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Advancements in photovoltaic technology: A comprehensive review of recent advances and future prospects

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ABSTRACT

Photovoltaic (PV) technology has become a cornerstone in the global transition to renewable energy. This review provides a comprehensive analysis of recent advancements in PV technology and presents forward-looking insights into future trends. Beginning with a historical overview and the fundamental principles of photovoltaic conversion, the paper traces the evolution of commercial PV cells, such as crystalline silicon and thin-film technologies. Special attention is given to emerging materials, including perovskite, multi-junction, and organic photovoltaic cells, which hold significant promise for boosting solar energy conversion efficiency. The paper also explores cutting-edge innovations in PV device architectures, such as tandem cells, quantum dot cells, bifacial panels, flexible PV, and transparent solar cells, highlighting their potential in diverse applications. Key manufacturing processes and efficiency enhancement techniques, including silicon wafer production and thin-film deposition, are thoroughly examined. The review further explores the integration of PV systems into smart grids and building management systems, supported by real-world case studies. Economic and environmental analyses underscore the pivotal role of PV technology in reducing carbon emissions and fostering sustainable energy solutions. Finally, the review addresses pressing challenges, such as efficiency constraints, sustainability issues, and recycling concerns, while proposing directions for future research aimed at overcoming these hurdles and driving continued innovation in the field.

Introduction

Solar energy has become a pivotal component in the global transition toward renewable energy. According to the International Renewable Energy Agency (IRENA), the total installed capacity of solar photovoltaic (PV) reached 1418 GW (GW) globally by the end of 2023, accounting for 36.7 % of the world's renewable capacity. This significant growth underscores the rapid adoption of solar energy worldwide [1]. Looking ahead, the International Energy Agency (IEA) projects that renewable energy consumption across the power, heat, and transport sectors will increase by nearly 60 % between 2024 and 2030. In the electricity sector alone, the share of renewables is expected to expand from 30 % in 2023 to 46 % by 2030, with solar and wind energy contributing to almost all this growth. These projections highlight the

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critical role of solar energy in meeting future energy demands and achieving global sustainability targets [2].

Solar energy, particularly Photovoltaic technology, has become the most prominent sustainable energy alternative due to the worldwide effort to transition to renewable energy sources [3]. On light of the fact that the world is now struggling to address the issues of climate change and energy security, PV technology has emerged as an essential component on the path towards a more environmentally friendly future [4]. Solar energy systems have seen substantial improvements in terms of their efficiency, cost, and variety as a result of ongoing breakthroughs in PV materials [5], device architectures [6], and integration strategies [7] have significantly enhanced the efficiency, affordability, and versatility of solar energy systems [8]. This study aims to provide a comprehensive analysis of these recent advancements, emphasizing the innovative advancements in the field and exploring the possibilities for future modifications. The working principle of a solar cell and conceptual of a suitable solar PV system are illustrated in Fig. 1 and Fig. 2.

The technology of PVs has seen tremendous progress since its birth, with early improvements concentrating on enhancing efficiency and lowering prices. In addition to its capacity to supply clean energy, PV technology is significant because it has the potential to change the energy industry by providing a decentralized, dependable, and sustainable energy source [9]. This is the reason why PV technology is so important. The fast improvements in materials and device designs have been a significant factor in the success of solar energy as a viable alternative to conventional fossil fuels [10].

Emerging photovoltaic applications are expanding the scope and functionality of solar energy systems beyond conventional installations. Agrivoltaic systems, which integrate solar panels with agricultural land, demonstrate dual benefits of renewable energy generation and enhanced agricultural productivity under optimized conditions [11]. Aquavoltaic systems utilize water surfaces, such as reservoirs or fish farms, to deploy floating PV arrays, addressing land scarcity while reducing evaporation and improving solar panel efficiency [12]. Moreover, integrated systems, such as building-integrated photovoltaics (BIPV), provide energy solutions tailored to urban environments, reducing the energy footprint of buildings [13].

Recent advancements in these systems highlight their critical role in enhancing the adaptability and sustainability of PV technology. For example, hybrid systems that combine agrivoltaics and aquavoltaics with conventional PV installations maximize land and water resource use [14]. These innovations underscore the potential for PV systems to address diverse energy and environmental challenges in a wide range of applications.

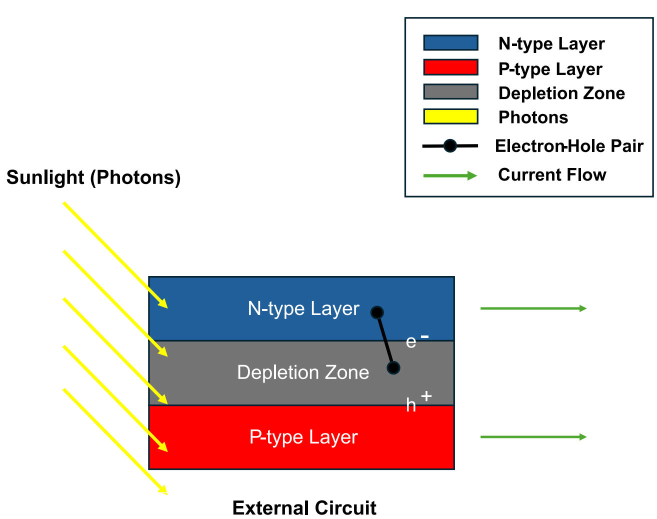

Fig. 1. the concept of suitable solar PV system [3].

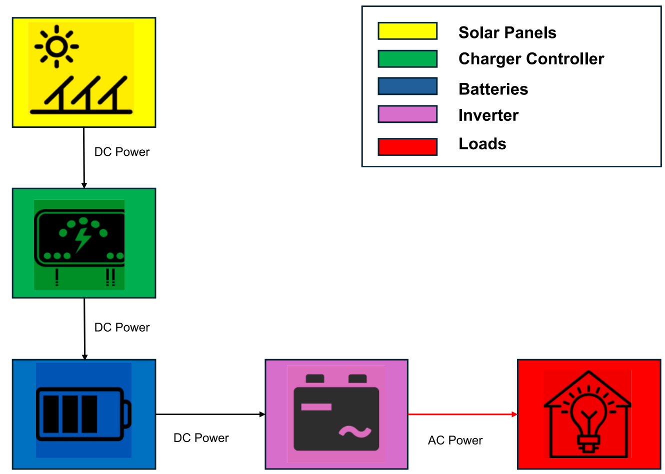

Fig. 2. The working principle of a solar cell [3].

Motivation and scope of work

This review is motivated by the need to provide a detailed examination of the latest developments in PV technology, considering the rapid pace of innovation in this field, especially in the last few years. The scope of this paper includes an exploration of new materials, such as perovskites and organic photovoltaics, as well as emerging device architectures like tandem and quantum dot solar cells. Additionally, the integration of PV systems into smart grids and buildings, and the associated economic and environmental impacts will be discussed.

Aim and objective

The primary aim of this review paper is to provide a comprehensive analysis of the recent advancements in PV technology and their significant role in advancing the renewable energy sector. The objectives of this paper include:

- Identifying Key Technological Developments: This involves examining new materials, creative cell designs, and system integration techniques that have led to improved photovoltaic efficiency and lower costs.
- Evaluate the Impact of PV Integration: Investigate how smart grids integrate PV systems and their role in energy storage and management.
- Analyzing Challenges and Future Prospects: The objective is to identify current obstacles in the PV industry, such as issues related to material stability and efficiency degradation and propose potential research avenues for future enhancements.

By achieving these objectives, the paper aims in general to offer valuable insights for researchers, industry professionals, and policymakers interested in the future of solar energy.

The review study is organized into key sections. Section 1 begins with an introduction that outlines the background, significance, motivation, and objectives. Section 2 presents an overview of photovoltaic technology, covering its development, principles, and types of cells. Next, we will delve into the latest developments in photovoltaic technology. Materials like perovskite and organic cells are studied. In Section 4, innovations in device architectures, including tandem and flexible PV cells are reviewed. In Section 5, manufacturing processes and techniques are discussed. Then, efficiency enhancement strategies are examined. Section 6 reviews integration in buildings and smart grids. Section 8 also showcases the economic and environmental impacts. Ultimately, the review presents challenges and future directions, culminating in a conclusion and recommendations for future work.

Overview of photovoltaic technology

This section offers a historical perspective on the development of PV systems and discusses their present standing within the renewable energy industry.

Historical development of photovoltaic technology

The invention of photovoltaic technology started in 1839 with the discovery of the photovoltaic effect by French scientist Alexandre Edmond Becquerel [15]. This phenomenon, known as the conversion of light into electricity, established the basis for subsequent advancements. Nevertheless, it was not until the mid-20th century that practical solar cells were developed [16].

In 1954, A significant breakthrough was made when Bell Laboratories produced the first solar cell made of silicon. Although these precursor cells were inefficient, they set the stage for further advancements [17]. Efficiency and cost reduction saw steady gains in the decades that followed, propelled by rising energy needs and new technologies [18].

The oil crisis of the 1970s heightened the focus on study and improvement in renewable energy, specifically solar power. During this era, there was a rise in several types of PV cells, including thin-film solar cells, and an increase in the use of PV technology beyond its initial application in space exploration [19].

By the late 20th century, PV technology has reached a state of maturity, characterized by a reduction in prices and a boost in efficiency. This facilitated the extensive use of solar electricity for residential, commercial, and utility-scale purposes [20].

The 21st century has brought about even more rapid progress as the photovoltaic sector is being motivated towards higher efficiency, lower prices, and greater sustainability by breakthroughs in materials, device layouts, and production methods [21].

Types of typical commercial photovoltaic cells

The following are the primary categories that are used to classify PV cells, which are the fundamental components of solar energy systems:

Crystalline silicon solar cells

Crystalline silicon solar cells are the most common type of PV cell [22]. They are made from silicon crystals, which are arranged in a highly ordered structure.

- Monocrystalline silicon: These cells are made from a single crystal of silicon, resulting in high efficiency but higher cost. They have a distinctive blue-black appearance [23].
- Polycrystalline silicon: These cells are made from multiple silicon crystals, leading to slightly lower efficiency but lower cost compared to monocrystalline cells. They have a characteristic blue-gray color [24].

Thin-Film solar cells

Thin-film solar cells are made by depositing a thin layer of semiconductor material onto a substrate. They are generally more flexible and lighter than crystalline silicon cells [25].

- Amorphous silicon: This type of thin-film cell is made from non-crystalline silicon. While it is less efficient than crystalline silicon, it is cheaper to produce [26].
- Cadmium telluride (CdTe): These cells have high efficiency and are becoming increasingly popular due to their lower cost compared to crystalline silicon [27].
- Copper indium gallium selenide (CIGS): This type of thin-film cell offers high efficiency and good performance in low-light conditions. However, the cost of materials can be a challenge [28].

Emerging solution-based thin-film technologies, such as perovskite solar cells and Organic Photovoltaics (OPVs), are gaining traction due to their potential for low-cost production and tunable properties [29]. These technologies show promise in achieving higher efficiency and flexibility for integration into diverse applications.

The commercial landscape of PV technology is evolving rapidly. Recent data show market shares, prices, and installed capacities for leading PV technologies. Crystalline silicon solar cells dominate the market due to their higher efficiency and durability [30]. However, thin-film technologies, particularly CIGS and CdTe, are gaining market share due to their flexibility and lower manufacturing costs [31] as shown in Table 1. Monocrystalline Silicon remains the most dominant technology, leading in market share due to its efficiency and reliability. Polycrystalline Silicon offers a balance between efficiency and cost, making it popular for residential installations. Thin-Film Technologies like CdTe and CIGS are gaining traction in specific markets due to their flexibility and adaptability to diverse installations. The lower-cost Amorphous Silicon thin-film technology is suited for applications where weight and flexibility are key considerations [32].

Crystalline silicon solar cells offer higher efficiency and durability, making them a popular choice for residential and commercial applications. However, their higher cost and rigid form factor can be limitations. Thin-film solar cells are more affordable and flexible, making them suitable for large-scale installations and integration into building materials. While their efficiency is lower, advancements in technology are improving their performance [38].

H. Kang in [39] provides a concise overview of the structure and arrangement of crystalline silicon, amorphous silicon, and hydrogenated amorphous silicon, emphasizing the distinctions in their structures. Next, the study provides a detailed comparison of crystalline silicon solar cells and a-Si solar cells, focusing on their individual features. The accompanying exploration focuses on the specific functions that different structures of silicon play in each feature of PV devices. The economic effectiveness of three distinct PV panel technologies: monocrystalline, polycrystalline, and thin film CIGS is examined in [40]. The analysis is based on data obtained from a test facility and considers varied weather circumstances. The measurements of the panels' yield from the site throughout a two-year period are utilized to create the techno-economic indicator performance for a proposed commercial installation [41].

Authors in [42] presents the latest advancements in flexible solar cells based on CIGS, CdTe, and amorphous silicon materials. This paper provides a comprehensive analysis of the progress made in the development of flexible foils, including their production techniques, stability concerns, and the present obstacles faced in their use. Additionally,

Table 1
Market Share and Price Trends of Various PV Technologies.

PV Technology	Market Share (2023)	Average Efficiency	Price Range (USD/Watt)	Key Advantages	Ref
Monocrystalline Silicon	55 %	18–22 %	0.25–0.35	High efficiency, long lifespan	[33]
Polycrystalline Silicon	30 %	15–18 %	0.20–0.30	Cost-effective, widely available	[34]
Thin-Film (CdTe)	8 %	13–16 %	0.18–0.28	Lower cost, flexible applications	[35]
Thin-Film (CIGS)	5 %	14–18 %	0.25–0.35	High efficiency in low light	[36]
Thin-Film (Amorphous Silicon)	2 %	6–10 %	0.15–0.25	Lightweight, cost-effective	[37]

potential solutions to these challenges are discussed, along with an examination of the industrial landscape around flexible foils. The text discusses problems and answers relating to the rate at which water vapor is transmitted through encapsulation. The optimal choice between crystalline silicon and thin-film solar cells depends on factors such as budget, available roof space, aesthetic preferences, and specific energy needs.

In Table 2, crystalline silicon and thin-film solar cells are compared based on efficiency, cost, durability, light sensitivity, environmental impact, temperature coefficient, and cost per Watt.

Recent advancements in PV materials

Recent advancements in PV technology have been largely driven by innovative materials such as perovskites, multi-junction cells, and organic photovoltaics. The perovskite crystal structure, a highly versatile and widely studied framework in materials science, is characterized by a cubic lattice, with large spheres representing the cations on the corners of that cube, smaller spheres indicating the internal cations, and the core sphere representing the central atom [44]. Oxygen anions (not shown explicitly) occupy the vertices of the lattice, forming octahedra around the B-site cations. This configuration is critical to the unique electronic, optical, and catalytic properties of perovskite materials. The flexibility of the perovskite structure allows for the substitution of various cations at both the A- and B-sites, enabling a wide range of compositions and functionalities. This adaptability has made perovskites a focal point of research for applications such as solar cells, LEDs, and other optoelectronic devices [45]. Perovskite solar cells (PSCs) have demonstrated significant efficiency gains, with some studies reporting efficiencies exceeding 25 % due to their adjustable bandgaps and ease of manufacturing. Recent literature emphasizes the importance of optimizing perovskite compositions and interfaces to enhance stability and performance, highlighting the potential for further improvements in commercial applications [29].

Multi-junction cells, which stack multiple semiconductor layers, have achieved efficiencies over 40 % in lab settings, making them ideal for high-performance and space applications. The integration of advanced materials and novel fabrication techniques has been crucial in pushing the boundaries of efficiency in these cells [46]. Organic photovoltaics, known for their lightweight and flexible nature, have also seen progress, with recent developments boosting their efficiency to around 18 %. However, they still fall short of traditional silicon cells. The latest research indicates that enhancing the charge transport properties and light absorption capabilities can lead to significant improvements in organic solar cell performance [47]. Despite these advancements, challenges related to stability and scalability for commercial use remain. Ongoing research is focused on addressing these issues by exploring new material combinations and fabrication methods to ensure long-term reliability and cost-effectiveness [48]. Overall, these materials represent a promising frontier in improving PV efficiency and expanding the potential applications of solar energy technologies [49].

Table 2
Comparison of Crystalline Silicon and Thin-Film Solar Cells [37,43].

Feature	Crystalline Silicon	Thin-Film
Efficiency	Higher (typically 15–22 %)	Lower (typically 8–15 %)
Cost	Higher initial cost	Lower initial cost
Durability	High, long lifespan	Generally, less durable
Appearance	Rigid, blue-black or dark blue	Flexible, various colors
Material	Thick silicon wafers	Thin layers of semiconductor materials
Manufacturing complexity	Higher	Lower
Light sensitivity	Good performance in various light conditions	Better performance in low-light conditions
Environmental impact	Less environmentally friendly due to material and production processes	Generally, more environmentally friendly
Temperature Coefficient	−0.35 %/°C (Monocrystalline)	−0.25 %/°C to −0.35 %/°C
Cost per Watt	Higher (~$0.25-$0.40/W)	Lower (~$0.15-$0.25/W)

Perovskite solar cells

PSCs have garnered significant interest due to their continually improving power conversion efficiency (PCE), economical material components, and straightforward solution-based fabrication methods. PSCs were first developed in 2009 with an efficiency of 3.8 %. Today, they have a lab-scale conversion rate for power of 23.3 %, which is comparable to the performance of traditional Mult crystalline si solar cells, CIGS, CdTe solar cells with thin films [50,51]. Perovskite materials are attracting significant attention from researchers due to their outstanding photovoltaic performance, inexpensive raw materials, and simple processing requirements [52,53], Due to their remarkable properties, perovskite materials are seen as prime candidates for next-generation photovoltaic technology. These include high electron mobility (800 cm^2/Vs) a carrier diffusion length exceeding 1 µm, a high absorption coefficient (greater than 10^5 cm^{-1}) due to s-p antibonding coupling, and a low exciton binding energy (less than 10 meV) ambipolar charge transport behavior, a tunable band gap, a high absorption coefficient, an extended exciton diffusion length, outstanding carrier mobility, and a low exciton binding energy [54].

Recent research has highlighted the versatility and composition of perovskite materials, emphasizing their distinctive ion mobility, a critical factor influencing performance in photovoltaic applications. Lead halide perovskites, recognized as mixed electronic-ionic conductors, exhibit significant ionic mobility that directly affects device stability. The presence of mobile ions can accelerate material degradation, as ion migration often leads to rapid breakdown. Studies in [55–57] have shown that this ionic mobility varies considerably depending on the specific cation and anion compositions within the material. Detailed investigations reveal that substituting multiple ions within the perovskite lattice can significantly alter the activation energy for ion diffusion, suggesting that optimized compositions could enhance both ionic conductivity and overall stability. For example, the incorporation of smaller cations into the lattice has been found to reduce barriers to iodide diffusion, thus improving ionic mobility and potentially boosting device performance. Additionally, the unique ion dynamics in these materials contribute to phenomena such as hysteresis effects in current–voltage characteristics, which arise from the accumulation of ions at interfaces during operation. This interplay between ion mobility and other material properties underscores the importance of a deeper understanding to inform future designs of more efficient and stable perovskite solar cells, ultimately advancing the commercial viability of this technology in solar energy applications [58–60].

Recent progress of perovskite silicon tandem cells

Efficiency Improvements: Recent developments in perovskite/silicon tandem cells have led to certified efficiencies reaching up to 29.1 %. This represents a substantial increase from earlier efficiencies, showcasing the rapid advancement in this technology [61]. The combination of Perovskite's tunable bandgap and silicon's established performance creates a synergistic effect that enhances overall energy capture.

Material Innovations: Advances in material design have been pivotal in improving the performance of perovskite/silicon tandem cells. Researchers have focused on developing wide-bandgap perovskite materials that can effectively absorb high-energy photons while allowing lower-energy photons to pass through to the silicon layer beneath. This optimization is crucial for maximizing the efficiency of tandem configurations [62].

Fabrication Techniques: The adoption of innovative fabrication methods, such as solution processing for perovskite layers, has simplified production and reduced costs. Techniques like blade coating have been employed to create uniform perovskite films on textured silicon substrates, achieving efficiencies around 26 % [61,63]. These methods enhance the compatibility between the perovskite top cell and the silicon bottom cell, addressing previous challenges related to interface quality.

Stability Enhancements: Addressing stability concerns has been a major focus in recent research. New strategies, including interface engineering and surface passivation, have been developed to improve the long-term performance of perovskite/silicon tandem cells under operational conditions. For instance, studies have demonstrated that certain modifications can significantly enhance thermal stability and reduce degradation over time [61,63].

Commercial Viability: The progress in perovskite/silicon tandem cells is not only academic but also points towards commercial viability. With ongoing improvements in efficiency and stability, these cells are increasingly seen as viable candidates for large-scale deployment in solar energy applications [61,64].

Advantages of perovskite quantum dot films

The architecture of perovskite quantum dot (PQD) films has emerged as a promising approach for achieving high power conversion efficiencies (PCEs) in photovoltaic applications. Recent research highlights several advancements and characteristics that contribute to the effectiveness of this architecture.

In the context of the remarkable advantages of Perovskite Quantum Dot (PQD) films, it is essential to briefly address their structural characteristics. PQD films are composed of nanoscale perovskite crystals, known as quantum dots (QDs), which exhibit unique quantum confinement effects that enhance their optical and electronic properties. This structure enables tunable bandgaps, efficient charge transport, and superior photostability, contributing significantly to the high performance of these films in photovoltaic applications. For a more comprehensive understanding of the structural design and technical intricacies of QD films, readers are referred to Section 4.2, 'Quantum Dot Solar Cells', where these aspects are discussed in greater detail.

High Efficiency: All-inorganic $CsPbI_3$ quantum dot solar cells have demonstrated remarkable efficiencies, with recent studies reporting stabilized power outputs of up to 15.1 %, positioning them among the highest efficiencies achieved in PQD technology. This efficiency is attributed to the unique properties of perovskite materials, which allow for effective charge transfer and minimal recombination losses at the interfaces within the device architecture [65].

Mechanical Stability: Perovskite quantum dot films exhibit superior mechanical stability compared to traditional bulk thin films. The nanoscale dimensions of PQDs contribute to enhanced flexibility and durability, making them suitable for a variety of applications, including flexible electronics [65]. The intrinsic properties of these quantum dots allow them to withstand mechanical stress without significant degradation in performance.

Defect Passivation: The incorporation of PQDs into perovskite films helps reduce defects that commonly compromise device performance. Research indicates that quantum dot passivation can lead to improved photoluminescence (PL) emission intensity and carrier lifetime, which are critical for enhancing the overall efficiency of solar cells [66]. This passivation effect also suppresses phase segregation in mixed-halide perovskite films, further stabilizing their performance under operational conditions.

Quantum Confinement Effects: The unique semiconducting properties of PQDs arise from quantum confinement effects, allowing for tunable electronic and optical characteristics. This tunability enables the adjustment of bandgaps across the visible spectrum, which can be optimized for specific applications in photovoltaics and other optoelectronic devices [67].

Hybrid Architectures: Recent developments in hybrid interfacial architectures combining PQDs with other materials, such as PCBM (phenyl-C61-butyric acid methyl ester), have shown promise in facilitating efficient charge transfer processes. These architectures create energy cascades that enhance charge extraction efficiency, thereby improving overall device performance [65].

Advancements and challenges in perovskite solar cell technology

The power conversion efficiency (PCE) of perovskite solar cells (PSCs) has dramatically risen from 3.8 % in 2009 to 25.5 % in 2021 [68]. Although an impressive power conversion efficiency of 26.1 % has been achieved later [69]. Despite their advantages, perovskite solar cells face significant challenges, particularly regarding their operational stability, which has become a growing area of concern [70]. Other challenges include issues of stability, large-area processing, and toxicity [71], which hinder their commercialization. There are five challenges a perovskite solar device must fulfil to become reliably commercial which are cost, stability, upscaling, environmental impact, and power conversion efficiency. Additionally, the presence of high-energy radiation in the space environment can cause premature failure of perovskite solar cells, making their use in space applications challenging [72]. However, the stability of PSCs remains a significant challenge, hindering their widespread commercialization. Defects on the surface and grain boundaries of perovskite films, caused by low-temperature solution processing and rapid crystallization techniques, can lead to ion diffusion, non-radiative recombination, and degradation of the perovskite material [73].

Recent research has proposed several strategies to address the challenges faced by perovskite solar cells. Enhancing stability has been a focus, with encapsulation techniques and the use of durable materials proving effective [74]. For example, adding protective layers can significantly extend the lifespan of PSCs when exposed to environmental stressors [75]. Moreover, the development of lead-free perovskite materials addresses toxicity issues, with studies indicating that these alternatives can maintain efficiency while reducing harmful substances [76,77]. Although scalability remains a significant obstacle, advancements in manufacturing methods, such as roll-to-roll printing, are being explored to enable large-scale production without sacrificing performance [78]. Additionally, optimizing the composition of perovskite materials can improve both efficiency and stability, making them more suitable for commercial use [79]. Collectively, these approaches aim to overcome the inherent limitations of PSCs and support their broader integration into renewable energy systems.

Authors in [80] used Tannic acid (TA) as a crosslinking agent to treat perovskite films, creating a cross-linked network on the surface. This treatment increased grain size, passivated defects, and enhanced charge separation while reducing interfacial recombination. The TA network also absorbed residual moisture, protecting the perovskite layer. As a result, the PCE improved from 21.31 % to 23.11 %, with reduced hysteresis and better air, thermal, and operational stability.

Multi-junction cells

Traditional PV cells are limited by the Shockley–Queisser limit. However, new alternatives have emerged that surpass this constraint. One such innovation is heterojunction cells, which combine different semiconductor materials to overcome previous limitations and utilize the benefits of both materials [81]. A specific type of these cells is multi-junction cells, which enhance the heterojunction concept by incorporating multiple junctions within a single cell. This approach has made multi-junction cells the leaders in conversion efficiency [82]. First developed in the 1980 s, these cells use multiple semiconductor layers to capture a wider range of sunlight, thereby improving energy conversion efficiency compared to traditional single-junction cells. Early studies underscored the promise of III-V semiconductor materials, which facilitated the development of the first practical multi-junction solar cells (MJSCs), achieving efficiencies greater than 30 % in laboratory conditions [83].

Device structure and material availability in multi-junction solar cells

The architecture of multi-junction solar cells (MJSCs) is designed to optimize energy capture across a wide range of the solar spectrum. Typically, MJSCs consist of multiple layers of semiconductor materials, each possessing distinct bandgaps. The topmost layer is characterized by the highest bandgap, tailored to absorb high-energy photons, while the underlying layers have progressively lower bandgaps to capture photons with less energy. This layered configuration enables the cell to absorb and convert a broader spectrum of sunlight into electricity, resulting in higher overall efficiency [84].

Common Materials:

- Gallium Indium Phosphide (GaInP): Frequently used for the top layer due to its high bandgap, ideal for capturing high-energy photons.
- Gallium Arsenide (GaAs): Often serves as the middle layer, balancing efficient absorption with optimal electronic properties.
- Germanium (Ge): Typically used as the substrate or bottom layer, where it helps in absorbing lower-energy photons that pass through the upper layers.

The design of these layered cells ensures that photons can penetrate the upper layers and be absorbed by subsequent layers, maximizing energy capture. This approach has been instrumental in achieving high efficiencies, with laboratory examples demonstrating efficiencies exceeding 46 % under concentrated sunlight conditions [85,86].

Material Availability The selection of materials is a critical factor influencing the performance and feasibility of MJSCs. While III-V semiconductors are the preferred choice due to their direct bandgap properties and high efficiency, their production costs and the complexities involved in manufacturing pose significant challenges. Research continues to explore alternative materials that could potentially lower costs while maintaining or even improving efficiency levels. For instance, replacing traditional Germanium substrates with silicon has been proposed as a cost-effective strategy without severely compromising performance [87].

Device structure and material availability in multi-junction solar cells

MJSCs offer notable advantages over traditional single-junction cells, primarily due to their capacity to capture a wider range of sunlight. Authors in [88] explain that by stacking multiple semiconductor materials, each tuned to different light wavelengths, these cells achieve higher efficiencies and improved energy conversion rates. This design enables them to surpass 40 % efficiency under concentrated sunlight, a significant enhancement over conventional cells. Furthermore, in [89] authors point out that multi-junction cells perform better in high-temperature conditions, which is essential for maintaining efficiency in practical applications. The development of multi-junction solar cells has advanced considerably over time, driven by innovations in materials and design. Early efforts were focused on enhancing the efficiency of individual junctions, leading to cells achieving over 30 % efficiency under concentrated sunlight conditions [90]. Recent research emphasizes the incorporation of new materials such as perovskites, which have the potential to further improve multi-junction cell performance by enhancing light absorption and reducing costs [91].

According to authors in [92] the efficiency of InGaP/InGaAs/Ge multi-junction solar cells reached 31–32 % under standard test conditions in 2005. This enhancement was attributed to advancements in fabrication techniques and improved material quality, in 2006 a world record efficiency of 37.4 % was set for a three-junction concentrator solar cell under concentrated sunlight, demonstrating the effectiveness of multi-junction designs in optimizing energy conversion.

In 2008, a GaInP/GaAs/GaInAs triple-junction solar cell with improved spectrum splitting achieved about 33 % efficiency, surpassing the performance of the GaInP/GaAs/Ge three-junction cell [93]. By 2016, multi-junction concentrator solar cells made from III–V semiconductors reached efficiencies exceeding 46 % [94]. By 2023, the highest recorded efficiency for a six-junction concentrator cell is 47.1 %, as illustrated in Table 3 [95].

Multi-junction solar cells, despite their high efficiency potential, encounter several significant challenges. One major problem is the complexity of their fabrication, which involves intricate layer structures that can drive up production costs and complicate scaling up manufacturing processes [96]. Additionally, managing heat is crucial, as excessive temperatures can impair performance and shorten the cells' lifespan [97]. Furthermore, integrating different semiconductor materials with varying thermal and electrical properties can lead to performance mismatches under different lighting conditions, making it challenging to optimize the cell's overall efficiency [98]. Two major challenges face multi-junction solar cells (MJSCs). First, the high cost of MJSC modules is a significant barrier to surpassing the market dominance of established silicon single-junction solar cells, limiting MJSCs to niche applications where surface area is a critical factor, such as space missions or unmanned aircraft and drones [99]. Second, while increasing MJSC efficiency could potentially justify their high cost for long-term renewable energy solutions, a balance between efficiency and cost must be considered when selecting solar cells. The challenges of MJSCs can be categorized into three main areas: economic barriers, technical limitations, and environmental factors. The economic barriers include the high manufacturing costs, which are largely due to the complexity of multi-junction architecture and the use of expensive materials. Technical challenges involve optimizing device performance, ensuring effective integration of different junctions, and addressing issues such as thermal management and reliability under varying operating conditions. Environmental factors include the energy and material inputs required for manufacturing, as well as the potential impacts of end-of-life disposal [86,100].

Organic photovoltaic cells

Organic photovoltaic cells are solar cells that use an absorber layer composed of organic semiconductors, which are usually polymers or small organic molecules, or a combination of both These cells are categorized as third-generation photovoltaic devices, due to their multiple bandgaps. OPV cells generally have an active layer situated between two transport layers that facilitate the movement of holes or electrons, along with two electrodes (cathode and anode) [101]. These electrodes encase the structure, collecting the charge carriers and directing the generated current to an external electrical circuit. Organic solar cells (OSCs) offer several benefits that make them a promising technology in photovoltaics. Their flexibility and lightweight nature allow for diverse applications, including integration into building materials and portable devices [102]. OSCs can also be produced using environmentally friendly materials and processes, such as non-halogenated solvents, which improves their sustainability [103]. Recent advancements have significantly increased power conversion efficiencies, with some OSCs achieving over 21 % efficiency under certain conditions [104].

Technological advancements in organic solar cells (OSCs) have leveraged organic materials to convert sunlight into electricity, offering

Table 3
Comparison of Efficiency Over the Years.

Year	Efficiency	Material Configuration	Reference
2005	31–32 %	InGaP/InGaAs/Ge	[92]
2006	37.4 %	Three-junction concentrator	[92]
2008	~33 %	GaInP/GaAs/GaInAs	[93]
2016	>46 %	III–V semiconductors	[94]
2023	47.1 %	Six-junction concentrator	[95]
2024	29.1 %	Perovskite/Silicon Tandem Cells	[61,63]

benefits such as lightweight construction, flexibility, and potential for low-cost manufacturing. Recent developments have achieved power conversion efficiencies (PCEs) exceeding 19 %, particularly with non-fullerene acceptors (NFAs) that outperform traditional fullerene-based systems [105,106]. The introduction of new materials, such as small-molecule NFAs like perylene diimide (PDI) and diketopyrrolopyrrole (DPP), has been pivotal, with efficiencies reported over 11 % and 13 %, respectively [106]. These innovations facilitate improved charge transport and exciton dissociation compared to fullerene counterparts. Additionally, OSCs are inherently flexible, making them ideal for applications like integration into building materials and portable devices. Recent efforts have also focused on developing transparent OSCs that maintain high efficiency while allowing light transmission, achieving optical transmittance over 60 % with competitive PCEs [107].

Non-fullerene acceptors (NFAs) have emerged as a notable advancement in organic solar cells (OSCs), particularly in achieving power conversion efficiencies (PCEs) exceeding 20 %. This progress is largely attributed to the unique properties of NFAs, which offer greater tunability and flexibility compared to traditional fullerene-based acceptors.

Key developments in non-fullerene acceptors

- Material Diversity: NFAs include a broad range of materials such as ITIC, Y6, and DPP-based acceptors. These materials exhibit strong absorption in the visible region and improved thermal stability, enhancing the overall performance of OSCs [106].
- Efficiency Records: Recent studies report that NFAs have enabled OSCs to achieve PCEs of over 20 %. For instance, A-D-A type NFAs have shown remarkable efficiency improvements due to their well-optimized molecular structures that facilitate better charge transport and exciton dissociation [106,108].
- Synthesis and Design Innovations: The design of NFAs has benefited from advances in synthetic methods, allowing for modifications that enhance their electronic properties. Techniques such as side-chain engineering and molecular design adjustments have been pivotal in improving the performance of NFAs [108,109].
- Comparative Advantages: Compared to fullerene acceptors, NFAs offer several advantages:
- Tunable Energy Levels: The ability to modify energy levels leads to better compatibility with various donor materials.
- Enhanced Stability: NFAs tend to exhibit greater morphological stability, which is crucial for long-term device performance [109].
- Broader Absorption Spectrum: Their strong absorption capabilities extend into the near-infrared region, which is beneficial for maximizing light harvesting [106].
- Challenges Ahead: Despite these advancements, challenges remain in optimizing NFA formulations for commercial applications. Continued research is necessary to address issues related to scalability, cost-effectiveness, and integration into existing solar technologies [108].

The ability to adjust the bandgap of organic semiconductors enables OSCs to capture a broader light spectrum, especially in the near-infrared region, which enhances photocurrent density [110]. Additionally, the development of semi-transparent OSCs provides new opportunities for energy-generating windows, offering both aesthetic and functional benefits [111]. Authors in [112] highlight that organic photovoltaic cells (OPVs) have a short energy payback time. They can absorb light across the entire solar spectrum and are known for their low fabrication costs. OPVs are also easy to produce because they use readily available materials and can be manufactured using solution-based processing. They do not require high manufacturing temperatures and are compatible with large-area production. Despite advancements in efficiency, organic solar cells face several significant challenges that hinder their commercialization. A key issue is the disparity between laboratory conditions and industrial production, particularly regarding device architecture and material compatibility, which complicates scaling up [113]. Additionally, the stability and longevity of OSCs are major concerns, as many materials do not adequately resist environmental factors such as air, light, and thermal stress, limiting their practical applications [114].

Transparency in Organic Solar Cells (OSCs) is essential for applications such as building-integrated photovoltaics (BIPV) and wearable electronics. Achieving high average visible transmission (AVT) while maintaining efficiency remains challenging. Recent research shows that TPVs can reach AVTs between 40 % and over 80 %, with efficiencies up to 10 %, by optimizing film thickness and donor–acceptor ratios [115,116]. Material innovations, such as ultrathin metal electrodes and transparent conducting polymers, have improved both transparency and efficiency. For instance, polymer nucleation layers facilitate the creation of continuous thin metal films, enhancing conductivity without reducing transmittance [115,117]. However, increasing transparency often reduces power conversion efficiency (PCE), leading to ongoing research to find a balance [115,116].

Flexibility Applications: The use of flexible substrates has expanded the potential applications of OSCs, from automotive surfaces to portable electronics. Flexible OSCs have been designed to withstand mechanical stress, with recent studies showing that graphene electrodes allow devices to bend more tightly while maintaining output compared to traditional indium tin oxide (ITO) electrodes [117]. Achieving ultra-flexibility and optical transparency is a key focus, with thinner device architectures reducing rigidity, allowing OSCs to endure extreme mechanical stress [116,117]. Devices using carbon nanotubes and other new materials as transparent electrodes have shown notable efficiency improvements while maintaining flexibility [109,118].

Furthermore, while efficiency has improved with recent developments, challenges related to solution processability, and the optimization of active layer morphology still impede achieving consistent performance across different manufacturing conditions. To overcome these obstacles, focused research on material stability, device engineering, and scalable manufacturing techniques is essential to enhance the commercial viability of OSCs in the competitive solar energy market [29]. Table 4 compare the three most recent photovoltaic materials.

Innovations in photovoltaic device architectures

Significant progress has been achieved in the field of photovoltaic technology in recent years, primarily due to advancements in module design. These advancements have improved efficiency, adaptability, and visual attractiveness, broadening the range of possible uses for solar energy.

Tandem solar cells

Tandem solar cells, a particular case of multi-junction cells, are a very promising technology capable of substantially enhancing efficiency. By vertically arranging multiple layers of semiconductor materials with varying bandgaps, tandem cells can capture a wider range of sunlight wavelengths. Consequently, this leads to superior energy conversion efficiencies in comparison to conventional single-junction cells. Tandem cells, particularly those using perovskite materials, are the subject of ongoing research and development efforts [120].

Tandem solar cells can surpass the Shockley-Queisser limit, which sets a maximum efficiency for single-junction solar cells. The tandem cell, which combines perovskite and silicon, is the most well-known type. Perovskites can absorb the blue and green wavelengths of light, whereas silicon can capture the red and near-infrared wavelengths. Tandem efficiencies have recently surpassed 30 %, which is a substantial improvement over conventional silicon cell [121].

All-Perovskite Tandems cells utilize several perovskite layers, each with distinct bandgaps, to accomplish spectral splitting of a similar kind

Table 4
Comparison of the Three Most Recent Photovoltaic Materials.

Feature	Perovskite Solar Cells	Multi-junction Cells	Organic Photovoltaic Cells
Efficiency (Recent Record)	Achieved up to 26.1 % under standard test conditions; theoretical limit is around 32.5 %. Further efficiency improvements are possible with tandem structures [68,69,78].	Recent records show up to 47.1 %, achieved with optimized multi-layer designs combining different semiconductor materials for broader spectral absorption [92,93,95].	Recorded at 19.5 % with non-fullerene acceptor materials; substantial progress in recent years, especially with new material designs to enhance charge transport [105,106,115].
Manufacturing Complexity	Moderate, involving solution processing and challenges in surface and grain boundary passivation; ongoing efforts focus on improving layer uniformity and interface engineering [69,71,79].	High due to the need for complex epitaxial growth processes and precise alignment of different semiconductor layers; these multi-layered structures require advanced fabrication techniques [94,99].	Generally low, with roll-to-roll printing being feasible; relies on solution-based processing, making it possible to manufacture at large scales [106,117,119].
Material Costs	Relatively low, utilizing abundant materials like lead and halide compounds; however, toxicity concerns are prompting research into alternative, safer materials [69,79].	High due to the expensive and rare semiconductor materials required; further impacted by the complexity of integrating multiple layers of different materials [86,94].	Low, as they use inexpensive and easily available organic compounds; recent developments focus on reducing the cost of electrode and encapsulation materials [105,117,119].
Flexibility and Application	Limited flexibility due to material rigidity; ongoing research is exploring flexible substrates for broader applications, including portable and wearable electronics [68,78,79].	Primarily designed for high-efficiency applications where flexibility is less critical, such as satellites and concentrated photovoltaics; integration in standard solar modules is common [92,95].	High flexibility, suitable for integration into flexible, semi-transparent, and even wearable electronics; advantages include lightweight and diverse design possibilities [106,115,117].
Stability and Longevity	Stability remains a significant issue; degradation from moisture, UV exposure, and thermal stress limits long-term performance. Encapsulation improvements are crucial [68,71].	Better stability compared to single-junction alternatives, but heat management is critical due to the high power output, which can accelerate material degradation [93,99].	Limited by sensitivity to environmental conditions (e.g., oxygen, moisture); ongoing research aims to enhance stability via new polymer and small molecule materials [105,106,119].
Commercial Viability	Steadily progressing, with ongoing efforts to overcome stability and toxicity concerns; potential for cost-effective tandem structures is promising [69,79].	Viable for niche markets, especially where efficiency is a priority, such as space applications; less competitive in general markets due to high costs [94,95,99].	Promising for low-cost, large-area applications, but widespread adoption is hindered by challenges in improving stability and scaling up manufacturing processes [106,115,119].

as illustrated in Fig. 3. All-perovskite tandems have a lighter weight and presumably lower production costs, making them a viable option.

The recent improvements facilitate the practical implementation of tandem cells in manners previously unsupported by earlier designs, including graded interlayer configurations, the integration of transparent conductive oxides (TCOs) with superior refractive characteristics, and advancements in interfacial layer engineering that enhance charge transfer and stability [122,123].

Quantum dot solar cells

Quantum dots (QDs) are a distinct category of semiconductors, consisting of nanocrystals formed from periodic series of II-VI, III-V, or IV-VI materials, capable of confining electrons through quantum confinement. As the size of a quantum dot approaches the exciton Bohr radius of the material, the effect of quantum confinement becomes significant, and the levels of electron energy transition from a continuous band to discrete energy levels. Consequently, QDs can be regarded as an artificial molecular with a gap in energy and energy level spacing contingent upon its size (radius). The energy band gap enlarges as the size of the quantum dot diminishes. As the size of a quantum dot increases, its absorption peak is redshifted due to a reduction in its bandgap. The tunable bandgap of quantum dots facilitates the development of nanostructured solar cells capable of capturing a greater portion of the solar spectrum. QDs possess substantial intrinsic dipole moments, potentially resulting in swift charge separation. QDs can emit up to three electrons per photon due to multiple exciton generation (MEG), in contrast to the single electron emitted by conventional crystalline silicon solar cells. Theoretically, this could enhance solar power efficiency from 20 % to as much as 65 % [125]. QDs solar cells employ tiny semiconductor particles, known as quantum dots, that possess distinctive electrical characteristics as a result of quantum mechanics. These dots may be manipulated to selectively absorb particular wavelengths of light by adjusting their size. Colloidal Quantum Dots (CQDs) are very promising because of their versatility and ability to be processed using low-cost solutions. In addition, they possess the ability to undergo multiple exciton formation, wherein a single photon may produce several charge carriers, hence possibly enhancing efficiency [126].

The combination of quantum dots and organic materials which are known as Hybrid Quantum Dot-Organic Solar Cells (HQDOSCs) can improve the absorption of light and the movement of electric charges. Although still in the early stages of research, these hybrid cells show promise for use in flexible and lightweight applications. Quantum dot solar cells, although still at the research and development stage, show potential for future use in wearable electronics and Building-Integrated Photovoltaics (BIPV) [127].

Bifacial panels

Bifacial solar panels have the ability to capture light from both their own front and back surfaces, resulting in higher efficiency compared to conventional monoracial panels. This advantage is particularly evident in settings with reflecting materials, such as snow or sand, as well as in metropolitan areas where sunlight tends to disperse [128].

Bifacial panels have the capacity to produce up to 30 % more energy in comparison to monoracial panels, under ideal circumstances. They are especially efficient in areas with high latitudes or installations with extremely reflecting ground surfaces [129]. These panels are often more resilient because of their dual-glass structure, which shields the cells from environmental elements. They can be put in many arrangements, such as vertical orientations, to maximize energy capture [130]. The introduction of dual-glass and frameless module designs and innovations in cell rear-side architecture have improved light capture and durability of bifacial cells [131].

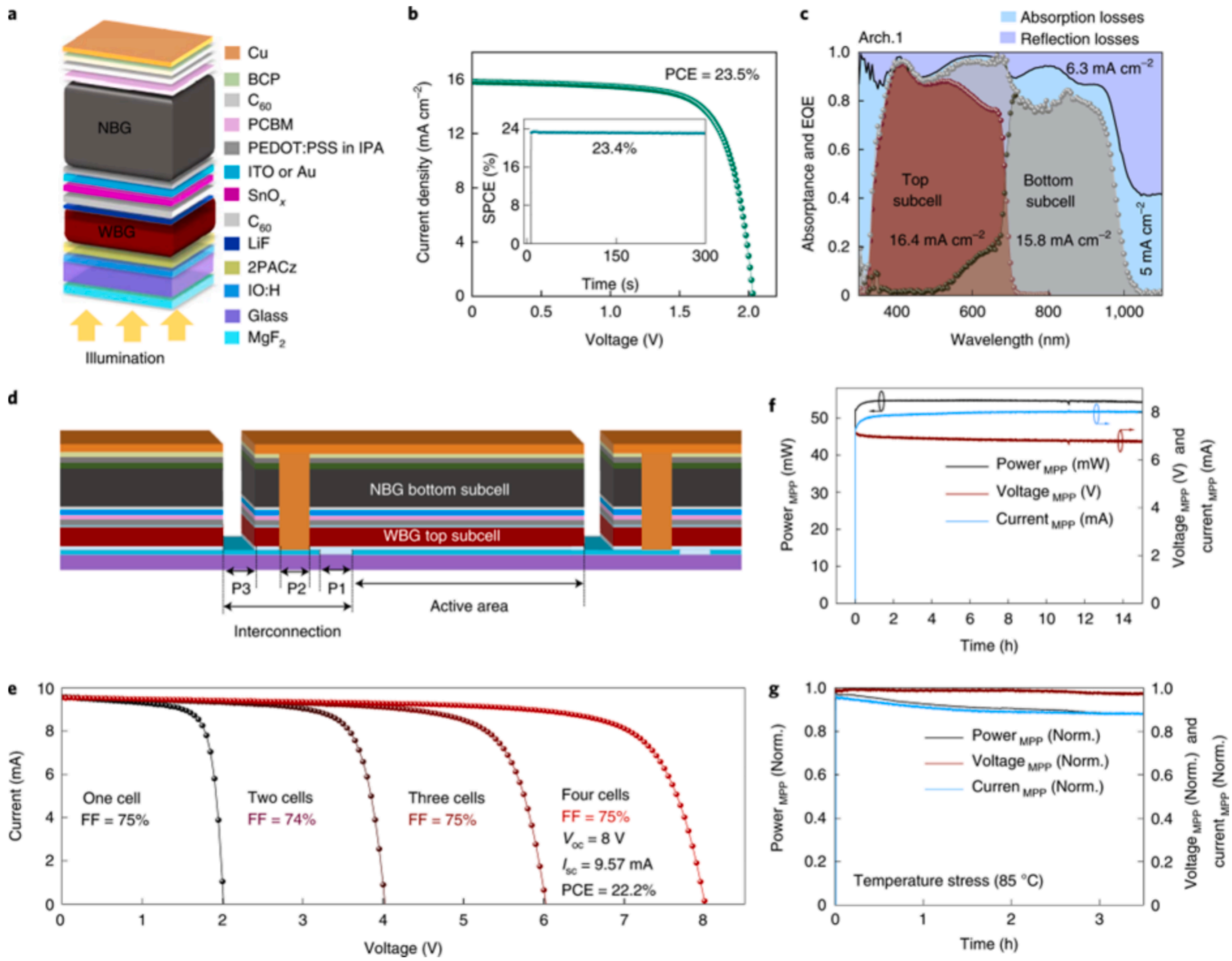

Fig. 3. The Architecture and Functionality of Tandem Solar Cells and Modules Made Entirely of Perovskites [124].

Flexible PV

Flexible photovoltaic devices are constructed using thin-film materials that possess the ability to flex without fracturing, hence creating opportunities for their incorporation into common items, structures, and even garments [132]. Commonly utilized materials for flexible photovoltaics include organic photovoltaics, perovskites, and specific thin-film technologies such as CIGS. These materials may be placed on lightweight and flexible surfaces, such as plastic or metal foils [133]. These cells are well-suited for wearable electronics, portable power sources, and BIPV. They can be easily incorporated into windows, facades, and roofs due to their flexibility and lightweight nature [134].

Transparent solar cells

Transparent solar cells are designed specifically to permit the transmission of visible light while also capturing near infrared and ultraviolet radiation to produce electricity. Transparent solar cells can be fabricated with organic materials, quantum dots, or very thin silicon layers. The primary obstacle is to achieve a harmonious equilibrium between transparency and efficiency. Excessive transparency diminishes the quantity of light accessible for energy conversion. These cells are well-suited for use in smart windows in buildings and cars, as they can generate electricity without blocking views or natural light [135].

The production of transparent solar cells utilizing nanometric (8 and 30 nm) intrinsic hydrogenated amorphous silicon films and employing oxide thin films as transparent carrier selective contacts are documented. The ultrathin devices exhibit photovoltaic effects and elevated average visual transmittance (AVT) [136]. The compositional, structural stability, and optical of transparent conductive oxide SnO2: Ta (1.25 at % Ta) thin films were investigated at 650 °C and 800 °C in air under isothermal circumstances [137].Transparent solar thermo-photovoltaic are a viable method for utilizing solar energy while maintaining the beauty and functionality of transparent surfaces. Metamaterials utilizing semi-conducting oxides can facilitate broadband absorption at ultraviolet and infrared frequencies while concurrently transmitting at visible frequencies [138]. A novel approach for the creation of an optically transparent frequency-selective surface absorber utilizing indium tin oxide (ITO) conductive film with varying sheet resistances. This unique optical transparent frequency-selective absorber has exceptional optical transparency, with visible light transmittance above 76 % [139].

Shingled solar cells

Shingled solar modules signify a notable advancement in photovoltaic module design, enhancing efficiency, aesthetics, and durability. In contrast to conventional modules that utilize busbars to interconnect solar panels, shingled modules feature overlapping tiny strips of cells, resembling shingles on a roof. This overlapping design obviates the necessity for metal bands on the cell surface, resulting in multiple benefits [140].

The authors in [141] study examines the shade tolerance of two kinds of solar modules utilizing shingle interconnection: the commercially available string approach and the matrix technology, wherein solar cells are interconnected both in series and in parallel. The diagonal and randomized shading within a 1.6 m^2 solar module is analyzed. Matrix technology exhibits power savings of up to 73.8 % for diagonally shading and upwards to 96.5 % for random shading when compared to the conventional string method. The research in [142] aims to enhance the metallization of solar cells in shingled PV modules. The researchers discovered that the rear Ag plates on crystalline silicon solar cells do not adhere to the Al layer due to issues with peeling. The application of a rear Ag plate and Back Surface Field (BSF) layer enhances the characteristics of the solar cell. The research indicated that the complete Al-BSF layer on the posterior side of the solar panels exhibited elevated values within the long-wavelength spectrum. The interconnected cell demonstrated an efficiency of 18.3 %, whereas the efficiencies of the two panels strips were almost 18 and 18.1 %, respectively. Shingled PV modules employ Electrically Conductive Adhesives (ECA) to serially connect solar cells, minimizing resistance losses and facilitating efficient production as presented in [143]. This method, however, heightens vulnerability to shading, a prevalent concern in urban structures. A provided string cross-connection technique that links shingled strings enhances the resultant degradation rate approximately 17 % when 25 % of the module's lower surface is shaded, allowing for a current bypass at 41.6 % and diminishing output to 52 %. Building-integrated photovoltaics (BIPV) generate energy by integrating solar power generation into the outside of buildings as presented in [144]. The goal of this study is to optimize the optical pairing effect for shingled technologies in order to improve the performance of BIPV modules. In comparison with traditional and black PV modules, white EVA reflecting incoming light coming from the upper layer additionally reduced maximum output energy loss by 117.14 % and 521.90 %.

Heterojunction solar cells

Modules of heterojunction technology (HJT) combine the advantages of thin-film and crystalline silicon technologies to provide improved performance and efficiency. A crystalline silicon wafer is encased in very thin amorphous silicon layers to form HJT cells.

The initial research highlighted the significance of identifying the optimal parameters for HJT solar cells. The authors demonstrated the impact of the emitter thickness and the intrinsic integrated layer of the solar cell structure. The authors demonstrated that the efficiency of the solar cell begins to rise following the deposition of an intrinsic transparent silicon layer. The dependence curve ascends to a peak and subsequently begins to decrease. This underscores the significance of accurately selecting the configuration of the solar panel. The authors of certain studies indicate that the quality of the silicon crystalline layer in the HJT arrangement is a critical parameter [145]. The density of surface malfunctions and the density of bulk imperfections are critical parameters; their values are contingent upon the procedure and quality of material development and influence the performance characteristics of solar power cells [146]. The thickness of the silicon crystalline layer within the HJT should range from 50 to 300 μm, contingent upon its structure, as indicated by the researcher's findings. The ideal thicknesses for the intrinsic layer and amorphous emitter are 3 to 5 nm and 5 to 10 nm, respectively. The material barrier between crystal and amorphous silicon, as well as between the TCO film and amorphous material, is one of the most significant elements influencing the efficiency of HJT cells. The examination of these factors is detailed in various theoretical publications focused on solar cell modeling [147].

Conclusion

These advancements in the designs of photovoltaic devices are expanding the limits of what can be accomplished with solar energy. These improvements are enhancing efficiency, variety, and integration of choices of solar power, making it a more widespread and dependable source of renewable energy. With ongoing research and development, we anticipate the emergence of new revolutionary technologies, which will lead to increased usage of solar energy in other industries.

Manufacturing processes and techniques

The production of photovoltaic silicon wafers and thin films involves a variety of manufacturing processes and techniques aimed at improving efficiency and reducing material waste [148]. Traditional methods like wire sawing are used for slicing silicon ingots, though they are limited by material brittleness and waste issues, Emerging kerf-less techniques, including "top-down" and "bottom-up" approaches such as slim-cut and smart-cut processes, offer the advantage of minimizing waste and producing thinner wafers [149]. For thin-film deposition, physical vapor deposition (PVD) methods like sputtering and e-beam evaporation are employed to create high-purity films suitable for photovoltaic applications, Additionally, chemical vapor deposition (CVD) techniques such as plasma-enhanced CVD and atomic layer deposition enable precise control over thin film properties [150]. Despite the promise these advanced techniques show in increasing efficiency and reducing costs, challenges remain in scaling production and ensuring uniform quality across large batches [151].

Silicon wafer production

Conventional photovoltaic cells are made from silicon wafers that directly convert sunlight into electricity. These silicon-based cells use crystalline silicon wafers ranging from 150 to 200 μm thick, which are often brittle and rigid. To overcome these limitations, researchers have developed flexible PV cells using low-temperature and solution processes with thin-film materials on flexible substrates. Although these flexible cells are lightweight, thin, and adaptable, they tend to have shorter lifespans, lower energy conversion efficiency, smaller active areas, and can include harmful materials. However, when silicon wafers are sufficiently thin, silicon-based PV cells can become flexible and perform better than many other flexible materials [152].

Limitations of Silicon-Based PV Cells: Conventional silicon PV cells, while efficient, are inherently brittle and rigid due to their crystalline structure, which limits their application on flexible substrates. Even when silicon wafers are sufficiently thin (below 100 μm), they may not achieve the flexibility and mechanical durability offered by advanced flexible materials like organic photovoltaics (OPVs) and perovskite solar cells (PSCs) [153,154]. Recent studies indicate that state-of-the-art flexible OPVs can achieve power conversion efficiencies (PCEs) around 6–10 % with substrate thicknesses as low as a few micrometers, demonstrating significant advancements in efficiency for flexible applications [155,156]. In contrast, while thin silicon cells can be made flexible, their efficiencies often do not surpass those of leading flexible technologies under comparable conditions.

Advances in Flexible Organic and Perovskite Solar Cells: Flexible OPVs have shown remarkable progress in achieving high transparency and flexibility while maintaining competitive efficiencies. For instance, ultra-flexible semitransparent OPVs have been developed with total device thicknesses around 2 μm, achieving efficiencies of 6.93 % [156]. This showcases the potential of organic materials to meet both mechanical and optical requirements for various applications. Similarly, flexible PSCs have been fabricated using low-temperature processes that allow for compatibility with flexible substrates. These cells can achieve efficiencies exceeding 20 % on rigid substrates, with ongoing research aimed at improving their performance on flexible platforms [154]. The ability to process these materials at lower temperatures also enhances their feasibility for integration into diverse applications. Both OPVs and PSCs offer advantages over silicon-based cells in terms of weight, adaptability, and the potential for roll-to-roll manufacturing processes. This adaptability is particularly important for applications requiring lightweight and conformable energy solutions.

Silicon wafer production involves several materials and processes that significantly impact the quality and efficiency of the final product. Traditional methods use high-purity quartz and silicon carbide as raw materials, which undergo carbothermic reduction in electric furnaces at temperatures around 2273 K (2000 °C). This method highlights the importance of the physical form of the charge material, as pellets and lumps exhibit different reaction mechanisms and efficiencies. Alternatively, electrochemical reduction of silicon dioxide (SiO2) in molten CaCl2 can be used, employing dimensionally stable anodes like Ti4O7 that do not release CO2 as a byproduct [157]. This approach operates at lower temperatures (850 °C) and is promising for producing silicon films and particles for photovoltaic applications. Furthermore, silicon wafer waste can be recycled into porous silicon materials for lithium-ion battery anodes, demonstrating potential for recycling within silicon production [158]. This diverse approach reflects the evolving nature of silicon wafer production, aiming to balance efficiency, environmental impact, and material innovation.

Authors in [159] states that the production of silicon wafers involves several critical steps necessary for creating high-quality substrates used in semiconductor and microelectronics industries. The process begins with slicing silicon ingots into thin wafers. This is followed by edge grinding to refine and ensure uniformity of the wafer edges. The wafers then undergo finishing, lapping, and polishing to improve surface quality and remove subsurface damage from slicing and grinding. After achieving the desired thickness through back thinning, the wafers are diced into individual chips for further processing.

Silicon wafer production encounters several significant challenges affecting both efficiency and quality. A key issue is the incorporation of new materials, such as glass wafers. Although these materials offer potential benefits, they pose difficulties due to their lack of opacity and electrical conductivity, as well as the risk of metallic and particle contamination. Addressing these issues requires advanced coatings and thorough particle removal processes to ensure compatibility with silicon fabrication techniques [160]. Additionally, scaling silicon wafers and the devices made from them is complicated by the need to enhance interconnectivity and performance. This demands innovative chemical processing methods that can handle both larger wafers and smaller device features while remaining economically viable. Moreover, transitioning to wafer-scale integration of 2D materials for high-performance applications adds further complexity, as existing production methods are still adapting to these advanced materials [161]. These challenges underscore the need for ongoing advancements in silicon wafer production to drive progress in semiconductor technology.

Thin-film deposition methods

Thin-film deposition methods play a vital role in enhancing the properties of materials used in various fields, such as electronics and optics. Important techniques include PVD, CVD, and Atomic Layer Deposition (ALD). PVD methods, such as sputtering and thermal evaporation, are preferred for their low contamination rates and controlled deposition rates. They are particularly useful in organic electronics, such as pentacene films for organic thin-film transistors (OTFTs) and organic light-emitting diodes (OLEDs) [162]. CVD and its variations, including ALD, are known for their ability to produce high-quality films with precise control over thickness and composition, making them suitable for applications in microelectronics and metal–organic frameworks (MOFs) [163]. ALD stands out for its simplicity and reproducibility, offering atomic-level control in film deposition. Each technique has its own set of advantages and limitations, which affect the choice of method based on the specific requirements of the application [164].

Thin-film deposition methods are essential for improving material properties across various applications. Key techniques include physical vapor deposition, chemical vapor deposition, atomic layer deposition, and chemical solution methods such as Polymer Assisted Deposition (PAD) and sol–gel processes. ALD is renowned for its ability to produce ultra-thin films with exceptional precision and conformality at the atomic level, making it ideal for applications that require exact control over film composition and thickness [163]. On the other hand, chemical methods like PAD provide a cost-effective solution for creating functional films over larger areas, though they may face challenges with maintaining thickness control in the sub-20 nm range [165]. Additionally, the SILAR method is noted for its effectiveness in producing high-quality hafnium oxide thin films, offering superior structural integrity and fewer defects compared to other techniques [166]. Each method has distinct advantages and limitations, which affect its suitability for different applications as shown in Fig. 4.

Thin-film deposition methods encounter several notable challenges that affect their effectiveness and versatility across different technologies. One key issue is the non-uniformity and patterning difficulties associated with traditional techniques such as mechanical exfoliation, which limits the scalability of transition metal dichalcogenides (TMDC) for integrated circuits [167]. Halide perovskite thin films, though promising for optoelectronic applications, face integration challenges due to the need for precise control over film properties—a requirement not fully met by traditional solution-based methods [168]. Directed energy deposition (DED) techniques also struggle with dimensional inaccuracies and poor surface quality, which arise from inconsistent powder flow and interlayer effects [169].

While atomic layer deposition provides advantages in film quality and control, it still encounters issues with substrate selection and precursor compatibility [163]. Additionally, metal–organic framework thin films need a better understanding of growth mechanisms and interface stability to improve their performance in applications such as energy storage and CO2 reduction [170]. Authors in [171] state that two major challenges in thin film solar cell research are: first, the development of materials that are suitable, stable, environmentally friendly, and durable, which can effectively convert a substantial portion of incident solar radiation into separated charges; and second, the need to devise practical manufacturing techniques to convert these materials into solar panels. These challenges listed in Table 5 underscore the ongoing need for research and innovation in thin-film deposition techniques.

Solution-based manufacturing techniques

Layer-by-Layer (LbL) Solution Processing: A notable advancement in organic solar cell (OSC) fabrication is the layer-by-layer solution-processing approach, recognized as a cost-effective method for large-scale production. Recent studies demonstrate that LbL OSCs fabricated with non-fullerene acceptors can achieve power conversion efficiencies (PCEs) exceeding 10 %, while exhibiting reduced energy loss and improved charge transport properties compared to traditional bulk heterojunction (BHJ) methods. This technique is particularly advantageous for roll-to-roll (R2R) manufacturing, enhancing scalability and efficiency in production processes [172].

Multijunction Organic Solar Cells: The development of solution-processed multijunction OSCs has gained traction, employing multiple active layers to reduce energy losses and enhance overall device efficiency. Recent research indicates that these multijunction devices can achieve efficiencies approaching those of conventional thin-film technologies. Strategies such as optimizing the design of interconnecting layers and utilizing optical interference effects have been pivotal in improving light absorption and photocurrent generation [173].

Advancements in Flexible Organic Photovoltaics: The push towards flexible OSCs has led to significant innovations in solution-processing techniques. Recent reviews highlight that flexible organic

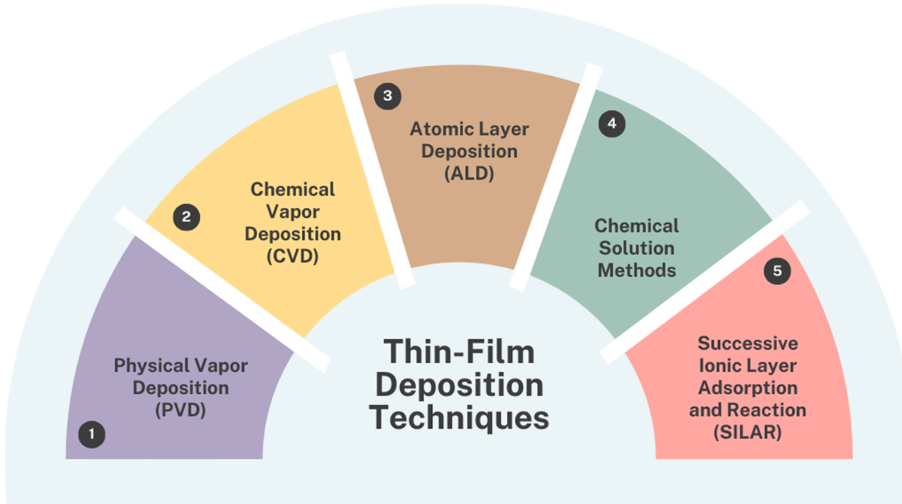

Fig. 4. Thin Film Deposition Techniques.

Table 5
Challenges Facing Thin-Film Deposition Methods.

Challenge	Description	Reference
Non-uniformity in TMDCs	Mechanical exfoliation methods face non-uniformity, limiting TMDC scalability for integrated circuits.	[167]
Integration of Halide Perovskites	Precise control is needed for integrating halide perovskite thin films, which is challenging with traditional methods.	[168]
Dimensional Inaccuracies in DED	Directed energy deposition suffers from dimensional inaccuracies and poor surface quality due to inconsistent powder flow.	[169]
ALD Challenges	Atomic layer deposition faces issues with substrate selection and precursor compatibility.	[163]
MOF Thin Film Issues	Metal-organic framework films need better understanding of growth and interface stability for improved performance.	[170]
Thin Film Solar Cell Development	• Develop stable, environmentally friendly materials for efficient solar energy conversion. • Improve manufacturing techniques for solar panels.	[171]

photovoltaics can achieve certified PCEs by over 19 % through the use of advanced narrow-bandgap small-molecule acceptors and wide-bandgap polymer donors. The emphasis on high-throughput solution processing aligns with the requirements for large-scale commercial applications, such as roll-to-roll printing. Environmental Considerations: There is a growing emphasis on using environmentally benign solvents and materials in the solution processing of OSCs. Research has demonstrated that using hydrocarbon solvents can lead to significant improvements in PCE while maintaining a focus on sustainable manufacturing practice [174].

Efficiency enhancement strategies

Recent advances in PV technology underscore the critical role of both optical and electrical enhancement strategies in achieving higher energy conversion rates. This section includes strategies like anti-reflective coatings, light-trapping structures, and defect passive action, reflects a holistic approach to efficiency enhancement. By addressing both optical and electrical factors, these methods contribute to substantial improvements in PV performance, as evidenced by recent publications. This comprehensive focus supports PV systems' increased applicability in diverse settings, from residential rooftops to large-scale power plants. Anti-reflective coatings (ARCs) minimize the reflection of sunlight off the surface of solar cells, hence enhancing the absorption of light and its conversion into power [175]. Light-trapping structures enhance the distance that light travels within the material of a solar cell, resulting in a stronger interaction between photons and electron-hole pairs. This leads to a higher likelihood of generating charge carriers and improves the efficiency of converting energy [176]. Efficient PV technologies are essential for tackling the worldwide energy dilemma and diminishing our dependence on fossil fuels [177]. By integrating anti-reflective coatings, light-trapping structures into solar cells, and Defect Passivation Strategies in Photovoltaic Efficiency Enhancement, scientists and engineers can greatly enhance the efficiency of these devices, hence increasing the feasibility and cost-effectiveness of solar energy as a means of power production [178].

Anti-reflective coatings

Efficient light control is a crucial element in the design of PV cells to enhance light absorption and enhance the overall efficiency of solar systems. Effective techniques for managing light include anti-reflection coatings [179], texturing, plasmonic nanoparticles [180], and back reflectors [181]. These strategies aim to efficiently catch a significant amount of sunlight, improve photon absorption in the active semiconductor material, and minimize losses caused by reflection and transmission.

Solar cells apply anti-reflection coatings to their surfaces to reduce the reflection of incident light. Fig. 5 illustrates how the reduction in reflection losses allows a greater amount of light to penetrate the active region of the solar cell, thereby improving light absorption and overall efficiency. Recent research employed a thin layer of amorphous carbon nitride as an anti-reflective coating in crystalline silicon (c-Si) solar cells. This implementation resulted in a significant improvement in efficiency, increasing from 5.52 % to 13.05 %. A separate investigation discovered that the application of moth eye anti-reflection material to organic solar cells resulted in a 3.5 % increase in their efficiency. The use of multilayer ARC has the potential to further enhance efficiency [182].

Surface texturization, the process of creating many micro/nanoscale textures on surfaces, is employed to enhance the efficiency of solar cells. According to Fig. 6, this technique enhances the passage of light and reduces reflection at the boundaries, which is essential for enhancing the efficiency of solar cells in converting sunlight into energy. Microstructures, such as pyramids, 1D V-groove arrays, and micro-groove lens structures, can be employed to enhance light trapping and optimize the optical path length. Furthermore, using a rear reflector can increase the

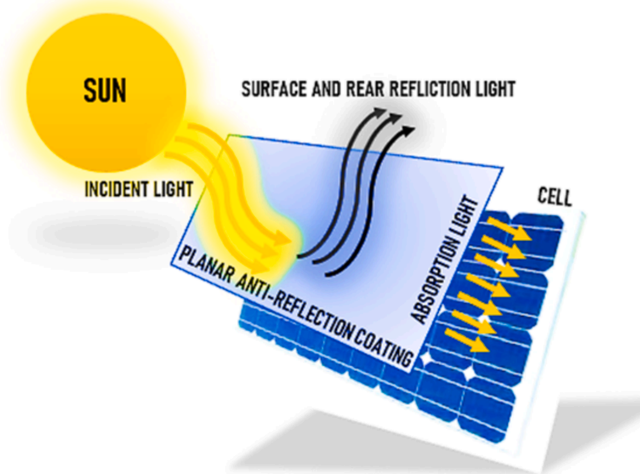

Fig. 5. Reduction in Reflection Losses Due to ARC Planar Layer [182].

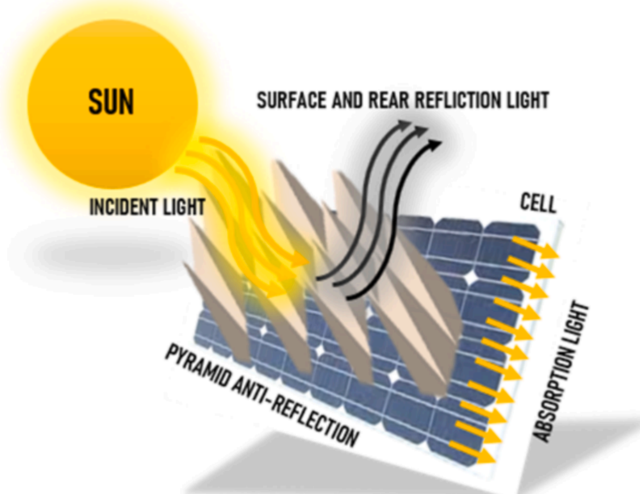

Fig. 6. Reduction in Reflection Losses Due to ARC Pyramid Layer [185].

likelihood of the solar cell effectively capturing light. Located after the absorber layer of a solar cell, a rear reflector typically consists of materials like ZnO/Ag or SiO2/Ag. The primary purpose of the absorber layer is to capture and absorb incoming light, whereas the job of the reflector layer is to redirect the absorbed light back into the cell [183]. Solar cells employ Lambertian surface roughness to introduce randomness in light propagation. This scattering of light towards the absorber, combined with back reflection, increases the optical path length and improves the absorption rates of photons [184].

A comparative review of optical efficiency strategies is crucial for comprehending their distinct and complementary functions in improving PV cell performance. Fig. 5 and Fig. 6 condense many optical methodologies, utilising new quantitative research to provide a comparative analysis. This visual illustrates the advantages and current limits of each approach, offering insights into their prospective uses and effects on overall cell efficiency. This review highlights current advancements that substantially enhance cost-effective, high-efficiency photovoltaic technologies.

Solar cells employ nanostructures for both the active layers and light-management approaches. The enhancement of plasmonic in solar cells encompasses two fundamental mechanisms. First, the relaxation of localized surface plasmon resonances (LSPR) leads to radiative effects. These effects send light back into the layer that absorbs it and make the electric fields there stronger. This improvement includes the phenomena of light scattering and electromagnetic near-field enhancement, as described by Matheu et al. Moreover, non-radiative effects, associated with the relaxation of localized surface plasmon resonance, strive to effectively distribute energy to nearby semiconductors, leading to a significant boost in current generation within the solar cell. Non-radiative effects refer to processes such as hot electron transfer and plasmon resonant energy transfer [186].

Fig. 7 depicts the impact of plasmonic enhancement processes on perovskite solar cells, particularly emphasizing the radiative and non-radiative effects induced by metallic nanostructures to augment light absorption and promote charge carrier generation. The illustration is segmented into three sections, each exhibiting unique positioning techniques for plasmonic nanoparticles within the solar cell architecture, hence illustrating diverse interaction effects and efficiency improvements:

1. Superior Surface Plasmonic Augmentation ((Fig. 7a) [187]): The left panel illustrates metallic nanoparticles, such as gold or silver, positioned on the upper surface of the solar cell. These nanoparticles engage with incident light, reflecting it back into the active layers and extending light path lengths within the cell. The scattering effect enhances the interaction between photons and the semiconductor material, resulting in increased absorption, which is particularly advantageous for thin-film solar cells with restricted light capture. The localised surface plasmon resonance (LSPR) effect produced by these nanoparticles amplifies the electric field at the surface, facilitating greater photon absorption and resulting in enhanced charge carrier production at the cell's front interface.
2. Inserted Plasmonic Nanoparticles ((Fig. 7b) [188]): The central panel illustrates nanoparticles inserted directly within the perovskite layer. This design utilises both radiative and non-radiative phenomena, encompassing hot electron injection, wherein energised electrons from the nanoparticles are transferred into the perovskite layer. Embedding nanoparticles in the light-absorbing layer maximizes the field effect from LSPR, enhancing light-matter interactions and increasing the likelihood of photon absorption. The closeness of the nanoparticles to the active layer promotes plasmonic energy transfer, so augmenting carrier generation without necessitating thicker layers, which preserves a compact cell architecture.
3. Posterior Plasmonic Augmentation ((Fig. 7c) [189]): The right panel depicts metallic nanostructures located on the rear side of the cell, beneath the absorber layer. The plasmonic nanoparticles function as back reflectors, efficiently redirecting transmitted light into the active layer. This configuration also capitalizes on the LSPR effect, as the reflected light re-enters the active layer with amplified electric fields, hence enhancing light-trapping efficiency. This design is highly effective in optimizing light utilization, particularly when spatial limitations necessitate a thinner absorber layer. The rear reflectors provide a dual function, both reintegrating light and amplifying electric fields via plasmonic phenomena.

The configurations—top surface, embedded, and back-side positioning of nanoparticles—exhibit unique yet complimentary methods for integrating plasmonic nanostructures within perovskite solar cells. Each configuration utilizes both radiative and non-radiative plasmonic phenomena to augment light absorption and carrier production, hence boosting total power conversion efficiency while maintaining cell stability. The use of these strategies is essential for enhancing the efficiency of perovskite solar cells, evidenced by their improved light absorption and diminished recombination losses [190].

Light-trapping structures

Extensive study has been conducted on light trapping systems due to

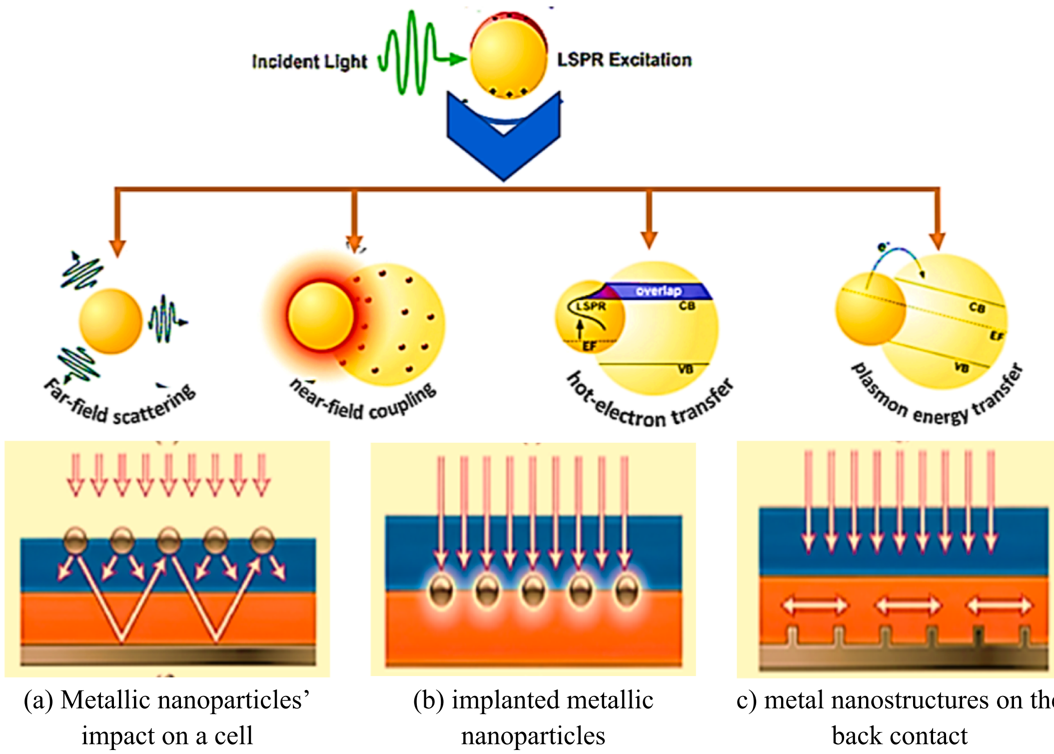

Fig. 7. Radiative Effects of Plasmon Enhancement Mechanisms [182].

the pursuit of efficient solar energy conversion. The initial enquiries were centered around comprehending the underlying interactions between light and materials employed in solar cells. Fen Qiao et al present a thorough examination of the initial phase, emphasizing the capacity of full-spectrum solar cells to augment light absorption via trapping structures and plasmons. Scientists investigated many methods to modify light within the solar cell, with the goal of increasing its path length and reducing reflection losses [191].

Expanding on these fundamental investigations, later research further explored the use of nanostructures to improve light trapping. Alsaigh et al and Amalraj Peter Amalathas et al focus on this matter [192,193]. Alsaigh et al suggest using multi-layer light trapping structures for silicon solar panels, which might enhance daily optical collecting by up to 7.18 % and 159.93 % [192]. Amalraj Peter Amalathas et al. highlight the significance of nanostructures in thin film solar cells, particularly in addressing the issue of limited light absorption. The researchers intend to enhance light absorption and alter the optical response of the device by utilizing nanostructures [193].

As researchers gained more knowledge about nanostructures, they shifted their focus towards investigating plasmonic effects. Chuan Fei Guo et al and Chun-Hsien Chou et al investigate the application of metallic nanostructures to produce localized surface plasmon resonances. The presence of these resonances can greatly amplify the absorption of light and promote the creation of charge carriers in the solar cell. Chun-Hsien Chou et al. specifically concentrates on organic photovoltaic systems, showcasing the capability of plasmonic to enhance their efficiency [194].

Recent research has focused on the incorporation of nanostructures and plasmonic components. The study conducted by Shrestha Basu Mallick et al explores many techniques for effectively capturing and confining coherent light in thin film solar cells. These techniques include the use of photonic crystals, metal nanostructures, and multilayer stacks. Ihsan Ullah et al and Tauseef Ahmed et al provide concrete illustrations of nanostructured solar cell configurations [195,196]. Ihsan Ullah et al concentrate on perovskite solar cells, while Tauseef Ahmed et al focus on microcrystalline absorber layers. These investigations emphasize the significance of fine-tuning nanostructure parameters in order to attain optimal light trapping effectiveness [195].

N. Ben Afkir et al. propose a new method that combines plasmonic nanostructures with a hydrogenated amorphous silicon thin film solar cell. The findings demonstrate a substantial increase in the short circuit current density by 98 % and 71 % for gold and copper nanodisks, respectively. This translates to efficiency increases of 28 % and 26 % [197].

This comparative Fig. 8 demonstrates the effect of anti-reflective coatings and light-trapping structures on photovoltaic efficiency in relation to the theoretical detailed balance efficiency limit. The baseline efficiencies, depicted in grey, indicate the performance of solar cells devoid of enhancing techniques, established at 18 %. The blue bars represent the efficiency attained with the use of anti-reflective coatings or light-trapping structures, yielding enhancements of 22 % and 24 %, respectively. The green bars denote the detailed balancing limit, representing the theoretically achievable maximum efficiency, indicated

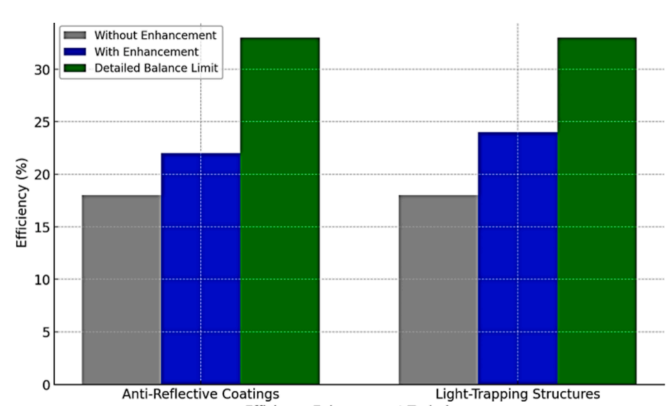

Fig. 8. Comparison of anti-reflective and light-trapping techniques with detailed balance limit.

here at 33 %.

The plot illustrates that both anti-reflective coatings and light-trapping structures markedly improve solar cell efficiency, with the latter offering a marginal advantage by augmenting photon interaction within the cell. This data illustrates that, despite their differing mechanisms—light-trapping increases internal photon route length, and anti-reflective coatings diminish surface reflection—both strategies yield significant efficiency improvements, therefore reducing the disparity to the theoretical efficiency limit.

Defect passivation strategies

Defect passivation is a crucial method for improving the performance and durability of perovskite solar cells (PSCs) by mitigating intrinsic material flaws that frequently result in charge recombination and deterioration. Recent research has emphasized novel molecular approaches to address these issues in both wide-bandgap and methylammonium-free perovskites. Zhuo Dong et al. [198] examined the application of 1,2,4-tris (3-thienyl) benzene (THB) for surface passivation in wide-bandgap inverted perovskite solar cells, which are essential for tandem cells designed to surpass the Shockley-Queisser efficiency threshold. By aligning the THB molecule with the halogen ion vacancies on the perovskite surface, the researchers established a robust connection with $Pb2+$ ions, which significantly diminished surface defects and impeded halogen ion migration, a key contributor to phase instability. This led to a notable enhancement in efficiency, with a peak power conversion efficiency (PCE) of 20.75 % and sustaining 99 % stability over 1512 h under moderate humidity circumstances. Haoxin Wen et al. [199] employed a multifunctional ionic liquid passivator, 1-aminoethyl-3-methylimidazolium tetrafluoroborate (AMFB), to concurrently mitigate $A+$, $B2+$, and $X–$ defects, therefore improving charge transfer and moisture resistance. This method resulted in a PCE enhancement from 22.16 % to 24.41 % with strong stability, as devices maintained over 90 % of their efficiency during extended heat and humidity exposure, highlighting the passivator's effectiveness in facilitating the commercialisation potential of PSCs.

Recent progress in defect passivation techniques has been achieved via the utilisation of bifunctional compounds aimed at improving adhesion and reducing ion movement inside the perovskite framework. Dhruba B. Khadka et al. [200] investigated piperazine dihydriodide (PZDI) for methylammonium-free perovskites, demonstrating that an alkyl core and electron-rich NH terminal significantly diminish surface and bulk defects. The enhanced carrier extraction capabilities and reduced defect densities of these passivated films resulted in an efficiency of 23.17 %, illustrating the influence of surface adsorption and Mulliken charge distribution on the stability of PSCs. Liu L et al. [201] presented piperazine iodide (PI) as an addition to polycrystalline perovskite films, enhancing crystallinity and ensuring steady optoelectronic performance in perovskite-based devices, even after 7000 bending cycles. This method was effectively utilised in two-dimensional hybrid perovskites, where the introduced molecules altered local electron density to suppress non-radiative recombination, hence confirming the adaptability of defect passivation for advanced flexible and wearable solar technologies. Collectively, these results highlight the significance of molecular engineering in defect passivation techniques, establishing a basis for the future advancement of high-efficiency, durable perovskite solar cells.

Key techniques for enhancing photovoltaic efficiency

Recent advancements in photovoltaic technology have introduced innovative methods to enhance energy conversion efficiency. Tandem solar cells, such as perovskite-silicon combinations, have surpassed the Shockley–Queisser limit, achieving efficiencies exceeding 31 % by utilizing complementary absorption spectra. Micro- and nano-scale surface texturing has significantly improved light absorption, leading to efficiency gains of up to 5 % in commercial silicon cells. The application of passivation layers, such as aluminum oxide (Al_2O_3), has effectively reduced surface recombination losses, resulting in a 2–3 % improvement in efficiency. Furthermore, the integration of quantum dots and plasmonic nanoparticles has broadened the absorption spectrum, increasing the efficiency of organic solar cells from 10 % to over 15 %. Advanced multi-layer anti-reflection coatings have also been developed to minimize optical losses, contributing to a 2 % enhancement in the efficiency of crystalline silicon cells. These techniques exemplify the significant strides made in advancing the performance of PV technology and underscore the ongoing efforts to achieve higher efficiency and sustainability in solar energy systems.

Integration of photovoltaics in buildings and smart grids

The incorporation of photovoltaics into buildings and smart grids, as in Fig. 9, signifies a notable progression in the pursuit of sustainable energy solutions. With the increasing need for clean and sustainable energy sources, the use of photovoltaic systems in urban areas presents a viable solution to decrease dependence on conventional fossil fuels, improve energy efficiency, and support the stability of the power grid [202]. Through the use of solar energy on the premises, buildings can transform into energy generators rather than solely energy consumers. This leads to advancements in BIPV and the creation of intelligent power grids that can effectively handle the fluctuations and irregularities of solar electricity [203]. This study examines multiple case studies and research endeavors that aim to enhance the integration of photovoltaic systems in buildings. It emphasizes the obstacles, advantages, and technological progress that shape the future of energy-efficient urban construction [202].

PV systems in smart grids

The incorporation of renewable energy sources, specifically PV systems, into the electrical grid has stimulated the advancement of smart grid technology. Chr Lamnatou et al. present a thorough analysis of this developing area, highlighting the interaction between photovoltaic systems, energy storage, buildings, and environmental factors [205]. The study emphasizes the significance of incorporating PV systems into building structures, implementing energy storage solutions, and conducting thorough environmental studies. Expanding on the groundwork laid by previous smart grid research, further studies have concentrated on addressing difficulties and exploring potential prospects within this field [206]. Luis Avila and his colleagues address the problem of optimizing energy generation from photovoltaic arrays in the presence of changing weather conditions, specifically focusing on the impact of partial shadowing. The authors provide a new method that employs deep reinforcement learning to enhance the optimization of maximum power point tracking (MPPT) in difficult circumstances. This strategy achieves a variation of less than 1 % from the theoretical maximum power point [207].

Abdul Motin Howlader and his colleagues redirect attention towards the effects of integrating PV systems at the grid level. This text examines the function of intelligent PV inverters in reducing voltage and frequency fluctuations resulting from the sporadic nature of solar power production. The paper showcases the efficacy of active power curtailment, volt-watt, and frequency-watt control techniques in preserving grid stability, as supported by experimental findings from the Maui Advanced Solar Initiative Project. The growing adoption of electric vehicles has broadened the range of smart grid research [208]. Sandra Aragon-Aviles and her colleagues examine the incorporation of PV systems, charging infrastructure, and the electric mobility industry. The report highlights the significance of power electronics in connecting these components and presents prospective research avenues for future progress [209].

Shiyong Zheng et al. examine the difficulties and possibilities of

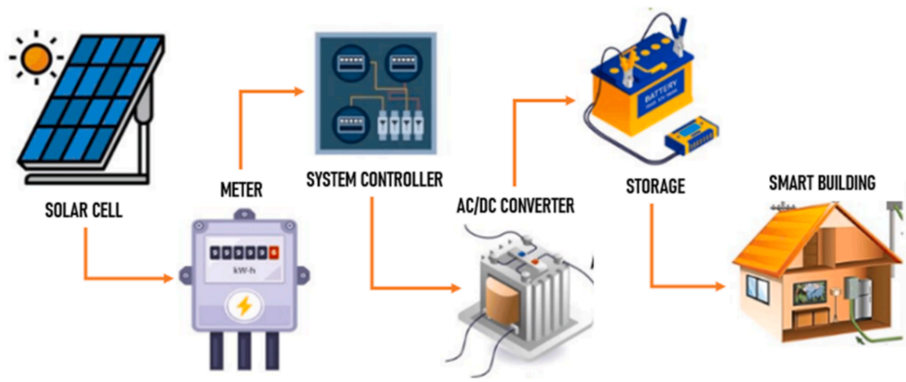

Fig. 9. Integration Architecture for Smart Building and PV System [204].

integrating renewable energy sources, specifically solar PV, with distributed generation systems. The authors present a resilient antlion optimizer algorithm for MPPT and develop charge controllers to guarantee the stability of the system. The study emphasizes the significance of power scheduling in optimizing the operation of the system and minimizing expenses [210]. Expanding upon these progressions, Qiao Peng et al. explore the function of flexible active power control (FAPC) in facilitating the integration of PV systems into the electrical grid. The research highlights the significance of adapting MPPT algorithms flexible power point tracking, (FPPT) to offer ancillary services, such as voltage and frequency support. The use of power reserve regulation (PRC) is proposed as a method to improve grid stability [211].

The idea of decentralized energy systems has become increasingly popular, with an emphasis on enhancing the dependability and effectiveness of the power grid. S. Rauf et al. investigate the possible advantages of direct current (DC) grids for distributed generation of solar systems. DC grids provide a promising method for improving energy efficiency by reducing power conversion losses and allowing direct use of DC electricity for different applications [212]. Carlo Makdisie and his colleagues explore the incorporation of solar PV systems into intelligent power networks, emphasizing the significance of dependability, adaptability, and effectiveness. The authors suggest utilizing a photovoltaic active power line conditioner as a case study to showcase the capabilities of these devices in enhancing grid performance [213]. Ramakrishna Kappagantu and his colleagues offer valuable insights on the deployment of smart grid technologies in India, with a specific focus on the rooftop solar PV industry in Puducherry. The study examines obstacles to the adoption of rooftop solar and analyses the influence of government actions on the promotion of integrating renewable energy [214].

PV in building management systems

The integration of artificial intelligence (AI) in smart grids greatly enhances their operational efficiency, security, and management capabilities. AI technologies enable real-time optimization, predictive analytics, and autonomous control, which are essential for managing the complexities introduced by decentralized energy sources and potential cybersecurity threats. By leveraging AI, smart grids achieve not only more efficient energy distribution but also increased resilience against a range of operational risks, reinforcing the reliability and adaptability of these systems.

AI applications within smart grids include optimization and forecasting, where algorithms help predict energy demand and optimize distribution to improve overall energy management [215]. Deep learning and machine learning facilitate real-time data analysis, enabling more informed decision-making for grid operations [216]. Additionally, AI-based security measures, like generative adversarial networks (GANs), significantly boost cybersecurity by achieving high detection rates for potential cyber threats [217]. However, the use of AI also presents challenges, including increased cybersecurity risks that require advanced encryption and other security protocols [218]. Moreover, managing the extensive data generated within these grids demands sophisticated AI strategies for efficient analysis and storage [219]. While AI holds transformative potential for smart grids, careful attention to data privacy and ongoing advancements in security are essential to mitigate evolving threats.

PV in building management systems

Energy management systems and building management systems (EMS and BMS) are integral to maximizing PV efficiency in urban and residential applications. However, the landscape of these systems is diverse, often involving different terminologies and functional overlaps. The provided schematic clarifies these relationships and helps identify where these systems intersect, highlighting potential synergies with PV integration. Recent studies underscore the significant role of EMS and BMS in optimizing energy usage and enhancing autonomy in smart buildings, positioning them as key players in sustainable urban development.

Developing advanced Energy Management Systems (EMS) is essential for optimizing energy usage in both residential and commercial facilities. Rim Missaoui and her colleagues propose a three-layer EMS design that aims to optimize user comfort while minimizing energy expenses. The research highlights the necessity of employing sophisticated simulation tools to verify control algorithms and precisely simulate the dynamics of buildings. Expanding on this basis, Wessam El-Baz et al emphasize the significance of precise photovoltaic generation predictions for efficient energy management system operation. Researchers can enhance building autonomy and save energy expenses by creating a probabilistic forecast model. In this study [220], C. Chellaswamy et al present a new residential energy management system (REMS) that makes use of Convolutional Neural Networks (CNNs) to efficiently regulate energy usage by analyzing real-time power and meteorological data. These studies illustrate the capacity of data-driven methods to improve energy management tactics [221].

Incorporating renewable energy sources into buildings is an essential element of sustainable energy solutions. Emiliya Dimitrova and her colleagues investigated the incorporation of a hybrid photovoltaic plant as a substitute power source for building management systems, with a focus on enhancing energy efficiency [222]. In this study, Grazia Barchi and colleagues introduce a prototype system that integrates photovoltaic generation, battery energy storage, and a Building Energy Management System (BEMS) in a retail mall. This system showcases the ability of such setups to optimize the utilization of locally produced renewable energy [223].

In order to meet aggressive carbon reduction goals, the construction sector necessitates the implementation of sophisticated energy management strategies. Xinbin Liang et al. present an Internet of Things

(IoT)-based intelligent EMS for buildings with net-zero emissions. The system optimizes the scheduling of Heating, Ventilation, and Air Conditioning (HVAC) while taking into account user comfort and battery health. The study highlights the need of utilizing data-driven forecasting and optimization methods to attain energy saving objectives [224]. Enrico Giglio and his colleagues investigate the incorporation of photovoltaic systems and storage systems in multi-story structures, with a specific emphasis on maximizing economic benefits and enhancing energy efficiency. The research showcases the capacity of machine learning in forecasting demand and emphasizes the economic advantages of the suggested method [225]. Abdul Hazeem Hamzah and Yun Ii Go prioritize BIPV and highlight the significance of aesthetic factors with energy production. The article showcases a case study on a coloured Building Integrated Photovoltaic (BIPV) system, illustrating the ability to maintain the visual appeal of buildings while still generating sustainable energy [226].

The last phase of Integration focusses on investigating new patterns in enhancing building energy efficiency and integrating smart grids. Balakumar P. et al. tackle the issue of predicting electric power consumption and renewable energy output in smart buildings over a short period of time. The research presents a machine learning-driven forecasting model and a day-ahead dynamic pricing mechanism to enhance energy consumption optimization and grid management [227]. I. Lillo-Bravo et al. examine the influence of the amount of integration of photovoltaic modules into buildings on energy efficiency. They introduce a novel measure to quantify the thermal radiation of PV modules. The study offers useful insights for enhancing the design of BIPV systems [228]. Hussein Ali and Ergün Erçelebi propose a BMS that utilizes Raspberry Pi and Arduino platforms to oversee and regulate the environmental conditions of server rooms. The system showcases the capabilities of affordable technologies in adopting energy-efficient solutions for managing buildings [229].

Case studies and applications

The research conducted by Martin Thebault and Leon Gaillard focusses on maximizing the integration of photovoltaic systems on building roofs and facades in order to improve self-consumption. It is crucial for mitigating power fluctuations and alleviating strain on the system. When examining France specifically, the analysis demonstrates that many factors such as the height of buildings, the pattern of energy usage, and the amount of energy consumed have a substantial impact on the most effective integration of photovoltaic systems. The research findings indicate that including façade integration is frequently advantageous for increasing self-consumption, reducing energy transfers with the grid, enhancing grid stability, and maximizing economic profitability [230].

Pegah Hosei Zadeh and her team focus on designing a tall office building that incorporates solar panels. The goal is to decrease energy usage by generating electricity from these panels. The aim is to supply a minimum of 20 % of the monthly lighting electricity needed during important times, like June. The study, conducted using Rhinoceros software with Honeybee plugins powered by the Energy Plus engine, determines that the proposed BIPV system is capable of satisfying 51.3 % of the lighting requirements in February. The system's efficacy is confirmed by empirical data from Mashhad, Iran, showcasing substantial decreases in GHG emissions and thermal energy usage, highlighting its environmental advantages [231].

Hamza Abid and his colleagues analyze the technological and economic viability of combining solar photovoltaic systems with pumped hydro storage (PHS) and electric batteries in Burkina Faso. The study examines the use of photovoltaic technology in both rural areas without access to the electricity grid and metropolitan areas connected to the grid. It concludes that combining PV with pumped hydro storage is the most economically efficient approach for both scenarios, even though the initial costs of PHS infrastructure are substantial. Although battery storage is technically possible, it still presents economic difficulties due to its expensive initial investment and limited lifespan. The results emphasize the necessity of implementing legislative measures to decrease photovoltaic expenses and encourage environmentally friendly electrification in West Africa [232].

Charafeddine Mokhtara and his team investigate the incorporation of hydrogen (H2) generation into a grid-connected PV/battery/H2 hybrid renewable energy system (HRES) for a university campus in Ouargla, Algeria. The study utilizes a sector-coupling approach, specifically targeting the areas of building and transportation, in order to optimize self-reliance and facilitate tram operation. The research examines two scenarios: one that emphasizes cost reduction with limited reliance on non-renewable energy sources, and another that aims to minimize non-renewable energy usage to the greatest extent possible. The analysis determines that a combination of a grid and photovoltaic system is the most cost-effective option. However, including hydrogen (H2) into the system better aligns with future energy requirements, resulting in substantial reductions in CO2 emissions and enhanced system reliability [233].

X Barrutieta and colleagues conduct an analysis of positive energy buildings (PEB) and net-zero energy buildings (NZEB), examining the ideal proportion of photovoltaic area needed for office buildings to achieve self-sufficiency. The study demonstrates that buildings equipped with photovoltaic (PV) systems that cover 10–20 % of their total floor area achieve self-sufficiency ratios ranging from 100 % to 150 %. Installing photovoltaic systems on building facades is essential for achieving a favorable energy balance. The study emphasizes the significance of the PV to floor area ratio and the deliberate utilization of building façades to maximize energy generation, particularly in areas with abundant solar irradiation [234].

Chrysanthos Charalambous and his colleagues present a novel AC-DC distribution system that combines a solar system, battery, and DC heat pump to be used in historical buildings in Cyprus. The suggested system establishes a direct connection between DC devices and the DC grid, thereby reducing energy losses caused by conversions. AC loads, on the other hand, are connected to the AC grid. The results indicate substantial advantages, such as a decrease in imported energy and an overall renewable energy proportion surpassing 85 %. The study asserts that the combination of hybrid AC-DC systems with inventive storage methods presents a very effective and environmentally friendly method for managing energy in buildings, especially in historical settings [235].

The investigation of recent case studies in Table 6 underscores developing trends and persistent patterns in photovoltaic (PV) integration across diverse building and grid applications. A significant trend is the focus on optimising self-consumption via novel photovoltaic installations on building facades and rooftops, as demonstrated in Thibault and Gaillard's study, which revealed that façade integration enhances grid stability and diminishes energy transfers. Comparable solutions in high-rise office buildings, as illustrated by Hoseinzadeh et al., reinforce this trend by attaining significant decreases in greenhouse gas emissions and minimising energy use through optimal photovoltaic deployment. Furthermore, there is a significant emphasis on the integration of photovoltaic systems with sophisticated energy storage options, such pumped hydro storage (PHS) and battery systems, to enhance energy resilience and economic efficiency. Abid et al.'s investigation in Burkina Faso highlighted the cost-effectiveness of PHS, demonstrating an increasing interest in hybrid energy storage to enhance PV performance in rural and urban settings.

A recurring theme identified in these studies is the deliberate implementation of sector coupling and hybrid systems to enhance energy self-sufficiency. Mokhtara et al. shown that including hydrogen generation into PV-battery systems can markedly improve system reliability and diminish CO_2 emissions, especially in university campus environments. This strategy consists of international objectives of decarbonization and energy independence. Barrutieta et al. determined that attaining self-sufficiency in office buildings necessitates a

Table 6
Summary of Previous Cases Studies Research.

Ref.	Description	Objective	Methodology	Key Findings	Implications
[230]	Martin Thebault, and Leon Gaillard	Maximize integration of PV systems on building roofs and facades	Analysis of building height, energy usage patterns, and energy consumption in France	Façade integration enhances self-consumption, reduces energy transfers, and improves grid stability	Improves PV efficiency in urban environments, promoting economic profitability and grid stability
[231]	Pegah Hoseinzadeh et al.	Design a tall office building with integrated solar panels	Simulation using Rhinoceros software and Honeybee plugins powered by EnergyPlus engine	BIPV system can meet 51.3 % of lighting needs, significantly reducing GHG emissions and energy use	Promotes sustainable building design and energy efficiency in office buildings
[232]	Hamza Abid et al.	Assess economic viability of PV with PHS and batteries in Burkina Faso	Technological and economic analysis of PV, PHS, and battery systems	PHS is most cost-effective; battery storage is technically viable but economically challenging	Supports legislative measures for reducing PV costs and fostering sustainable electrification in Africa
[233]	Charafeddine Mokhtara et al.	Incorporate hydrogen generation into PV/battery/H2 hybrid systems	Sector-coupling approach for building and transportation in a university campus	H2 integration reduces CO2 emissions, increases system reliability, and aligns with future energy needs	Optimizes campus energy self-reliance and sustainable transportation
[234]	X. Barrutieta et al.	Evaluate PV area required for PEB and NZEB to achieve self-sufficiency	Analysis of PV to floor area ratio and façade utilization	10–20 % PV coverage achieves 100–150 % self-sufficiency; façade installation is crucial	Guides the design of energy-efficient office buildings, especially in solar-rich areas
[235]	Chrysanthos Charalambous et al.	Develop an AC-DC hybrid distribution system for historical buildings in Cyprus	Design of a hybrid system connecting DC devices to DC grid and AC loads to AC grid	Hybrid system reduces energy losses, surpasses 85 % renewable energy use	Offers a sustainable energy management solution for historical buildings

photovoltaic-to-floor area ratio of a minimum of 10–20 %, a ratio that is progressively recognized in the design of energy-positive structures. These studies consistently emphasize the utilisation of photovoltaic (PV) systems for enhancing energy efficiency, providing environmental advantages, and ensuring economic viability, hence highlighting the increasing significance of PV integration in fostering sustainable and resilient urban infrastructure.

Economic and environmental impacts of photovoltaic technology

Photovoltaic technology has emerged as a critical component in the global transition to sustainable energy systems. As the world grapples with the twin challenges of economic growth and environmental sustainability, PV technology offers a solution that addresses both. Its economic and environmental impacts are profound, affecting both micro and macroeconomic factors as well as significantly contributing to the mitigation of climate change. This section explores these impacts in detail, including the role of optimization techniques in enhancing the economic and environmental benefits of PV technology [11].

Economic impacts of photovoltaic technology

The economic impacts of photovoltaic technology are transformative, driven by significant cost reductions and efficiencies that have made solar energy increasingly competitive with traditional energy sources. Over recent decades, the dramatic decline in PV module costs, driven by economies of scale and technological advancements, has significantly improved the financial viability of solar energy. Additionally, the land use and resource consumption associated with PV systems are being optimized through innovative practices and technologies, such as agrivoltaics and advanced recycling methods. Evaluating the return on investment (ROI) and payback period further illustrates the economic benefits of PV technology, demonstrating its potential for providing substantial long-term savings and attractive financial returns. Together, these factors highlight the growing economic significance of PV technology in the global energy landscape [236].

Cost trends and economies of scale

Photovoltaic technology has witnessed transformative cost reductions over recent decades, making solar energy one of the most cost-competitive energy sources today. By contextualizing the financial data globally, this analysis reflects the evolving economic viability of PV technology across regions and market segments. Comparative cost trends and economies of scale have been illustrated in a revised format, allowing for a clear visualization of the learning curve effect. The continued reduction in PV costs emphasizes solar energy's potential to rival and complement conventional energy sources worldwide.

Over the past few decades, the cost of PV technology has seen a significant decline, making it more accessible and economically viable. In 2000, the average cost of PV modules was approximately $4.50 per watt, while in 2024, this cost has dropped to below $0.20 per watt, thanks to advancements in manufacturing processes, economies of scale, and increased competition within the industry. This reduction in cost has made solar energy one of the most competitive energy sources, rivaling traditional fossil fuels in many regions [237]. The reduction in costs is closely linked to economies of scale. As the production volume of PV modules increases, the cost per unit decreases. This relationship is governed by the learning curve effect, which suggests that for every doubling of cumulative production, the cost of PV modules decreases by approximately 20 %. This trend is depicted in Fig. 10. This graph shows the declining cost per watt as cumulative production increases, demonstrating the learning curve effect [238].

Job creation and economic growth

The photovoltaic (PV) industry is a significant contributor to job creation, encompassing manufacturing, installation, operation, and maintenance sectors. In 2023, the global renewable energy sector employed approximately 16.2 million people, marking an 18 % increase from 13.7 million in 2022. This growth is particularly prominent in countries with robust renewable energy policies, such as China, the United States, and the European Union. Employment in the PV industry is categorized into direct, indirect, and induced jobs. Direct jobs include roles in manufacturing and installation; indirect jobs pertain to the supply chain, such as component manufacturing and logistics; and induced jobs arise from economic activities generated by the incomes of those employed directly or indirectly in the PV industry [239].

Fig. 11 provides a breakdown of the distribution of jobs across the different sectors of the PV industry: manufacturing, installation, operation, and the supply chain. The data, referenced from IRENA's 2023 report, is derived from global industry statistics and workforce analysis conducted across major PV markets. The calculation of percentages reflects the proportion of total PV employment attributed to each sector, highlighting manufacturing as the largest contributor at approximately

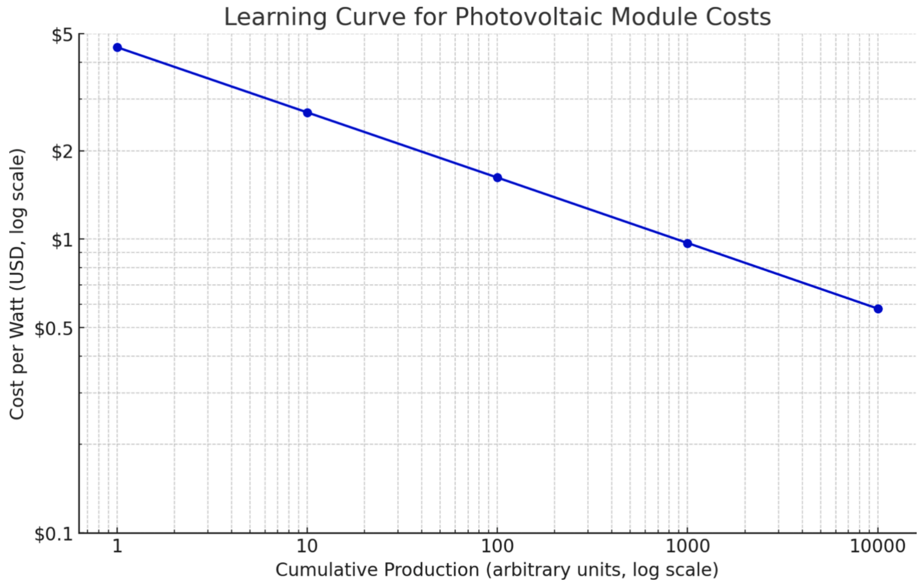

Fig. 10. Learning Curve for Photovoltaic Module Costs [238].

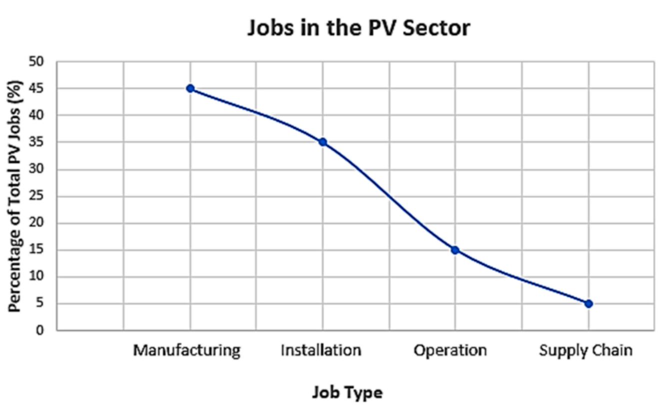

Fig. 11. Distribution of Jobs in the PV Sector [240].

45 %, followed by installation at 35 %. Operation and supply chain roles account for smaller but still significant portions of employment, demonstrating the diverse economic impacts of the PV industry. This graph emphasizes the critical role of manufacturing and installation in driving job creation, which aligns with the industry's expansion trends and the increasing demand for PV systems globally. Understanding these distributions helps policymakers and industry stakeholders prioritize investment in workforce development and streamline supply chain efficiencies to sustain economic growth [240].

A comprehensive evaluation of the economic returns of PV installations—spanning small residential to large utility-scale systems—is crucial for understanding solar technology's viability across various scales. This section includes updated datasets and contextual details, providing a nuanced view of payback periods and return on investment (ROI) for different applications. By visualizing ROI and payback periods, this analysis enhances the comparative understanding of PV's financial benefits, affirming solar energy's role as a sound investment in the renewable energy portfolio.

Return on investment (ROI) and payback period

One of the key economic metrics for evaluating the viability of PV investments is the return on investment and payback period. For residential PV systems, the payback period can range from 5 to 10 years, depending on factors such as location, system size, and local electricity prices. In regions with high electricity costs and generous incentives, the payback period can be as short as 3 to 5 years. For commercial and utility-scale installations, the payback period is often shorter due to economies of scale and higher energy production efficiency [241].

The ROI for PV systems is generally favorable, with many systems providing returns of 5 % to 10 % annually over their 25 to 30-year lifespan [242]. Table 7 provides a comparison of ROI and payback periods for different types of PV installations.

Optimization techniques play a crucial role in enhancing the economic performance of PV systems. Techniques such as MPPT and smart inverters optimize the energy yield of PV systems, thereby improving the ROI [246].

Environmental impacts of photovoltaic technology

The environmental impacts of photovoltaic technology are crucial in assessing its role in sustainable energy. PV systems are renowned for their ability to significantly reduce greenhouse gas emissions by providing a clean energy source that minimizes reliance on fossil fuels and their associated carbon footprints. While the installation of PV systems requires land and involves resource consumption, innovative approaches are being developed to address these challenges. Efficient land use practices, such as agrivoltaics and floating solar panels, help mitigate the environmental footprint. Furthermore, advancements in recycling technologies are enhancing the sustainability of PV systems by improving the recovery of valuable materials and reducing waste. These environmental benefits underscore the importance of PV technology in contributing to a cleaner, more sustainable future [247].

Reduction in greenhouse gas emissions

One of the most significant environmental advantages of PV technology is its potential to reduce greenhouse gas emissions. Unlike fossil fuel-based power generation, PV systems produce electricity without burning fuel, resulting in no direct emissions of carbon dioxide (CO2) or

Table 7
ROI and Payback Periods for Different Types of PV Installations.

System Type	Average Payback Period (Years)	ROI (%)	Ref
Residential (Small)	5–10	5–10	[243]
Commercial (Medium)	3–7	7–12	[244]
Utility-Scale (Large)	3–5	8–15	[245]

other greenhouse gases. Over its lifetime, a typical PV system can offset several tons of CO2, depending on its size and location. For example, a 5-kW residential PV system in a sunny region can offset approximately 100 tons of CO2 over 25 years. On a global scale, the widespread adoption of PV technology could contribute significantly to the reduction of emissions, helping to mitigate the impact of climate change. Fig. 12 compares the CO2 emissions of different energy sources [248].

The widespread adoption of PV technology has the potential to significantly reduce global GHG emissions. In 2023, solar power contributed to a reduction of approximately 1.2 billion metric tons of CO2, equivalent to the annual emissions of 258 million passenger vehicles [249].

Land use and resource consumption

The land used associated with large-scale PV installations has raised environmental concerns, particularly in ecologically sensitive areas. However, compared to other energy sources, the land use of PV systems is relatively low. For instance, a utility-scale PV plant requires about 3.5 to 4.5 acres of land per megawatt of installed capacity, which is comparable to or even lower than the land requirements for coal or nuclear power plants when considering the entire fuel supply chain. Moreover, innovative solutions such as agrivoltaics—combining agriculture and PV installations on the same land—are being explored to optimize land use and reduce environmental impacts [250].

To optimize land use and reduce environmental impact, innovative solutions such as agrivoltaics and floating solar farms are being developed. Agrivoltaics involves the simultaneous use of land for both solar power generation and agriculture, which can enhance land productivity and reduce competition for land resources. Floating solar farms, installed on bodies of water, minimize land use and can also reduce water evaporation [251]. Table 8 illustrate Comparison between Utility-Scale PV, Coal Power Plant and Nuclear Power Plant for the instance.

Resource consumption and recycling

In addition to land use, resource consumption in PV manufacturing is an important environmental consideration. The production of PV panels requires the extraction and processing of raw materials, including silicon, silver, and other metals. While the manufacturing process does consume energy and water, advancements in technology have led to significant improvements in resource efficiency. For example, the water consumption in PV manufacturing has decreased by more than 50 % over the past decade, and the energy payback time (the time it takes for a PV system to generate the energy used in its production) has been reduced to less than 2 years for most systems [255].

End-of-life management and recycling of PV panels is an emerging environmental issue as the first generation of PV systems approaches the end of their operational life. PV panels are typically composed of materials that can be recycled, such as glass, aluminum, and silicon. However, the recycling infrastructure for PV panels is still in its early

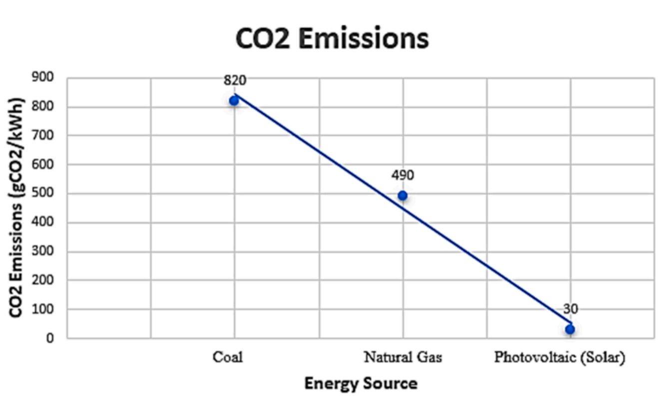

Fig. 12. CO2 Emissions Comparison Between Energy Sources [248].

Table 8
Comparison between Utility-Scale PV, Coal Power Plant and Nuclear Power Plant.

Installation Type	Land Use (Acres/MW)	Ref
Utility-Scale PV	3.5–4.5	[252]
Coal Power Plant	1.8–2	[253]
Nuclear Power Plant	6–8	[254]

stages. Developing effective recycling processes is crucial to minimizing the environmental impact of decommissioned PV systems and recovering valuable materials for reuse in new panels [256]. Table 9 summarizes the recycling processes and recovery rates for different PV materials.

Optimization techniques are also being applied to improve resource efficiency in PV manufacturing and recycling. Techniques such as Life Cycle Assessment (LCA) are used to evaluate the environmental impact of PV systems from production to disposal, identifying areas where resource consumption can be minimized. Advanced recycling technologies, such as chemical vapor deposition for silicon recovery, are being developed to increase the recovery rates of valuable materials from end-of-life panels [261]. Fig. 13 shows the stages of a PV system's life cycle, including material extraction, manufacturing, operation, and recycling, with key environmental impact metrics highlighted.

The economic and environmental impacts of photovoltaic technology underscore its pivotal role in the global energy transition. Economically, PV technology has become increasingly viable, driving job creation, economic growth, and favorable returns on investment. Environmentally, it offers a cleaner, more sustainable alternative to fossil fuels, contributing to significant reductions in greenhouse gas emissions and mitigating the effects of climate change. As technology continues to advance, the economic and environmental benefits of PV technology are likely to grow, making it a cornerstone of sustainable energy strategies worldwide [262].

Challenges and future directions in photovoltaic research

In spite of the notable progress in photovoltaic technology, the industry encounters certain persistent obstacles that need to be tackled in order to fully use the potential of solar energy. The problems encompass issues such as reduced efficiency, material durability, environmental consequences, and scalability. Gaining comprehension and successfully surmounting these obstacles are of utmost importance for the extensive acceptance and enduring sustainability of solar energy.

Long-term performance

Efficiency degradation is the progressive decline in the capacity of a solar cell to convert sunlight into energy as time passes. This deterioration might arise as a result of many factors like dust, delamination, hotspot, discoloration, crack and temperature and humidity [263–265]. The efficacy of solar panels can be reduced as a result of exposure to these elements over time [266].

Photovoltaic cells based on silicon can experience a decrease in efficiency due to exposure to sunlight, a phenomenon known as Light-Induced Degradation (LID). The presence of oxygen impurities in the silicon is often linked to the development of this phenomenon, which

Table 9
Recycling Processes and Recovery Rates for Photovoltaic Materials.

Material	Recycling Process	Recovery Rate (%)	Ref
Glass	Crushing and separation	90–95	[257]
Aluminum	Melting and refining	95–98	[258]
Silicon	Chemical and thermal purification	85–90	[259]
Silver	Electrolytic refining	95–98	[260]

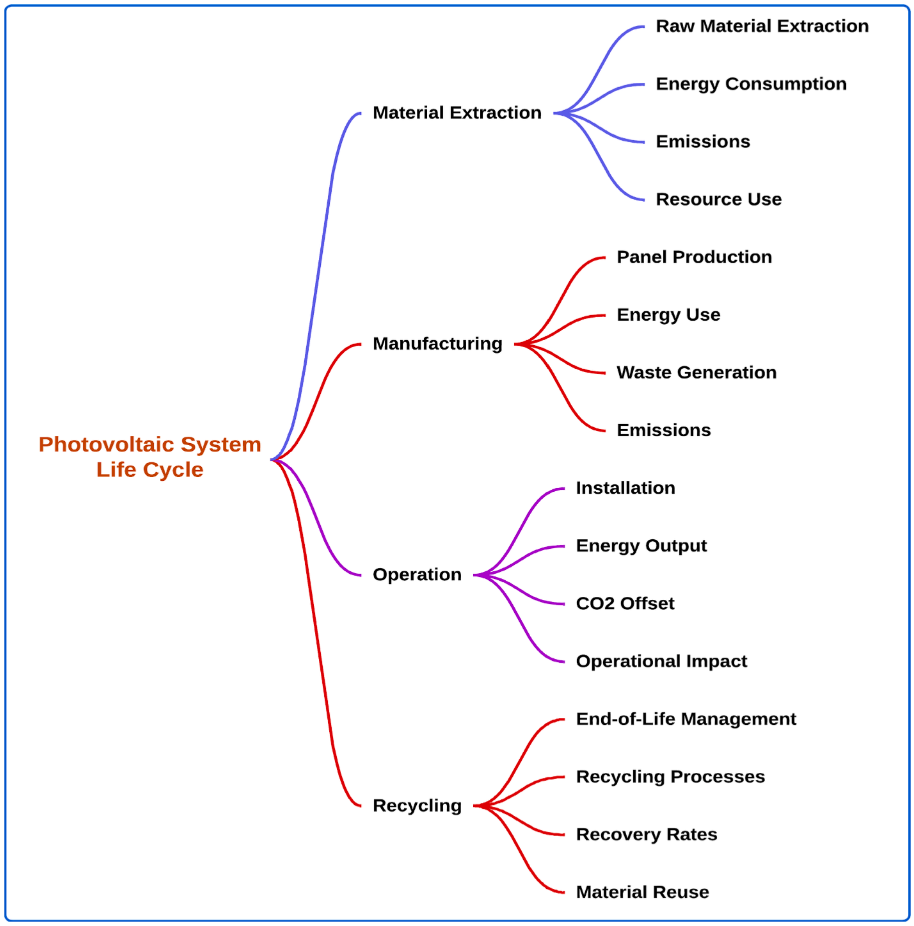

Fig. 13. Life Cycle Assessment (LCA) of a PV System.

reduces the efficiency of the cell by combining with boron [267–269].

Thermal degradation refers to the deterioration of materials in solar cells when exposed to high temperatures, resulting in a decrease in their efficiency. This issue arises in regions characterized by hot climatic conditions, where the confluence of elevated temperatures and abundant sunlight can expedite the degradation of solar modules [270].

PV modules in humid regions are more susceptible to degradation caused by moisture. Moisture seeping into the module can cause corrosion of the metal connections and degradation of the encapsulant material, ultimately resulting in a drop in efficiency [265].

Potential-Induced Degradation (PID) refers to the phenomenon of ion migration within a photovoltaic module due to voltage potential variations between the module and the ground. This migration can negatively affect the performance of the cells [271,272].

Material stability

The long-term properties of the materials utilized in PV cells, especially in developing technologies such as perovskites and organic photovoltaics, continue to pose a substantial obstacle. Although perovskite solar cells have demonstrated significant enhancements in efficiency, their ability to maintain stability over extended periods of time in real-world environments remains uncertain. Perovskites exhibit sensitivity to moisture, oxygen, and UV radiation, which can cause fast breakdown if not well enclosed [121].

The organic materials utilized in OPVs have the potential to deteriorate when exposed to ultraviolet (UV) radiation and subjected to temperature stress. Although they possess advantages like flexibility and being lightweight, enhancing their stability is crucial for ensuring their economic viability. Thin-film solar cells, such as CIGS and CdTe, have stability problems, namely with the diffusion of components and the deterioration of layers when exposed to sunlight for extended periods [273].

Cost

Although there has been a substantial decline in the cost of PV modules in recent years, it is crucial to achieve additional cost reduction to facilitate wider adoption. This may be accomplished by making progress in manufacturing processes, using appropriate materials, and taking use of economies of scale. Research is investigating cost-effective manufacturing techniques, such as thin-film technologies and solar cells based on perovskite [274].

Environmental impact

The environmental ramifications of photovoltaic production, implementation, and disposal at the end of its lifecycle are a matter of concern that need continuous focus [275].

Resource scarcity is a worry for the sustainability of widespread implementation of some photovoltaic technologies. This is because these technologies depend on elements that are either scarce or dangerous, such as indium in CIGS and cadmium in CdTe. The extraction and processing of these compounds may result in significant ecological consequences [276].

Alongside the growing use of solar panels, there is a corresponding growth in the demand for efficient recycling and disposal techniques for decommissioned PV modules. The existing recycling methods are characterized by high energy consumption and incomplete effectiveness, which raises problems regarding waste management. While photovoltaic systems provide environmentally friendly electricity, the manufacturing process, particularly for silicon-based cells, requires a significant amount of energy. Minimizing the energy payback time, which refers to the duration needed for a solar panel to generate the same amount of energy consumed during its manufacturing process, is a continuous challenge [277].

Scalability and integration

The increasing demand for solar energy necessitates the expansion of production and the incorporation of photovoltaic systems into the current energy infrastructure, which poses many obstacles [278].

The intermittent nature of solar power can present a challenge when attempting to integrate a significant quantity of it into the grid as illustrated in Fig. 14. Efficient management of supply and demand, as well as maintaining grid stability, necessitates the use of energy storage systems and smart grid technology [279].

Manufacturing scalability is the crucial difficulty of increasing the output of developing photovoltaic technologies, including perovskites and quantum dot solar cells, while ensuring high quality and cost-effectiveness. This involves the creation of scalable manufacturing methods capable of producing high-efficiency cells at a minimal expense. The establishment of large-scale solar farms necessitates substantial land expanses, potentially leading to competition with agriculture and other land uses. Exploration is underway to solve space limitations through innovations in BIPV and floating solar farms [325].

Future research directions

In order to tackle these issues and stimulate more advancements in the photovoltaic industry, future research should prioritize the following areas [281,282]:

- Materials development includes investigating novel materials and material combinations, such as perovskites, organic–inorganic hybrids, and quantum dots, in order to improve efficiency, reduce costs, and increase stability.
- Developing innovative device architectures, such as tandem cells, bifacial modules, and transparent solar cells, to enhance energy capture and broaden the potential applications of these devices.
- Improving the efficiency of PV cells through methods such as light capture, heated carrier extraction, and interfacial engineering.
- Improving the long-term stability and endurance of PV modules by utilizing improved encapsulating materials and protective coatings.
- Grid integration involves the development of advanced technologies and energy management systems to maximize the performance of large-scale photovoltaic installations and maintain the stability of the power grid.
- Environmental sustainability includes advocating for manufacturing processes that are sustainable, minimizing the negative effects on the environment during the manufacture and disposal of PV modules, and investigating ways for deploying PV systems in a way that optimizes land usage.

To maintain its significance in the shift towards a clean and sustainable energy future, the photovoltaic industry must confront these obstacles and explore novel research avenues.

Conclusion and future work

Photovoltaic technology continues to evolve rapidly, driving the growth of solar energy as a cornerstone in the renewable energy landscape. This review has highlighted significant advancements in PV materials, device architectures, and integration techniques, underscoring their role in enhancing efficiency, reducing costs, and expanding

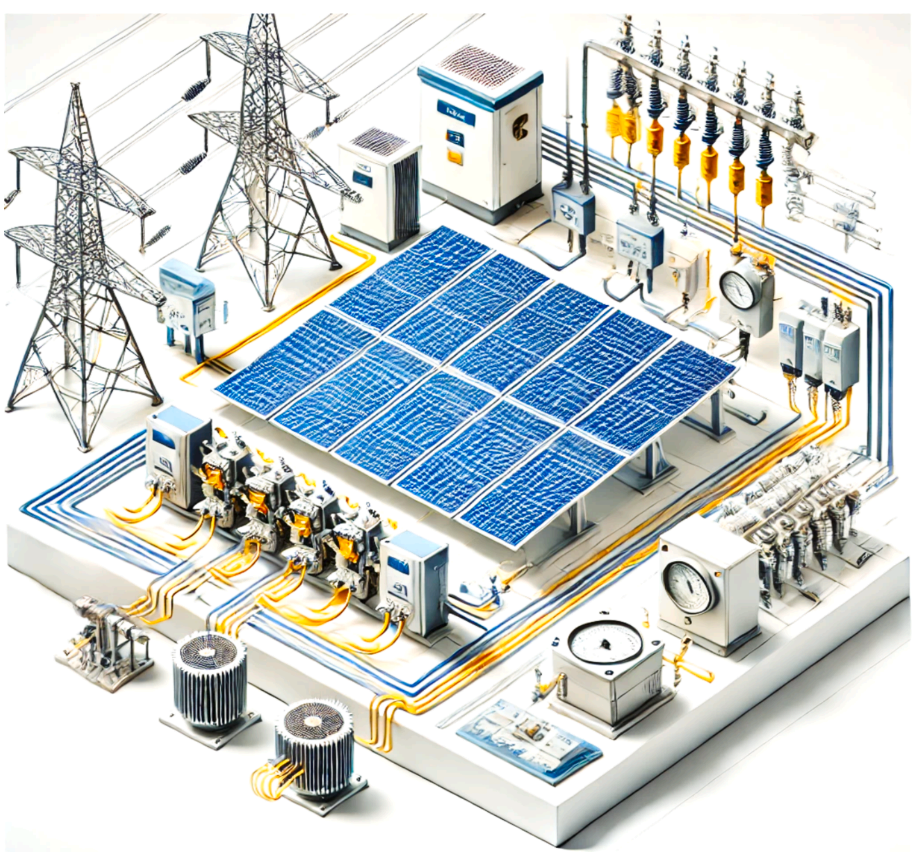

Fig. 14. The integration of large-scale PV systems into the grid [280].

application areas. The shift from traditional crystalline silicon cells to cutting-edge technologies like perovskite, quantum dot, and organic solar cells reflects the transformative potential of PV systems in achieving sustainable energy goals. Additionally, innovations such as tandem cells, flexible PV, and transparent solar cells have broadened the scope of PV applications, enabling integration into diverse systems like smart grids, portable electronics, and building-integrated photovoltaics. Key advantages of the proposed advancements include improved energy conversion efficiency, reduced reliance on scarce materials, and adaptability to various deployment scenarios. For instance, agrivoltaic and aquavoltaic systems demonstrate how PV technology can be integrated with existing infrastructure to enhance energy generation while supporting agriculture and water management. Furthermore, the integration of PV systems into smart grids and energy storage solutions is crucial for addressing intermittency challenges and optimizing energy management. Despite these advancements, challenges remain in improving material stability, efficiency retention under varying environmental conditions, and recycling. Addressing these issues will require focused research on durable and sustainable materials, cost-effective manufacturing processes, and robust recycling mechanisms. Exploring the socioeconomic impacts and scalability of emerging PV technologies will also be essential to accelerate their adoption globally.

Looking ahead, the integration of PV systems into diverse applications, such as electric vehicles, off-grid solutions, and advanced energy management systems, will unlock new opportunities for solar energy to play a pivotal role in the global transition to sustainability. Collaboration between researchers, policymakers, and industry stakeholders will be critical to overcoming barriers and fostering innovation in the field. By addressing existing challenges and leveraging ongoing advancements, PV technology is poised to remain at the forefront of renewable energy solutions, driving a cleaner, more resilient, and sustainable energy future.

CRediT authorship contribution statement

Abdelrahman O. Ali: Validation, Methodology. **Abdelrahman T. Elgohr:** Supervision, Project administration, Investigation. **Mostafa H. El-Mahdy:** Writing – original draft, Visualization. **Hossam M. Zohir:** Project administration, Formal analysis. **Ahmed Z. Emam:** Writing – review & editing, Data curation. **Mostafa G. Mostafa:** Methodology, Investigation. **Muna Al-Razgan:** Validation, Funding acquisition. **Hossam M. Kasem:** Resources. **Mohamed S. Elhadidy:** Writing – review & editing, Validation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

No data was used for the research described in the article.

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