategies to better diminish recombination and voltage losses at the interface. For multicrystalline cells, a clearer understanding of the impact of grain boundaries is also imperative to the optimization of future solar cells. In order to overcome the Shockley-Queisser efficiency limit for single-junction solar cells, developing high-efficiency cell architectures such as bifacial panels, as shown in Figure A1 in the appendix [8], and cross-fertilizing different technologies, such as the emergence of tandem solar cells, which integrate high-performing perovskite layers with mature crystalline silicon cells, is also a crucial strategy. Additionally, further research is also needed on solving the scarcity of materials for CdTe and CIGS, eliminating their detrimental effects on the ecology, and formulating more suitable recycling processes [15]. Despite being incremental, ongoing improvements will secure commercial PV technologies as the central pillar of the global solar industry for years to come.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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APPENDIX

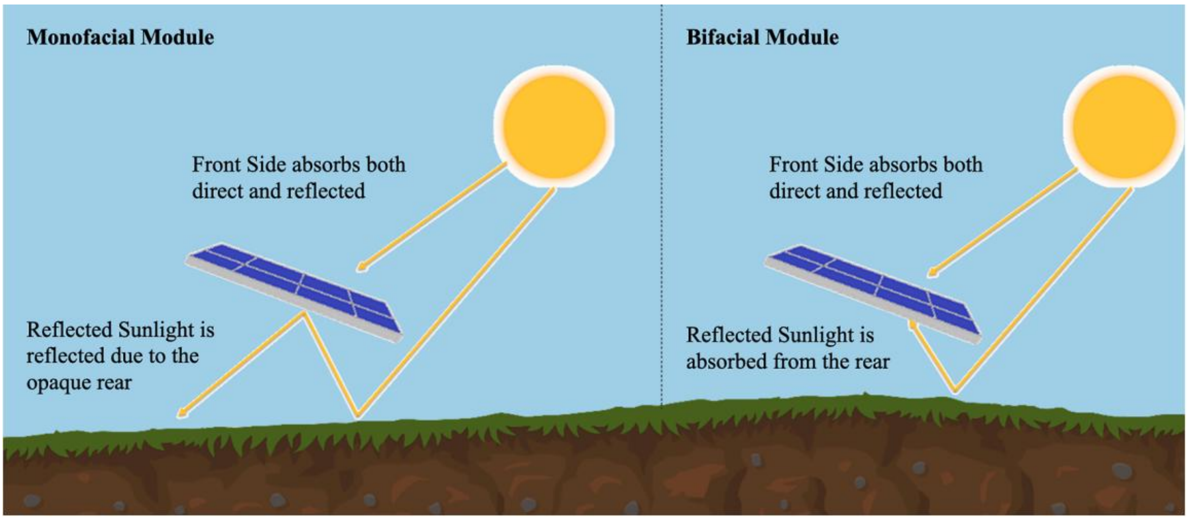

Figure A1 The Operational Concept of a Monofacial Module vs. a Bifacial Module [8]

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* Commercial amorphous silicon (a-Si) solar cells are typically hydrogenated (a-Si:H), and in the PV industry, the two terms can be used interchangeably.