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The next generation of photovoltaic cells: Emerging materials, efficiency improvement strategies, and sustainability pathways

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Abstract

Photovoltaics (PV) have taken centre stage in the world's clean-energy transition. As of 2023, the cumulative installed capacity is more than 1.6 TW with a projection of over 6 TW by 2030. In the last 25 years, there have been extraordinary increases in conversion efficiency, making crystalline silicon cells the highest efficiency (over 26%), thin-film CdTe and CIGS devices the highest efficiency (over 23%), and perovskite cells the highest efficiency (over 26%). In addition, new tandem architectures have already crossed the 33% mark. The given review is a comparative overview of the first, second, and third-generation PV technologies, critically examining the leading strategies for efficacy enhancement, i.e., the management of the optical, the state of the cell design, the thermal control, and the optimization with the help of artificial intelligence. Several issues persist: operational instability when working in the real world, the toxicity of some materials, the lack of certain critical raw elements, and the high manufacturing cost. Future solar technologies will also incorporate a combination of environmentally friendly materials, some principles of the circular economy, and the concepts of multiple applications, like agrivoltaics, floating PV, and building-integrated photovoltaics (BIPV). Finally, the AI-enabled design and predictive digital twins will redesign the scalability and robustness of sustainable PV systems, ensuring the role of solar energy as one of the key pillars of the net-zero transition.

Keywords: Photovoltaics; Solar energy; Perovskite; Thin-film; Tandem cells; Artificial intelligence.

1. Introduction

The ever-growing energy transition in the world is driven by the pressing need to reduce climate change and satisfy the ever-increasing demand for electricity. Modern civilization has mainly been based on fossil fuels; however, they lack sustainability because of greenhouse gas emissions, environmental degradation, and their non-renewable nature [1]. Unlike this, solar energy is the most natural, universal, and clean energy source; the amount of solar radiation the Earth receives within an hour is more than all the world consumes annually. Tapping into this vast potential, photovoltaics (PV) have become the most rapidly developing renewable technology, with the cumulative installed capacity exceeding 1.6 terawatts (TW) in 2023 and projected to pass 6 TW by 2030 (IRENA, 2024) [2].

Over the last five decades, PV technology has undergone three generations of development characterized by unique materials, architectures, and trade-offs [3].

The current market is mainly dominated by first-generation crystalline silicon (c-Si) devices, with commercial efficiencies ranging between 15 and 22% and the highest laboratory efficiencies of more than 26%. Their achievements lie in material maturity, reliability, and scalable production. Yet they are limited by large, energy-consuming production, and the theoretical limit in Shockley–Queisser's theory is about 29% [4].

Second-generation thin-film technologies, such as cadmium telluride (CdTe), copper indium gallium selenide (CIGS), and amorphous silicon (a-Si), were also developed to consume less material and be less expensive. These provide light and flexible modules and reduced temperatures, but they have high barriers: toxicity (Cd), unavailability of essential elements (In, Ga, Te), and average long-term stability.

Third-generation emergent PVs, including perovskites, organic photovoltaics (OPVs), quantum dots, and tandem structures, have captured the world's attention by generating record efficiencies of up to 26–33% with theoretical performance levels of up to 40%. Their dramatic ascent highlights their disruptive potential, but stability, scalability, and greenness remain problematic.

Table 1 summarizes the comparative properties of the various PV generations. Figure 1 follows the history of efficiency increases, starting with the consistent silicon improvements and the commercial viability of thin films, up to the blistering advances of perovskite and tandem technologies. Figure 2 shows the trade-offs of efficiency and cost: silicon is the best choice because of the established technology, thin films come with low-cost alternatives, and perovskites are promising due to their middle range of high efficiency and low cost, but their instability limits their future. Tandem designs are already at or above 33% efficiency, but are still restricted by complex fabrication and the high cost of manufacture.

PV technologies need to consider challenges at the system level, such as intermittency, land-use issues, and life cycle sustainability, on top of material and efficiency considerations. Intermittency requires new energy storage approaches, hybrid designs,

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and smart grids, whereas sustainability demands the use of a circular economy mindset, new recycling methods, and the removal of dangerous substances. Although many reviews have focused on individual materials or efficiency improvement methods, limited reviews have presented a combined approach in connecting material innovations, device architectures, efficiency optimization practices, and the new role of artificial intelligence (AI). The current review will offer a bridging point for this gap, bringing together the latest developments, critically evaluating the barriers hindering progress, and delineating the future-looking directions towards developing long-lasting, cost-efficient, and sustainable PV technologies.

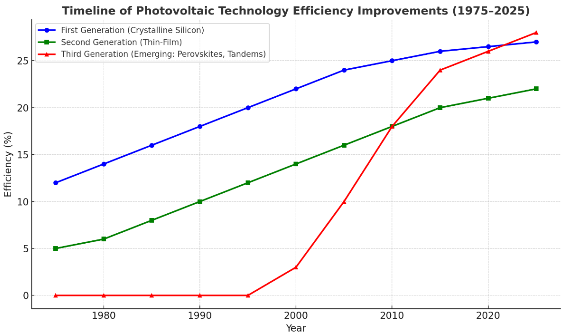

Figure 1: Timeline of photovoltaic technology efficiency improvements (1975–2025).

This number demonstrates how the power conversion efficiency (PCE) of solar technologies has evolved throughout three generations. First-generation crystalline silicon has had consistent, incremental gains; second-generation thin-film technologies have made moderate gains while reducing materials usage; and perovskite and tandem solar cells have achieved rapid gains in efficiency over the last ten years, reaching 26% and promising further gains as they are scaled up.

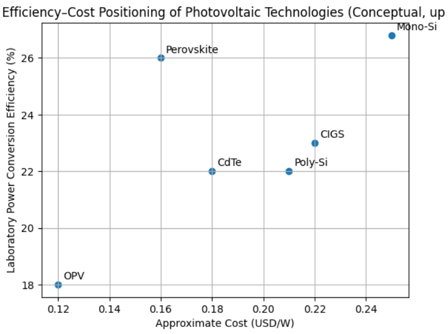

Figure 2: Efficiency versus cost comparison of major photovoltaic technologies.

This number compares laboratory power conversion efficiency (PCE) with the approximate cost per watt of dominant PV technologies. The market leader is crystalline silicon, which is highly efficient and cost-effective. Thin-film CdTe and CIGS offer competitive low-cost alternatives, while perovskites promise high efficiency and potentially very low costs but face stability issues. Tandem architectures hold record efficiencies (33%), but are restricted by high fabrication cost, whereas OPVs and quantum dots remain in research with lower efficiency and commercialization barriers. Photovoltaic (PV) technology has experienced sustained global growth, with cumulative installed capacity surpassing 1.6 TW by 2024–2025, driven by rapid cost reductions, policy support, and continuous efficiency improvements. According to recent reports and efficiency benchmarks published up to 2025, silicon-based technologies remain dominant, while emerging photovoltaic concepts—particularly perovskite-based and tandem architectures—are redefining the upper limits of power conversion efficiency [5, 6].

Table 2 presents a comparative sustainability-based evaluation of key PV technologies, which emphasizes the environmental trade-offs that are becoming the defining aspect of technology choice beyond efficiency considerations. Although crystalline silicon has shown the most well-developed circular economy route owing to the existing recycling infrastructures, its sustainability levels are nonetheless affected by the costly purification systems and silver use in metallization. Thin-film technologies, especially CdTe and CIGS, have efficiency advantages in material usage, but are limited by the toxicity of cadmium and the unavailability of rare elements like indium, gallium, and tellurium. New photovoltaic materials, like perovskite, organic, and quantum dot solar cells, have a promise of high efficiency and low material cost, but current constraints include the use of lead-based materials, short lifetimes under operational conditions, and the lack of recycling routes at an industrial scale. Tandem and multi-junction designs are the most efficient, but have a technology-dependent sustainability profile and face end-of-life separation challenges and material complexity. In general, the comparison highlights that future photovoltaic implementation must offset efficiency gains against material safety, recyclability, and lifecycle effects.

2. Fundamentals of photovoltaic technology

Photovoltaic (PV) technology is constructed on the principle of direct transformation of sunlight into electricity using the photovoltaic effect initially discovered by Edmond Becquerel in 1839, then developed for real devices in the mid-20th century. A PV cell is a semiconductor junction that absorbs photons, creates electron-hole pairs, and separates them by an internal electric field to make a direct current (DC). The quality of the junction, light absorption, and carrier collection are the main factors that determine the performance of a PV cell, which depends on the material and its band gap. Over the years, PV technologies have been divided into three broad generations depending on the materials, device designs, and trade-off between cost-effectiveness and efficiency.

2.1. First generation: Silicon-based solar cells

The photovoltaic industry is still dominated by crystalline silicon (c-Si) solar cells, occupying over 90% of the world market. Two major types are monocrystalline silicon (mono-Si) and polycrystalline silicon (poly-Si). Mono-Si cells, which generally have greater efficiencies of 20–26%, are more expensive than poly-Si cells, which are slightly less efficient at 15–20% but cheaper to produce [7]. The popularity of silicon technology is greatly attributed to its stability in long-term operation, availability of raw materials, and highly developed manufacturing procedures. However, several obstacles remain, such as comparatively expensive production, the inflexibility and mass of modules, and a theoretical maximum efficiency set by the Shockley–Queisser limit (approximately 29%).

2.2. Second generation: Thin-film solar cells

The second-generation photovoltaic technology was created to minimize the number of materials and cost of manufacture through thin absorber layers of as little as 1–2 μm (compared to the silicon technology of the time, where the wafers were much thicker). Cadmium telluride (CdTe) is among the most significant of the thin-film technologies, as it is relatively inexpensive and reasonably easy to manufacture, and its highest efficiency records

Table 1: Comparative overview of photovoltaic technology generations.

PV Generation	Main Technologies	Typical Efficiency (Lab / Commercial)	Key Advantages	Main Challenges
First Generation (Crystalline Silicon)	Mono-Si, Poly-Si	20–26% / 15–22%	Mature technology, long-term stability, abundant raw materials, and a well-established industry	High production cost, rigid/heavy modules, limited by Shockley–Queisser limit (∼29%)
Second Generation (Thin-Film)	CdTe, CIGS, a-Si	18–23% / 10–20%	Lower material consumption, flexible and lightweight, lower cost potential	Toxicity (Cd), scarcity (In, Ga, Te), lower stability, Staebler–Wronski effect (a-Si)
Third Generation (Emerging)	Perovskites, OPVs, Quantum Dots, Tandems	26–33%+ (lab) / 20% (pilot)	High efficiency potential, tunable bandgap, low-cost fabrication, novel architectures (tandem, bifacial, semi-transparent)	Poor long-term stability, toxicity (Pb, Cd), scalability challenges, moisture/UV degradation

Table 2: Sustainability and environmental aspects of photovoltaic technologies.

PV Technology	Critical / Toxic Materials	Recyclability Status	Main Environmental Concerns	Sustainability Outlook
Crystalline Silicon (c-Si)	None (trace Ag, Pb in solder)	High (industrial recycling available)	Energy-intensive purification, silver consumption	High – mature circular economy pathways
CdTe Thin-Film	Cadmium (Cd), Tellurium (Te)	Medium–High (closed-loop recycling possible)	Toxicity of Cd, limited Te supply	Moderate – depends on recycling enforcement
CIGS Thin-Film	Indium (In), Gallium (Ga), Selenium	Medium	Scarcity of In/Ga, complex separation	Moderate–Low
Perovskite Solar Cells	Lead (Pb) (dominant), Sn (emerging)	Low (lab-scale only)	Lead leakage, moisture instability	Promising but conditional on Pb-free solutions
Organic PV (OPV)	Minimal toxic elements	Low–Medium	Short lifetime, encapsulation waste	Moderate for niche applications
Quantum Dot Solar Cells	Pb, Cd (in most designs)	Low	Heavy-metal toxicity, stability issues	Low–Moderate (early research stage)
Tandem / Multi-Junction	Technology-dependent	Medium	Complex material stacks, recycling difficulty	High efficiency but sustainability challenges

are over 22% [8]. Nevertheless, cadmium's toxicity and tellurium's scarce resources are still acute environmental and resource issues. By contrast, copper indium gallium selenide (CIGS) cells have a high absorption coefficient and a tunable bandgap of 1.0 to 1.7 eV, permitting better spectral utilization, and have achieved efficiencies of over 23% [9]. However, the shortage of indium and gallium and the complicated deposition process still make large-scale implementation difficult. Another thin-film technology is amorphous silicon (a-Si), which is lightweight, flexible, and relatively cheap. Despite these benefits, it has low commercial potential due to small efficiencies (6–10%) and inherent instability problems like the Staebler–Wronski effect.

2.3. Third generation: Emerging solar cells

Third-generation solar cells include new photovoltaic technologies that aim to overcome the cost-efficiency trade-off inherent in traditional single-junction devices and surpass the Shockley–Queisser limit. Perovskite solar cells (PSCs) exhibit tremendous growth, with a meteoric increase in power conversion efficiency from 3% in 2009 to more than 26% in less than a decade [10, 11]. Their advantages are cheap solution processing, tunable band gaps, and compatibility with tandem architecture. Their broad use is, however, deterred by their instability in wet, hot, and ultraviolet (UV) light conditions and lead toxicity, which has become an environmental and regulatory issue.

Organic photovoltaics (OPVs) are a technology based on π-conjugated polymers and small-molecule semiconductors, with distinct benefits: mechanical flexibility, semi-transparency, and roll-to-roll fabrication on large scales. Recently, the development of non-fullerene acceptors (NFAs) has pushed OPV efficiencies to levels exceeding 15%, providing a major breakthrough for this material class. However, short working life, susceptibility to oxygen and moisture, and performance deterioration under light conditions remain hindrances to their commercial applications.

Quantum dot solar cells (QDSCs) utilize quantum confinement effects to tune band gaps and permit multiple exciton generation, which theoretically can overcome traditional efficiency limits. Currently, QDSCs show efficiencies of 13–16%, with the potential to exceed 30%, making them an interesting next-generation technology once stability and toxicity concerns linked to heavy metals such as lead and cadmium are addressed.

Finally, tandem and multi-junction architectures embody the most direct route toward ultrahigh-efficiency photovoltaics. By stacking absorber layers with complementary band gaps, these devices maximize the capture of the solar spectrum. Perovskite/silicon tandem cells have achieved over 33% efficiency, while III–V multi-junction devices under concentrated sunlight have surpassed 40% [12]. However, III-V materials' high cost and complex fabrication confine their use mainly to space and specialty applications. In contrast, scalability and long-term stability remain the critical hurdles for perovskite-based tandem systems.

3. Advances in photovoltaic materials

The performance, cost, and sustainability of photovoltaic (PV) systems largely depend on the nature of the absorber and charge transport material. In the last twenty years, many studies have been conducted on developing new classes of semiconductors, such as thin films, perovskites, organic compounds, and quantum dots, and on improving well-established silicon-based systems.

This section gives an overview of these developments and explains the progress that has been made and the challenges that still affect them.

3.1. Silicon-based materials

The monocrystalline silicon cells are considered the state of the art in photovoltaic technology, with recent laboratory results showing efficiencies above 26% [5]. New technologies such as PERC structures, the heterojunction structure based on amorphous silicon stacking, and enhanced texturing that optimises light absorption have increased conversion rates. Scientists are giving growing attention to thinning down the wafer without reducing rigidity and to bifacial surfaces, which access sunlight on both sides and increase the energy yield [13]. Poly-Si ensures reduced capital outlay due to simplicity in manufacturing, with existing commercial equipment achieving nearly 20% efficiency. Development in this direction is achieved by active doping to passivate defects, intentional design of grain boundaries, and cast-mono ingot processes that confer specific monocrystalline properties, effectively reducing the yield gap to monocrystalline boundaries. Nevertheless, the community faces the larger question of bringing output to its theoretical limit of about 29% without sacrificing cost trajectory.

3.2. Thin-film materials

To cut down on material usage and hence costs, thin-film solar cells were invented, where layers of absorber are used a few micrometers in depth. Of these, cadmium telluride (CdTe) has performed well because of its high absorption coefficient, and therefore, thin absorbers can be realized in 2 μm. New records of more than 22% efficiency have been reached with doping, surface passivation, and tandem integration plans. Nonetheless, there is still concern over cadmium toxicity and low tellurium supply. Copper indium gallium selenide (CIGS) cells, whose bandgap can be tuned (1.0 to 1.7 eV), allow optimal spectral selection and have been optimized to exceed 23% efficiency. Their scalability is limited, however, by the lack of indium and gallium and by a complicated deposition process [14]. Amorphous silicon (a-Si) is another thin-film strategy that is lightweight, flexible, and cheap. Its efficiency has been enhanced with hydrogenation treatments and in tandem configurations with microcrystalline silicon (μc-Si). Still, it can only perform at 6–10% because of inherent stability problems, such as light-induced degradation.

3.3. Perovskite solar cells (PSCs)

Perovskite solar cells have been considered the most promising third-generation technology, having already achieved phenomenal improvements in efficiency, surpassing 3% in 2009 and exceeding 26% in recent years [10]. Their major strengths are low cost, solution-based processing, tunable bandgap between 1.2 and 2.3 eV, and compatibility with tandem architecture. The formation of hybrid two-dimensional/three-dimensional perovskite structures to facilitate stability, the engineering of interfaces, and the application of additives to decrease the density of defects have facilitated breakthroughs [15, 16]. Tandem devices based on perovskite/silicon have already surpassed 33% efficiency. However, critical issues have not been addressed, including the long-term stability of the product under moisture, heat, and UV conditions, as well as the reduction of lead toxicity and scaling from laboratory-scale to industrial production [12].

3.4. Organic photovoltaics (OPVs)

Organic photovoltaics based on π-conjugated polymers and small molecular semiconductors are appreciated for their mechanical flexibility, lightweight design, and compatibility with low-cost roll-to-roll manufacturing. They also suit semi-transparent modules, which can be incorporated in buildings. Recent advances have been motivated by the creation of new non-fullerene acceptors (NFAs), which have set efficiencies at 18% and provided further improvements in device stability through improved encapsulation and new donor-acceptor combinations. Despite these advantages, OPVs are still restricted by comparatively brief operation durations, sensitivity to oxygen and moisture, and reduced efficiencies compared to their inorganic counterparts.

3.5. Quantum dot solar cells (QDSCs)

Quantum dot solar cells use the size-tunable bandgap of semiconductor nanocrystals, which allows tuning the spectrum and generating multiple excitons (MEG). Recent devices commonly achieve efficiencies of between 13 and 16%, with theoretical models pointing to possible efficiencies of over 30%. Modifications in this area include using lead sulfide (PbS) and perovskite quantum dots, better surface passivation, and connecting them into tandem designs. However, these devices are impaired by stability, surface trap, and environmental factors associated with the utilization of toxic heavy metals like lead and cadmium.

3.6. Multi-junction and tandem cells

Using absorbers with complementary band gaps, tandem and multi-junction designs are among the most efficient ways to overcome the Shockley–Queisser limit. Perovskite/silicon tandem cells have achieved efficiencies higher than 33%, while III-V multi-junction devices, such as gallium arsenide (GaAs) devices, have provided more than 40% efficiency records under concentrated sunlight, rendering them highly applicable in space missions [17]. Nevertheless, III-V semiconductors are prohibitively costly to implement on Earth, and perovskite tandem devices continue to suffer stability and large-scale integration issues.

4. Efficiency enhancement techniques

The key focus in solar energy research is to increase the power conversion efficiency (PCE) of photovoltaic (PV) devices because an increase in the PCE directly lowers the levelized cost of electricity (LCOE) and increases competitiveness with fossil fuels. In the past 20 years, researchers have devised several strategies to reduce optical, electrical, and thermal losses. They can be categorized into five primary types: optical management, carrier dynamics optimization, advanced device architectures, thermal regulation, and artificial intelligence-based optimization.

4.1. Optical management

The initial efficiency enhancement technique is to achieve the most excellent photon absorption in the active layer. Many anti-reflective coatings (ARCs) like silicon nitride (SiNx) and titanium dioxide (TiO_2), which offer anti-reflective surfaces with gains of 2–3% in absolute efficiency, have become the standard in commercial silicon modules. Through resonance effects, optical path length is increased by surface texturing and nanostructures, and light trapping and absorption are enhanced by plasmonic nanoparticles and photonic crystals. These techniques are particularly useful in thin films and nanostructured devices [18].

4.2. Carrier dynamics optimization

In addition to absorbing light, the performance of devices relies on the minimization of recombination and efficient charge extraction. Passivation of the surface and interface with Al_2O_3, SiO_2, and other materials inhibits defect-related recombination and enhances carrier lifetimes. Heterojunction designs (e.g., HIT cells) use optimized band alignment to enhance electron-hole separation, and selective carrier contacts improve open-circuit voltages by ensuring efficient charge collection with minimal energy loss. All these combined add 1–4% efficiency gains and are commonly used in industrial production [19].

4.3. Developed architectures

Going beyond single-junction designs, new designs utilize more of the solar spectrum. Bifacial photovoltaics use direct and reflected light, which increases the effective energy yield by up to 30% in the real world [13]. Perovskite/silicon tandem devices have already achieved 33% efficiency in the lab, and III-V multi-junction cells have already achieved over 40% with concentrated light. Concentrator photovoltaics (CPV) additionally enhance performance by concentrating sunlight on small high-efficiency cells, attaining 40–45% system efficiency, but are deployed in a limited niche.

4.4. Thermal regulation

Thermal control is essential because an increase in temperature decreases PV performance and increases degradation. Passive methods such as radiative coatings, phase-change materials, and heat sinks radiate heat without needing extra energy. Active cooling, including liquid-based microchannel or photovoltaic-thermal hybrid (PV/T) systems, recaptures waste heat to be used again, increasing annual output by 5–10% [20]. These methods are instrumental in hot and dry environments with fast solar deployment.

4.5. Digital optimization and artificial intelligence

Over recent years, artificial intelligence (AI) and machine learning (ML) have become revolutionary optimization tools for PV: predicting layer thickness, band alignments, and material selection. AI algorithms and machine learning models are used to monitor in real time to identify micro-cracks, hotspots, or shading abnormalities [21, 22]. Moreover, predictive maintenance, performance forecasting, and lifetime optimization with the help of digital twins, which are virtual copies of PV assets, become more prominent and enhance the efficiency of systems at the system level by some 3–5% [23, 24, 25]. Table 3 provides a comparative overview of these efficiency strategies, indicating their respective mechanisms, anticipated performance improvement, and commercial adoption frequency.

5. Challenges and limitations

Although photovoltaic (PV) technologies have made impressive progress, several enduring challenges limit their mass use and durability. These are material, device, economic, and system challenges, and solving them is essential to realising PV's full potential in the global clean energy transition. The key constraints can be divided into five domains: stability and degradation, environmental and toxicity issues, material availability and scalability, economic competitiveness, and system-level integration.

5.1. Stability and degradation

One of the most critical challenges is operational stability. Although the crystalline silicon cell has been shown to have a long life, there is light-induced degradation (LID) due to the presence of boron-oxygen complexes. CdTe and CIGS thin-film technologies exhibit declining performance because of moisture intrusion, thermal cycling, and prolonged exposure to adverse weather conditions. Perovskite solar cells are also susceptible to water, oxygen, UV radiation, and heat, despite the cells having efficiencies of over 26%. Likewise, organic photovoltaics are also vulnerable to degradation by oxygen and moisture, and require expensive encapsulation. Therefore, the most critical obstacle to next-generation PV is enhancing long-term stability in real-world environments.

5.2. Environmental and toxicity concerns

Some PV technologies use dangerous or limited materials. CdTe modules and lead found in perovskites are highly dangerous to health and ecology, not only in production and deployment, but also during disposal. The heavy metals commonly used in quantum dot devices include cadmium and lead, which are toxic. Unless effective recycling and end-of-life management is provided, these materials pose a threat to the goals of sustainability. Alternatives with increased safety, such as tin-based perovskites, cadmium-free thin films, and lead-free quantum dots, are also under investigation, but most are currently in early laboratory development.

5.3. Material availability and scalability

The large-scale adoption of some thin-film and emerging PV technologies is constrained by reliance on scarce elements such as indium, gallium, and tellurium. These critical raw materials are limited in supply and subject to geopolitical risks. Scaling perovskite devices from laboratory-scale cells to gigawatt-scale modules is also hindered by challenges in defect passivation, edge isolation, and stability under prolonged illumination. Furthermore, silicon feedstock's energy- and carbon-intensive purification adds to crystalline technologies' cost and environmental footprint.

5.4. Economic competitiveness

Although the levelized cost of electricity (LCOE) for silicon PV has fallen dramatically, next-generation technologies typically face high pre-commercial costs. Tandem and multi-junction cells achieve record efficiencies but remain economically viable only in niche applications such as space missions. Emerging concepts such as building-integrated PV (BIPV) and agrivoltaics show promising lifecycle benefits, but high upfront integration costs and design complexities slow their adoption. Achieving cost competitiveness without compromising efficiency or durability is thus essential for widespread commercialization.

5.5. System-level integration

Finally, PV deployment at high penetration levels introduces system-level challenges. Intermittency requires storage solutions, demand-side management, or hybridization with complementary generation. High PV shares can induce voltage fluctuations, requiring advanced inverter control, grid flexibility, and smart grid coordination. In addition, module overheating in hot climates reduces yield and accelerates degradation, highlighting the importance of thermal management strategies. Table 4 presents a comparative overview of these challenges, summarizing the main issues across different PV generations, their impacts, and potential mitigation strategies.

6. Conclusion and future Work

Photovoltaics (PV) has transformed in the last twenty years from a silicon-driven industry into a vast ecosystem with thin films, perovskites, organics, quantum dots, and tandem designs. The successive generations have brought about extraordinary improvements in efficiency and cost-cutting, and have shown new challenges in stability, toxicity, and high-capacity manufacturability. The commercial cornerstone is still silicon, which is mature and reliable. Still, new materials are appearing—including thin films and perovskites—set to redefine the frontier of cost-effectiveness. Future progress will depend on improving long-term stability, replacing toxic elements with greener alternatives, and developing sus-

Table 3: Summary of efficiency enhancement techniques in photovoltaic devices.

Technique	Mechanism	Approx. Efficiency Improvement	References
Anti-Reflective Coatings (ARCs)	Reduce surface reflection and enhance photon absorption (e.g., SiNx, TiO_2)	2–3% absolute	[3, 4]
Surface Texturing & Nanostructures	Scatter incident light, increase optical path length	1–2%	[7, 8]
Plasmonics & Photonic Crystals	Concentrate and trap light within the absorber via resonance effects	2–4%	[9, 19]
Surface & Interface Passivation	Suppress recombination at defect states, increase carrier lifetime	1–3%	[10, 11, 15]
Heterojunctions & Selective Contacts	Improve charge separation and transport through optimized band alignment	2–4%	[16, 12]
Bifacial Photovoltaics	Harvest light from both direct and reflected sources	Up to 30% energy yield in field conditions	[13, 26]
Tandem & Multijunction Cells	Utilize complementary band gaps (e.g., Si/Perovskite, III–V) for full-spectrum absorption	33% (lab), 40% (concentrated)	[17, 14, 18]
Concentrator Photovoltaics (CPV)	Focus sunlight via lenses/mirrors onto small high-efficiency cells	40–45% system efficiency	[27]
Thermal Management (Passive/Active, PV/T)	Reduce thermal degradation and recover waste heat	5–10% annual yield	[19, 20]
Artificial Intelligence (AI/ML Optimization)	Predictive design (layer thickness, band alignment), real-time monitoring, and maintenance	3–5% system-level	[21, 22, 23]

Table 4: Key Challenges of photovoltaic technologies.

Challenge Domain	Main Issues	Impact	Mitigation Approaches
Stability & Degradation	LID in Si, moisture/thermal stress in thin films, instability in perovskites/OPVs	Reduced lifetime, efficiency loss	Advanced encapsulation, hybrid perovskites, interface engineering
Environmental & Toxicity	Cd in CdTe, Pb in perovskites/QDs, heavy metals	Health & ecological risks, recycling burden	Lead-free perovskites, Cd-free thin films, circular economy
Material Availability & Scalability	Scarcity of In, Ga, Te; silicon purification energy cost; scaling perovskites	Supply bottlenecks, high costs	Use of earth-abundant materials (e.g., CZTS), improved deposition methods
Economic Competitiveness	High cost of tandem/III–V cells, expensive BIPV integration	Limited market adoption	Cost reduction via scaling, modular designs, and policy incentives
System-Level Integration	Intermittency, grid fluctuations, overheating	Reliability issues, reduced yields	Energy storage, smart grids, and advanced thermal management

tainable supply chains for raw materials, while reducing the cost of producing advanced architectures. Another crucial area is innovations at the system level, such as better thermal management, integration with storage technologies, and smooth integration into intelligent grid infrastructures.

PV systems will continue to develop as electricity-producing installations into multifunctional and adaptable infrastructures. Building-integrated photovoltaics (BIPV) will transform the city landscape; agrivoltaics will develop the food-energy symbiosis in water-deficient areas; and floating PV will maximize the number of renewable sources on water surfaces. AI, machine learning, and digital twins will speed up the process of material discovery, predictive maintenance, and optimization in real time—closing the gap between laboratory discoveries and gigawatt implementation. By 2040, more than 30% of the world's electricity could be provided through photovoltaics, making solar power the most abundant, flexible, and smart cornerstone of the clean energy transition.

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