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A comprehensive review on solar photovoltaics: Navigating generational shifts, innovations, and sustainability

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ABSTRACT

The consumption of fossil fuels presents a combined issue of environmental degradation and depletion of the current limited resources. In this context, solar photovoltaic (PV) technology provides a fundamental component in the global shift towards addressing climate change, reducing harmful emissions, and supporting sustainable energy alternatives. In order to recognize the growth of this technology, this study conducts an investigation and exploration, covering recent improvements in solar PV. The paper provides a comprehensive overview for researchers seeking an up-to-date summary of the current status of this technology. Perovskite/Silicon and III-V/Silicon tandem cells currently possess the highest efficiency, with a record-breaking achievement of 34.6 % and 36.1 % in recent research. Furthermore, both Perovskite and tandem cells exhibit the most reasonable energy payback time (EPBT) and levelized cost of electricity (LCOE) at the laboratory scale in comparison to conventional solar cells. Perovskite/Perovskite tandem cells showed the lowest LCOE and EPBT among all other types of cells by $0.042/kWh and 0.2 to 0.4 years, respectively. The integration of bifacial and tracking systems has the potential to enhance productivity by approximately 30 %, and 20 to 57 %, respectively, depending on the tracking technology and study location. Nevertheless, the use of materials like Pb, Sn, Cd, and Te requires careful management due to their potential harmful effect on human health, especially during recycling, decommissioning, and manufacturing processes. Although third-generation and tandem solar cells show promise, they necessitate additional research to tackle issues such as costly manufacturing, scalability, stability, and durability.

1. Introduction

In the quest for environmentally green energy options, one effective and promising option is solar energy. Different technologies have been developed, offering a range of applications, and highlighting the adaptability of solar energy in meeting various energy needs, including heating, cooling, dryers, electricity, and water desalination. Solar photovoltaic (PV) technology is an outstanding solution in the search for sustainable energy. It harnesses the power of sunlight to generate electricity by using semiconducting materials that demonstrate the PV effect (Dale and Scarpulla, 2023; Oteng et al., 2021). This technology presents an essential part in the sustainable energy alternatives development. Most solar PV modules rely on silicon-based cells as their main component. This design allows converting solar energy into electrical energy by releasing electrons from their atomic orbits with the use of photons.

Solar PV has advanced quickly in the renewable energy sector (Creutzig et al., 2023). In 2022, it reached an important record by

Abbreviations: a-Si, amorphous silicon; AZO, aluminum-doped zinc oxide; BIPV, building-integrated photovoltaics; CdTe, cadmium telluride; CIGS, copper indium gallium selenide; CIS, copper indium selenide; c-Si, crystalline silicon; DSSC, dye-sensitized solar cell; EPBT, energy payback time; ETL, electron transport layer; EVA, ethylene vinyl acetate; FTO, fluorine-doped tin oxide; GaAs, gallium arsenide; GZO, gallium-doped zinc oxide; HNO_3, nitric acid; HTL, hole transport layers; ITO, indium tin oxide; LCA, life cycle assessment; LCOE, levelized cost of electricity; MAI, methylammonium iodide; OSC, organic solar cell; PCE, power conversion efficiency; Pk/Si, Perovskite/silicon tandem; PSC, Perovskite solar cell; PV, photovoltaic; R2R, roll-to-roll; TCO, transparent conducting oxides; ZnO, zinc oxide.

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generating 270 TWh, showing a significant increase of 26 % (Solar-IEA, 2023). This advancement pushed solar PV ahead of wind energy, becoming the first time in history that solar PV outperformed wind energy in terms of electrical power generation growth. Solar PV technology currently ranks as the third major contributor to global renewable energy output. Solar PV accounted for 4.5 % of total worldwide electricity output in 2022, behind both hydropower and wind energy (Solar-IEA, 2023). China's market dominates global solar PV technology, providing 38 % of the world's solar PV potential in 2022 (Solar-IEA, 2023; Wang et al., 2021a; Chadly et al., 2024). Furthermore, both the United States and the European Union have achieved major improvements in the solar PV industry. In fact, they have collectively accounted for 15 % and 17 % of worldwide capacity expansions, respectively (Solar-IEA, 2023). Fig. 1 illustrates the 89 % decline in the LCOE "levelized cost of electricity" for solar PV systems since 2010, according to the IRENA "International Renewable Energy Agency". Moreover, by 2022's end, solar PV installations worldwide have exceeded 1047 GW. The earlier statistics indicate a substantial increase of about 26 times in the adoption of this technology from 2010 (International Renewable Energy Agency, 2023).

The efficiency of PV technology has shown significant progress in recent years, from an initial efficiency of 6 % in 1954 (Chapin et al., 1954). Currently, researchers are making major progress in the creation of solar cells, leading to the attainment of high levels of efficiency, approaching the theoretical limit known as the Shockley-Queisser limit. These achievements are important and demonstrate the significant progress made in this field.

Solar cells are divided into 3 generations determined by their characteristics and technical advancements. The 1st generation of solar cells includes both single and multi-crystal variations, which are widely recognized as the dominant type. Nevertheless, these cells exhibit a critical disadvantage in terms of their increased cost and very modest efficiency. The second generation mainly includes thin-film technology, which includes many types such as a-Si, CdTe, and CIGS. Despite having lower efficiency than first-generation cells, second-generation cells are considered cost-effective (Kibria et al., 2023). The third generation is considered the most recent and technologically advanced category. The current generation comprises a diverse range of technologies, including

Table 1
The highest verified conversion efficiency for research cells across several solar technologies. (Data Source: NREL, 2023).

Solar Cell Type	Best Achieved Efficiency (%)	Company/Institution
Crystalline Silicon (Single)	26.1	Institute for Solar Energy Research Hamelin
Single-Crystal Concentrator	27.6	Amonix
Silicon heterostructures	27.3	LONGi
Multicrystalline	23.3	Helmholtz-Zentrum Berlin
Thin film crystal	21.2	Solexel
Perovskite Cells	26.7	University of Science and Technology China
Organic Solar Cells	19.2	Shanghai Jiao Tong University
Organic Tandem Cells	14.2	Institute of Chemistry, Chinese Academy of Sciences
Quantum Dot Cells	19.1	Ulsan National Institute of Science & Technology
CZTSSe Cells	14.9	Institute of Physics, Chinese Academy of Sciences
Dye-Sensitized Solar Cells	13	École polytechnique fédérale de Lausanne
Amorphous Si:H (Stabilized)	14	National Institute of Advanced Industrial Science and Technology
Thin-Film CdTe	23.1	First Solar
CIGS	23.6	Evolar/Uppsala University
CIGS Concentrator	23.3	National Renewable Energy Laboratory
Single-Junction GaAs (concentrator)	30.8	National Renewable Energy Laboratory
Perovskite/CIGS Tandem	24.2	Helmholtz-Zentrum Berlin
Perovskite/Si Tandem	34.6	LONGi
Perovskite Tandem	30.1	Nanjing University and Renshine Solar
Perovskite/Organic Tandem	23.4	Solar Energy Research Institute of Singapore
III-V/Si Tandem	36.1	Fraunhofer Institute for Solar Energy Systems and Dutch research institute

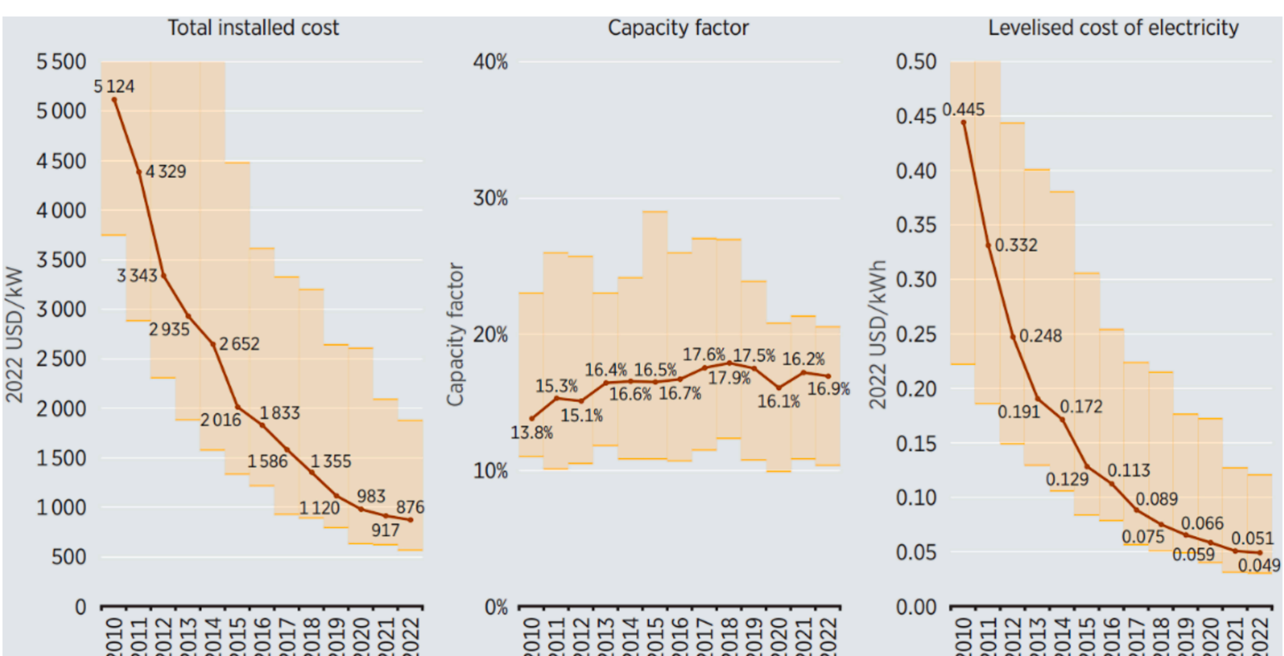

Fig. 1. Average total installation costs, capacity factors, and LCOE for PV systems around the world, 2010–2022 (International Renewable Energy Agency, 2023). (Source: IRENA, Open Access)

hybrid, organic, inorganic semiconductors, and nanostructured solar cells (Kim et al., 2014; Stranks et al., 2013). Table 1 displays the highest solar cell efficiency attained as of the publication date of this work.

Significant advancement has been achieved with solar cell technology, specifically in improving the efficiency of Tandem, GaAs, and Perovskite solar cells. Currently, scientific investigation is mostly directed at researching third-generation solar cells, which constitute a growing topic of study in solar PV, as shown in Fig. 2. These types of cells have the potential to significantly enhance performance. The current investigations have mostly focused on Perovskite solar cells (PSC), organic solar cells (OSC), and dye-sensitized solar cells (DSSC). Despite focused efforts, DSSC and OSC have not yet exceeded an efficiency of 20 %, as indicated by the data obtained from NREL and displayed in Table 1. This highlights the existing obstacles and emphasizes the need for ongoing research to overcome present limitations and advance these technologies towards better efficiency levels. Fig. 2 also illustrates that, even with lower efforts dedicated to the Perovskite/Si tandem cells, achieving a 34.6 % efficiency would not be possible without enhancing the Perovskite. Therefore, improving the efficiencies of Perovskite ultimately results in an improvement in tandem solar cells. However, commercialized solar cells, such as silicon-based and thin films, have achieved a high level of maturity and optimization (Chopra et al., 2004). Their current level of efficiency is already considerable, and any further enhancements are expected to be incremental and expensive. This diminishes their appeal as recipients of research funds, as such funding is often allocated to more pioneering and possibly breakthrough innovations.

Although single junction cells are becoming more widespread, their poor power conversion efficiency (PCE) limits their performance. However, the combination of multiple solar materials into tandem cells, enabling the efficient utilization of a wider range of solar wavelengths, has the potential for significant enhancements in efficiency. This novel methodology eliminates the need for extra physical space, hence potentially leading to a decrease in the LCOE in the near future (Li et al., 2018; Case et al., 2019). Therefore, the aim of this research is to improve the comprehension of PV technology by exploring current developments in several generations of PV cells and other commercially available technologies that optimize solar energy capture efficiency. The research additionally investigates the important factors for determining the life cycle of recently developed solar cells. Additionally, it assesses the effects of the materials used and the different methods of material recycling on the environment. This comprehensive overview provides a detailed summary of the latest developments in solar PV technology.

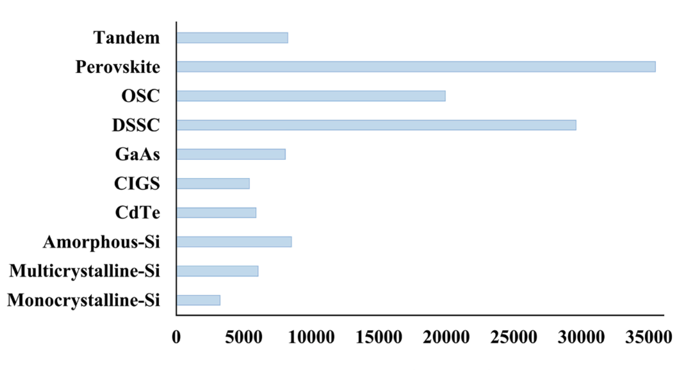

Fig. 2. Number of publications for different studied solar cells. (Data from Scopus)

2. Solar cell generations and manufacturing

2.1. First generation

Silicon (Si) is used in the majority of commercial solar cells, contributing to more than 90 % of the PV industry. Despite being rather expensive, first-generation PV cells provide a high level of efficiency (Soonmin et al., 2023). The two most common types used in these cells are monocrystalline and polycrystalline. Compared to polycrystalline silicon, monocrystalline silicon is more efficient but also more expensive to produce.

Monocrystalline silicon cells consist of a single silicon crystal, resulting in a single crystal volume. This cell has high commercial value and is widely used today. There are several advantages to using monocrystalline solar cells; including requiring less space than other cells due to their higher efficiency. Manufacturers also emphasize their excellent warranties, often offering a 25-year guarantee. These cells work well in low sunlight, making them ideal for cloudy conditions. However, many customers cannot afford these products due to their high prices. Temperature affects their performance, but not as much as other solar cells. Additionally, silicon production generates a lot of waste (Kant and Singh, 2022).

The first publicly available polycrystalline solar cells were in 1981. These cells have a unique characteristic that sets them apart from monocrystalline cells: they do not require cutting on all four sides. Instead, the procedure entails the melting of silicon and its subsequent pouring into mold cavities of equal sizes, leading to the creation of perfectly formed rectangular cells consecutively. Polycrystalline solar cells are recognized for their reduced manufacturing expenses in contrast to monocrystalline cells, making them a more cost-effective choice (Kant and Singh, 2022). Compared to monocrystalline cells, the cost of these cells is cheaper; however, it has a lower performance ratio and efficiency. Moreover, the polycrystalline panels have more thermal losses compared to the monocrystalline panels due to their higher temperature increase (Baghel and Chander, 2022).

In 2005, Amonix initiated the commercialization phase of solar cell development, which resulted in streamlining the processing, enhancing the yield, reducing costs, and improving performance. The solar cells manufactured using this innovative and inexpensive method have been assessed by independent laboratories and found to have an efficiency of 27.6 % when subjected to a concentration of 92.3x (Slade and Garboushian, 2005).

2.2. Second generation

Thin-film and multi-junction cells are the next development in solar PV technology, making up the second generation. This technology has already been successfully incorporated into the commercial domain. Hence, it is not in the experimental phase but rather a well-established and effective technology now utilized in various applications. By utilizing their layered structure, multi-junction cells exhibit higher efficiency compared to conventional single-layer solar cells (Papež et al., 2021). Fraunhofer ISE has several high-efficiency solar cell world records. These records include the highest efficiency value of 26 % for both-sides contacted silicon solar cells, additionally a four-junction cell with a maximum efficiency of 47.6 % that utilizes a III-V multi-junction cell architecture (Fraunhofer ISE, 2023).

The increasing desire to reduce costs has led to a rising need for research on thin films. These cells need fewer quantities of semiconductor materials to absorb similar amounts of sunlight. Compared to crystalline solar cells, they often use up to 99 % less material (Gangopadhyay et al., 2013). The procedure for creating thin-film solar cells involves covering a transparent substrate, such as glass or a transparent film, with a thin coating of a photoactive material. Common examples of semiconductors used as photoactive materials are CIGS "copper indium gallium selenide", CdTe "cadmium telluride" and a-Si "amorphous silicon". Afterwards, it undergoes cell separation by applying a number of methods, including photolithography and laser ablation (Bian et al., 2013; Kartopu et al., 2023). Unlike crystalline silicon, thin-film cells only require a single manufacturing process. Thus, the production costs of these solar cells are reduced. However, the efficiency of conversion from sunlight to electricity can range between 5 and 13 % in thin-film solar cells, in comparison to 11–20 % in crystalline silicon cells (Sampaio and González, 2017).

CdTe is a feasible material for producing efficient and affordable cells (Scarpulla et al., 2023). The ideal bandgap of CdTe is 1.45 eV, which allows it to absorb the solar spectrum (Sampaio and González, 2017). However, cadmium (Cd) use is restricted due to concerns about its toxicity and the environmental barriers associated with it. A recent study by researchers revealed a breakthrough in solar cell technology. They obtained a record 22.3 % cell efficiency in a CdSeTe solar cell without Cu by integrating arsenic doping (Mallick et al., 2023). The increased open-circuit voltage (V_{oc}), which has now exceeded 900 mV, accounts for the increased efficiency. This has also caused the V_{oc} bandgap deficit to drop below 500 mV. The success of this result has been made possible by the stability of a higher carrier concentration. Furthermore, the current open-circuit voltage readings of 917 mV in conjunction with a fill factor greater than 80 % point to a possible route toward attaining 23 % efficiency. This led to a development of a CdTe by FirstSolar with an efficiency of 23.1 % in 2024 (PV magazine, 2025).

GaAs is less commonly used in solar panels. Although GaAs is more expensive than silicon, it has higher efficiency, making it the favored option for high-performance applications like spacecraft solar panels (Al-Ezzi and Ansari, 2022). The main reason for this is that they have a broad-spectrum coverage, which is far greater in space than it is on Earth. Additionally, they find application in the aviation and military sectors due to their flexibility and weight, making them particularly suitable for unmanned aerial vehicles (UAVs). Moreover, they are utilized in concentrators, enabling solar cells to function well under extremely high temperatures. Nevertheless, in terms of practicality, this solar cell kind is too expensive for widespread utilization. The prices might fluctuate based on the complexity of the technology, specifically the number of junctions. The high price is determined by both the wafer's cost and the following manufacture, which involves costly equipment (Papež et al., 2021).

2.3. Third generation

Advancements in solar technology have resulted in the emergence of 3rd generation solar cells during the last 20 years. These cells have shown significant improvements in efficiency, demonstrating prospective suitability for large-scale applications. The increased efficiency has led to a decrease in manufacturing costs, mainly due to the reduced area requirements and smaller weight of these cells (Benda and Černá, 2020).

DSSC "Dye-sensitized solar cell" is a variant of PV cells, which employ a dye to capture sunlight and transform it into electrical energy. Solar cells of this type have numerous advantages compared to silicon solar cells, including reduced production costs, the ability to be manufactured in various colors, and enhanced efficiency under low-light conditions. There have been significant advancements in DSSC efficiency. Researchers in 2022 produced the best efficiency yet for a DSSC employing a conventional liquid electrolyte, a PCE of 15.2 % (Ren et al., 2022). The DSSC's efficiency is now comparable to certain commercial silicon solar cells. Although silicon solar cells continue to have lower production costs, the cost of producing DSSCs is rapidly decreasing. The production costs, including both materials and manufacturing, for laboratory-scale DSSCs were comparatively cheaper in comparison to conventional silicon-based cells (Ragoussi et al., 2013).

The term "Perovskite" is derived from the ABX_3 crystal structure of the absorbing material. In this structure, site A may allow both organic and inorganic cations such as Formamidinium (FA) Methylammonium (MA), or Cesium (Cs). Site B contains divalent metal ions, including Tin (Sn), Lead (Pb), and Germanium (Ge). Meanwhile, X denotes negatively charged halogens, such as Chloride, Bromide, or Iodide (Tsiba Matondo et al., 2021). Perovskite is a material that possesses a crystalline structure that closely resembles that of minerals. The main component is a hybrid compound consisting of a mixture of organic and inorganic materials, specifically tin halide or lead. This combination serves as an active layer responsible for absorbing light (Manser et al., 2016). In 2009, Perovskite solar cells made their appearance with a 3.8 % efficiency for the single junction (Park, 2015; Kojima et al., 2009). Within a span of 11 years, further progress led to a notable increase in efficiency to 26.1 % by 2023 and 26.7 % for thin film perovskite by 2024, exceeding the previous highest efficiency achieved by single crystalline solar cells (NREL, 2023). These cells have great potential due to their ability to capture the visible solar spectrum, cost-efficiency, tunable direct band gaps, high tolerance to defects, and solution-based processing (Xie et al., 2015).

Organic solar cells (OSC) are cost-effective, efficient, and adaptable. OSCs are produced from cheap, commonly available carbon-based materials. Solution processing is used to make OSCs, which is easier and less costly than standard silicon cell production. Recently, OSCs have had significant advances in efficiency. The PCE of OSCs has now exceeded 18 %, reaching the level of standard silicon cells (Bati et al., 2023). Despite the improvements in OSC's efficiency, production costs remain high (He and Li, 2011). However, OSC manufacturing costs are falling rapidly. According to recent research, it is projected that the LCOE for OSCs may potentially reach a minimum of \$0.04/kWh (Mulligan et al., 2015). This is comparable to the LCOE for other forms of sustainable energy technologies, such as wind and solar power. One additional benefit of OSCs is their flexibility. OSCs may be applied onto several substrates, including plastic and metal (Liu et al., 2021a). OSCs and DSSCs are highly suitable for several applications, such as wearable electronics and building-integrated photovoltaics (BIPV). Table 2 presents the benefits and drawbacks of the different 3rd generation solar cells.

2.4. Tandem solar cells

Stacking multiple layers of solar cells on top of one another produces tandem cells (Phung et al., 2023). Usually, the top layer is composed of high band gap cells, that convert a part of the sun spectrum into electrical energy, while allowing the rest of the infrared light to flow through to the lower layer, such as Perovskite cells. The lower layer often consists of low-band gap cells, such as silicon solar cells, which can be designed as bifacial cells to utilize light that is diffused and reaches the cell's backside. The highest PCE for single junction cells, as defined by the

Table 2
Third-generation solar cells pros and cons.

Solar Cell Type	Pros	Cons
Perovskite Solar Cells	High Efficiency Potential	Stability and Durability Concerns
	Low-Cost Manufacturing	Toxicity Concerns (Lead content)
	Versatility	Commercial Scale-up Challenges
	Tandem Cell Integration	
Organic Photovoltaic (OPV)	Flexibility and Light Weight	Lower Efficiency
	Low-Cost Production	Shorter Operational Lifespan
	Tunable Absorption	Sensitivity to Environmental Conditions
Dye-Sensitized Solar Cells (DSSCs)	Low Manufacturing Cost	Lower Efficiency in Direct Sunlight
	Low-Light Performance	Stability Issues (Dye Sensitivity)
	Aesthetic Integration (Different Dye colors)	Complex Electrolytes (in liquid-based DSSCs)

Shockley-Queisser limit, is 33.7 %. Nevertheless, tandem cells have the potential to increase this value to around 45 % by employing two stacked solar cells to capture the sunlight spectrum effectively (Marchant and Williams, 2023). There are other types of tandem solar cells, such as organic tandem cells, which are observed to be economical but have comparatively lower efficiency. Contrarily, inorganic tandem cells are readily accessible in the market, consisting of materials from the III-V group, and are frequently employed in multi-junction cells, showcasing the greatest level of efficiency. In addition, there are hybrid tandem cells composed of Perovskite cells, which have exhibited enhanced efficiency and reduced costs. The latest findings from the European Solar Test Installation confirm the success of the innovative Perovskite/silicon solar cell developed by King Abdullah University of Science and Technology, demonstrating a remarkable 33.7 % efficiency. Furthermore, the 1 cm^2 cell had an 81.3 % fill factor, an open-circuit voltage of 1.974 V, and a short-circuit current density of 20.99 mA/cm^2 (PV magazine, 2023a). Currently, Longi (PV magazine, 2023b) has obtained the world's last 2 PCE records of a tandem cell (33.9 % and 34.6 %) using a Perovskite/Silicon cell, a result that has been verified by NREL (Marchant and Williams, 2023; Liu et al., 2024). Oxford PV currently holds the record for the highest efficiency for Perovskite/silicon cells for industrial-size wafers (258.15 cm^2), which they achieved with 28.6 % (Oxford PV, 2023). A study from the Fraunhofer Institute for Solar Energy Systems and a Dutch research institute in 2025 claims that a wafer-bonded GaInP/GaInAsP//Si triple-junction solar cell has achieved a record efficiency of 36.1 % under AM1.5g illumination for III-V/Si tandem cells. Significant enhancements include a rear-heterojunction design for the middle cell, which increases the open-circuit voltage by 61 mV, and a metallodielectric rear-side grating that boosts the silicon subcell current by 1.4 mA/cm^2. These advancements enhance light trapping, radiative efficiency, and luminescent coupling, highlighting the potential of III-V/Si tandem solar cells for high-performance applications (Schygulla et al., 2025).

One of the main barriers to developing tandem solar cells is the use of transparent electrodes. In order for light to reach the bottom cell in a tandem stack, transparent electrodes are necessary. ITO "Indium tin oxide" is a material that is commonly employed for transparent electrodes (Armstrong et al., 2009). The high price, low conductivity, and poor stability of ITO are some of its main drawbacks (Alemu et al., 2012). The vacuum-based method of depositing ITO is costly and not practical for industrial-scale manufacturing (Kang et al., 2022). Some tandem solar cells may not be able to employ ITO because of its sensitivity to high temperatures (Azani et al., 2020). New transparent electrode materials are being developed by researchers to outperform ITO in terms of stability, cost, and scalability. Carbon nanotubes are transparent and have a high conductivity. Yet, producing a large area of film is challenging (Yu et al., 2016). Metal nanowires have excellent electrical conductivity and are transparent, but they are expensive to produce (Xue et al., 2017). TCOs "Transparent conducting oxides" are a group of materials that provide both conductivity and transparency, such as ZnO "Zinc oxide", GZO "gallium-doped zinc oxide", and AZO "aluminum-doped zinc oxide" are promising types of TCOs for tandem solar cells (Khan and Stamate, 2022; Sharma, 2021).

Solving scaling problems is an essential part of developing tandem cells. A fabrication method capable of handling high-volume production is necessary for the commercializing of tandem cells, as this will reduce costs. roll-to-roll (R2R) processing is one method to make tandem solar cells more scalable (Andersen et al., 2014). The electronics industry makes use of R2R processing, a production technique recognized for its high-throughput capabilities (Keranen et al., 2018). Using the R2R method, tandem solar cells may be manufactured on a continuous substrate roll, which significantly lowers production costs. However, R2R processing for tandem solar cells is still in the development stages. Among the things that need fixing is the lack of R2R compatible deposition procedures for the tandem solar cell's different layers (Yang et al., 2021). Verifying the reliability of the R2R process is the highest priority in order to protect the tandem solar cell's intricate layers from damages (Hakola et al., 2021). The objective is to create encapsulation technologies that are compatible with R2R in order to protect tandem cells from environmental impacts (Ahmad et al., 2023). Monolithic integration can potentially enhance the scalability of tandem cells. The process of monolithic integration involves creating one substrate with all layers of tandem cells (Jošt et al., 2020a). This eliminates the need for complex stacking and alignment procedures, which could prevent large-scale manufacturing. Combining tandem solar cells into a single unit, on the other hand, presents multiple challenges. It may be difficult to optimize tandem solar cell layers for their specific functions while keeping compatibility (Jošt et al., 2020a).

Another challenge is the production of stable tandem cells. Unfortunately, tandem solar cells are subject to severe environmental factors. Sunlight, rain, wind, and dust are all included in this. To make tandem solar cells more stable, scientists are trying out different approaches. As an example, encapsulation might be used to shield the tandem solar cell from potential hazards by covering it with a protective coating (Xiang et al., 2022). The process of carefully designing and optimizing the interfaces between a tandem cell's several layers is known as interface engineering. Reducing charge recombination and improving stability are both achieved with this technology (Bai et al., 2018). To improve upon the materials presently employed in tandem solar cells, researchers are actively working on finding new, more stable alternatives (Wu et al., 2021; Macdonald et al., 2023).

Tandem solar cells are not yet economically feasible due to their high price. Tandem cells currently have higher production costs than single-junction solar cells because of the more complicated fabrication technology and higher component costs (Chen et al., 2022). According to their projections, a Pk/Si tandem module using 2T tandem cells with an efficiency of 28.7 % will be within reach financially by 2025. This is possible if the perovskite cells' annual degradation rate is kept to 2 % and the tandem module costs half as much as a PERC module (Qian et al., 2019).

Another challenge to commercializing tandem solar cells is the absence of evidence of their reliability over extended periods of time. There is limited information about the performance of tandem cells in practical applications since their widespread development is still ongoing. Accelerated lifetime testing on tandem solar cells is being carried out by researchers in order to measure their endurance over time. The tandem solar cells are subjected to extreme conditions, including high temperatures, humidity, and ultraviolet light, as part of the tests (Liu et al., 2021b; Jošt et al., 2020b; Wang et al., 2021b).

There are more difficulties that particular types of tandem cells encounter. Degradation of Perovskite/silicon solar cells can occur when exposed to humidity, high temperatures, and ultraviolet light (Duan et al., 2023). Using innovative materials and advanced encapsulation processes, researchers are currently aiming to increase the tandem solar cells' durability. Regardless of the challenges they may face, the solar cell industry could be improved by tandem solar cells. Overcoming the PCEs of single-junction cells, tandem cells have the potential to lower solar electricity costs and increase their global availability.

2.5. Cells manufacturing and fabrication

The quality of a solar PV module is directly dependent on the level of precision in the manufacturing of its single solar cells. The procedure starts with the conversion of solar-grade Czochralski silicon ingots into wafers. The wafers are cut into pseudo-square shapes to enhance material efficiency. Moreover, multi-crystalline silicon square wafers are frequently utilized, possessing nominal dimensions of 12.5 × 15.6 cm and thicknesses ranging from 180 to 200μm. The conventional doping of these wafers with p-type (boron) their resistivity is generally between 0.5 and 6 Ω-cm (Alami et al., 2023a). Following this initial phase, solar cells undergo several treatments to prepare them for module integration, which involves establishing both series and parallel electrical connections. The first phase of module production involves the elimination of damage caused by sawing. Wafer-cutting procedures can result in abrasive marks and debris that compromise the wafer's structural integrity and surface quality. This is rectified by immersing the wafers in alkaline or acidic solutions, removing around 10 μm from each surface. Alkaline etching is preferred due to its low environmental waste profile, while acidic solutions provide better isotropic structures, particularly for multi-crystalline materials. After that, texturing is implemented to improve light trapping and optical performance. Different texturing techniques: chemical, physical, or mechanical are employed based on the material to create structures such as microscopic pyramids or inverted pyramids that efficiently scatter incident light. Following texturing, the phosphorus diffusion process incorporates an n-type layer into the p-doped initial wafers. This is accomplished using batch or continuous procedures, including the utilization of a quartz furnace or a belt furnace. The quartz furnace process ensures low contamination through the utilization of appropriate materials, whereas the belt furnace, with infrared heating zones, provides a more automated and scalable option despite challenges like potential contamination from the belt material. The manufacturing method incorporates optical improvements and metallization to increase the module's performance. Anti-reflective coatings, such as silicon nitride, are deposited by techniques including plasma-enhanced chemical vapor deposition. This process diminishes reflectivity and enhances surface passivation, hence optimizing light absorption and carrier collection efficiency. Contact fingers, usually composed of silver or aluminum paste, are then placed using screen printing, creating a conductive network that facilitates effective electron collection without blocking solar light reception (Alami et al., 2023a). Fig. 3 illustrates the sequence of manufacturing steps required to produce a high-quality solar cell.

Thin-film solar cells are produced by applying one or more photovoltaic layers onto substrates such as glass or plastic. Chemical Vapor Deposition is a common technology for deposition, including the reaction of gases such as silane and hydrogen within a furnace. Chlorine is frequently included to improve reactivity, yielding safer intermediates such as dichlorosilane or trichlorosilane gases. The process can be further enhanced by plasma, heat, or radio frequencies, under both atmospheric and low-pressure conditions, to improve the quality of the deposited films. Alternatively, Liquid Phase Epitaxy is employed to deposit molten silicon onto substrates at temperatures ranging from 700 to 1000 °C. The Traveling Solvent Method employs a solvent layer between a polycrystalline silicon source and the substrate, utilizing temperature gradients to promote silicon deposition (Alami et al., 2023b). CdTe cells are produced by depositing components onto soda-lime glass substrates. The general structure comprises a TCO, a cadmium sulfide (CdS) layer acting as an n-type window, and a p-type CdTe absorber. The deposition of these layers employs physical or chemical techniques, followed by annealing to enhance inter-layer adhesion and electrical characteristics. The simplicity and scalability of the CdTe deposition method make it a significant contributor to the thin-film industry. CIGS cells consist of a substrate, often soda-lime glass, covered with molybdenum as a rear contact. The active CIGS absorber layer is created by co-evaporation or sputtering of copper, indium, gallium, and selenium, thereafter, undergoing annealing in a selenium-rich environment. The annealing process, referred to as chalcogenization, promotes the formation of the CIGS phase. Additional layers consist of undoped and aluminum-doped ZnO to enhance conductivity and light transmission. Non-vacuum methods, including electroplating, are capable of depositing CIGS precursors onto conductive substrates. Electroplated layers are then annealed in a selenium environment to improve crystallinity and photovoltaic characteristics. Amorphous silicon cells are fabricated by Plasma-Enhanced Chemical Vapor Deposition, which deposits thin silicon films onto substrates covered with transparent conductive oxide. This procedure employs a silane and hydrogen gas mixture, catalyzed by radio frequencies or heated filaments, to deposit hydrogenated amorphous silicon layers in a p-i-n structure. Layers are designed to enhance light absorption and carrier mobility, with regulation of deposition factors such as gas flow, substrate temperature, and pressure (Alami et al., 2023b).

Manufacturing third-generation solar cells employs advanced methods designed to improve scalability, precision, and material efficiency. Fabrication is classified into solution-based methods and vapor-based methods, each utilizing different techniques for the production of high-quality perovskite films designed for photovoltaic and optoelectronic applications.

Spin coating employs centrifugal force for spreading a perovskite precursor solution across a rotating substrate. In one-step spin coating, organic/inorganic halide salts and lead halides are dissolved in a solvent, applied to the substrate, and then spin-coated. The solvent evaporates during rotation, resulting in crystalline layers after annealing. The two-step spin coating technique differentiates between precursor deposition and the reaction stage to enhance uniformity. Despite its simplicity, spin coating encounters challenges with large-scale production due to significant material waste and limited scalability. Spray coating is a scalable technique in which atomized precursor droplets create wet films on substrates, followed by drying and annealing. This procedure is efficient and reduces material waste. However, challenges include potential defects and difficulties in sustaining uniformity across large areas. Slot-Die Coating technique involves extruding a precursor solution through a die for deposition onto a substrate. This method enables wide deposition with minimal waste. However, slot-die-coated films may display surface roughness, requiring modification for enhanced smoothness. Blade coating involves the application of a precursor solution onto a substrate using a blade. Preheating the substrate accelerates drying, resulting in solid films. This technology is appropriate for scalable manufacturing; however, it may lack accurate thickness control, which could impact film quality. Inkjet printing employs microfluidic nozzles to directly deposit patterns onto substrates. This non-contact method is beneficial for producing films on curved or irregular surfaces. However, nozzle blockages and constraints in ink composition cause difficulties (Zhang et al., 2023). Fig. 4 shows the different solution-based fabrication methods.

In flash evaporation, solid perovskite precursors are subjected to heat in a vacuum to produce vapors that condense onto substrates, resulting in the formation of smooth, uniform films. This approach is suitable for industrial scale; however, it may create halogen vacancies that impact film quality. Co-evaporation involves the sublimation of precursors from

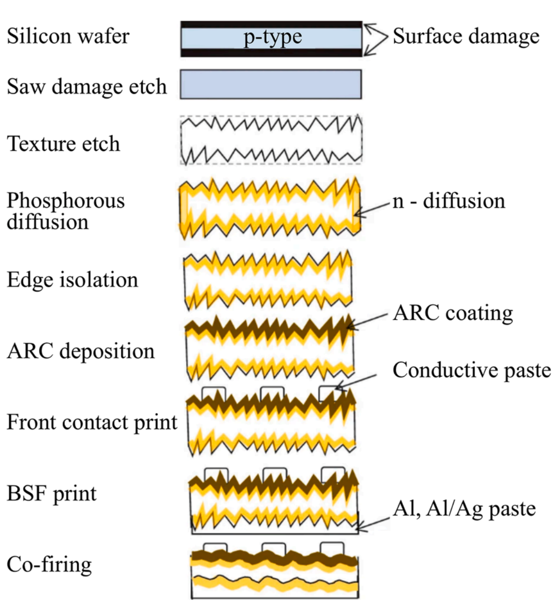

Fig. 3. Silicon solar cell manufacturing processes (Alami et al., 2023a). (With Permission, License Number: 5,954,660,855,078)

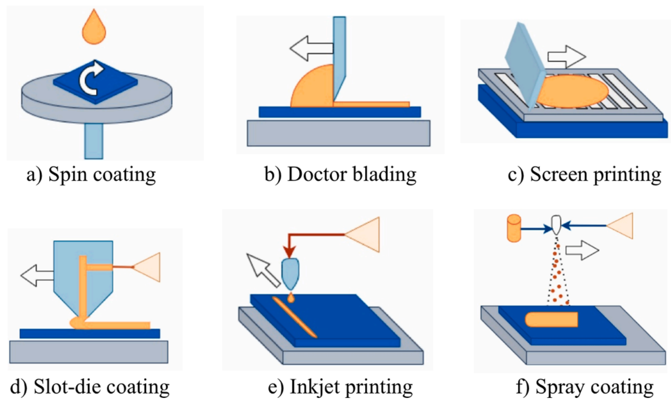

Fig. 4. Solution-based methods for layer deposition (Bhati et al., 2023). (Open Access)

separate sources under controlled conditions. This facilitates precise stoichiometric control and yields dense, high-quality films. Achieving uniform deposition across wide areas necessitates precise calibration. In sequential evaporation, precursor layers are deposited individually and then subjected to heating for diffusion and recrystallization. This technique yields better films; however, it is time-consuming and less appropriate for high-volume manufacturing. Chemical Vapor Deposition involves the vapor-phase reaction of precursors carried by inert gases to create films on substrates as shown in Fig. 5. It mitigates the necessity for high vacuum and annealing processes, hence decreasing expenses. However, the resultant films frequently exhibit amorphous areas and low charge-carrier mobility (Zhang et al., 2023).

The manufacturing procedure for Perovskite/silicon tandem (Pk/Si) cells is comprised of a number of stages, as shown in Fig. 6. The first stage (A1) involves the deposition of a transparent recombination layer on the front side of the Si Cell. This stage eliminates the need for a reflector or a solid metal electrode. The crystalline silicon cell and the recombination layer are both kept undamaged while the Perovskite cell is subsequently deposited on top of the recombination layer in step (A2) of the process. The next step, (A3), is to coat the Perovskite cell with a sputter buffer. The efficient functioning of the electronic carrier depends on this layer being both transparent and conductive. Its main purpose is to prevent damage to the Perovskite cell while the front transparent electrode is sputtered (A4). This technique is necessary for low sheet resistance and maximum transparency. The last step (A5) makes use of metal gridlines to lower the series resistance of the transparent conductor (Leijtens et al., 2018).

In all Perovskites tandem cells, a sputter buffer layer is deposited on a wide-bandgap front cell (B1). The wide-bandgap front cell is protected from any harm that the sputtering procedure could bring through this layer. Following this, a recombination layer is sputtered on top of the

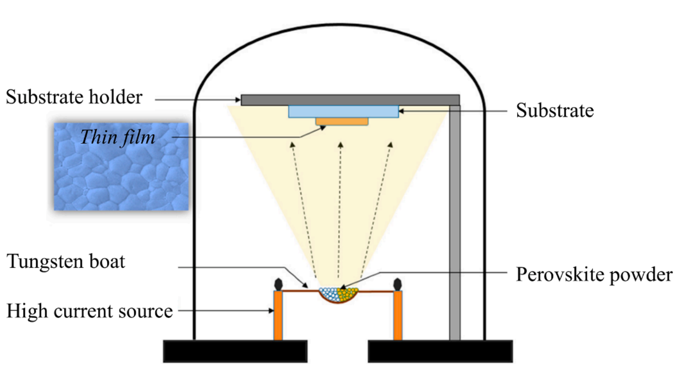

Fig. 5. Schematic of thermal evaporation system (Qaid et al., 2020). (Source: MDPI, Open Access)

sputter layer in step (B2). The small-bandgap cell solution approach is included in step (B3), and this helps in preventing damage to the underlying cell. The last step (B4) is to extend the light path by making contact with the rear cell that has a narrow bandgap using a reflecting metal electrode (Leijtens et al., 2018).

3. Performance and cost analysis

3.1. Levelized cost of electricity

To better understand and maximize the financial feasibility of solar energy generation, examining the LCOE "levelized cost of electricity" of PV systems using various types of modules is essential. Taking into account installation, maintenance, and operational costs, the LCOE determines the overall cost of producing electricity for the lifespan of a PV system. As solar technology develops, researchers typically evaluate several PV modules' efficiency and performance to find the most effective ones at the lowest possible cost. In addition to advancing solar technology by identifying critical elements that impact LCOE, this comparison advises developers and manufacturers on the financial impacts of module selection.

PV technologies, including a-Si, polycrystalline silicon, and monocrystalline silicon were analyzed and compared by Ameur et al. (2020). Based on their economic evaluation, p-Si is the most economical system in the case study, with an LCOE of under \$0.10/kWh. Table 3 shows the estimated LCOE along with the annual energy output comparison, system life cycle cost, and the degradation rate. In contrast, a-Si systems' greater initial cost relative to poly and monocrystalline technologies led to their highest LCOE of \$0.14/kWh. Even though the final yields of m-Si and p-Si PV types are comparable, the LCOE of p-Si systems is lower due to the higher initial cost of m-Si systems.

A techno-economic comparison of polycrystalline and copper indium selenide (CIS) systems with comparable ratings and environmental conditions was performed (Ali and Khan, 2020). The study compared the outcomes to one year of measured data from systems built in Lahore, Pakistan, using two 42 kW PV systems to simulate energy generation. The findings revealed that, in terms of performance ratio, CIS outperformed polycrystalline, showcasing higher annual energy production. However, p-Si demonstrated a more favorable LCOE, making it a more economically feasible solution in Pakistan. Specifically, the LCOE values for polycrystalline and CIS were 0.0493 and 0.051 \$/kWh, with corresponding annual energy production of 53,751 and 54,570 kWh.

A methodology for fabricating TiO_2 nanorod-based Perovskite solar modules was shown (Kukkikatte Ramamurthy Rao et al., 2021), and its manufacturing expenses were assessed. With a 3.5 MW production capacity, the reference Perovskite solar cell module's direct manufacturing cost was calculated to be \$80.23/m^2 and \$0.73/W. At a larger production capacity of 21 MW, these costs showed a drop of \$47.15/m^2 and \$0.43/W. According to sensitivity analysis, the associated cost ranges were \$0.24–0.58/W and \$40.07–55.24/m^2. The Perovskite solar cell panels in Alberta, Canada, have a competitive life cycle economics (LCOE) that ranges from \$0.07 to \$0.17/kWh when installed in residential dwellings. However, it was observed that the solar insolation at the installation site, module lifetime, and efficiency all had significant effects on the cost sensitivity.

Li et al. (2018) compared the LCOE of four different PV modules, polycrystalline silicon, planar Perovskite, silicon/Perovskite, and Perovskite/Perovskite. The analysis's findings are displayed in Fig. 7. The highest LCOE corresponds to module A, which is the traditional silicon module, with a value of \$0.055/kWh. As can be noticed, this value can be reduced by ~5 % using a silicon/Perovskite module (Module C). Furthermore, the potential of Perovskite solar cells can be more observed from the low LCOE of modules B and D, which correspond to planar Perovskite and Perovskite/Perovskite, with values of \$0.0434 and \$0.0422/kWh, respectively.

Rodríguez-Gallegos et al. (2020) conducted an economic analysis of

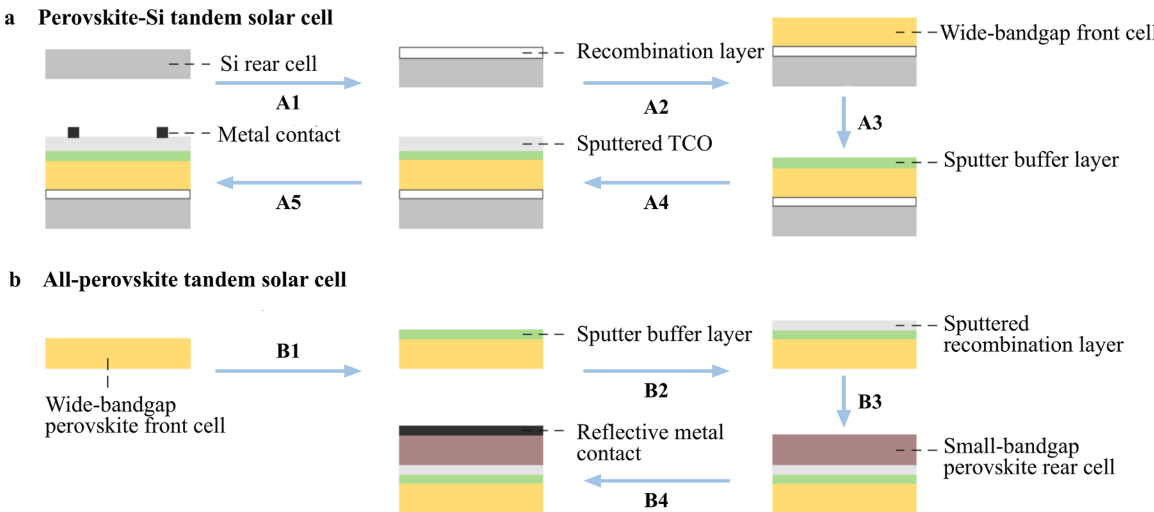

Fig. 6. The manufacturing processes for tandem solar cells. A) Perovskite/Si, B) All Perovskite. (Leijtens et al., 2018) (With Permission, License Number: 5,658,910, 359,847).

Table 3
Economic analysis of PV modules based on silicon (Ameur et al., 2020). (With permission, License number: 5,727,580,947,692).

PV module	a-Si	Polycrystalline	Monocrystalline
Life cycle cost ($)	4885	4485	4581
Yearly average energy output (kWh)	2889	3319	3330
Degradation rate (%)	0.8	0.3	0.3
LCOE ($/kWh)	0.14	0.10	0.11

PV farms using bifacial and mono-facial modules with fixed-tilt mounting, single-axis trackers, and dual-axis trackers. According to the findings, installations with single-axis trackers and bifacial modules had the lowest LCOE, while single-axis trackers and mono-facial module installations had the second lowest LCOE. When compared with mono-facial-fixed PV, the LCOE was 16 % and 14 % lower, respectively. The existing high prices of dual-axis tracker installations caused their LCOE values to be 4–8 % higher than fixed mono-facial installations, even though they generated more electricity. As a result of benefits in energy production and capital cost, single-axis tracking installations are preferred worldwide over dual-axis and fixed-tilt tracking installations.

3.2. Energy payback time

A critical parameter for evaluating the sustainability of solar power generation is the EPBT “energy payback time” of a PV system. It is the

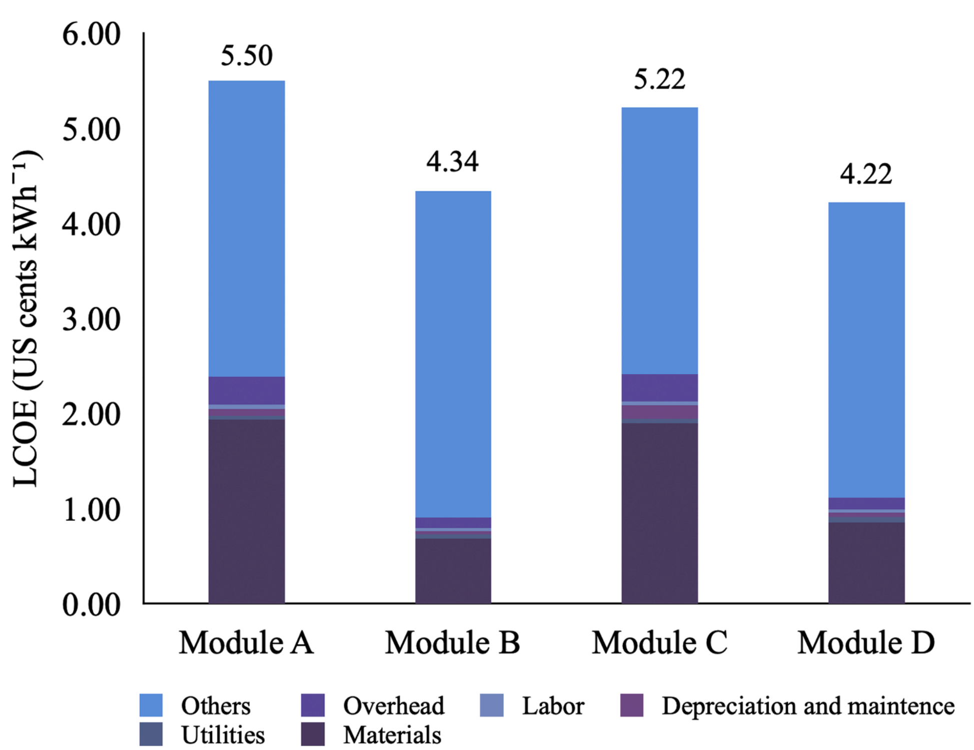

Fig. 7. The LCOE of four different PV modules; (A) Polycrystalline, (B) planar Perovskite, (C) silicon/Perovskite, (D) Perovskite/Perovskite (Li et al., 2018). (With Permission, License Number: 5,700,640,977,024)

period of time needed for a PV system to generate as much energy as it required in production and installation. Researchers usually analyze the influence of different PV modules on EPBT since this metric provides knowledge of solar technology's overall environmental performance and efficiency.

Using a life cycle assessment (LCA), Qaid et al. (2020) examined the impact of c-Si solar modules on the environment. According to the results, grid-connected PV electricity using c-Si solar modules has GHG emissions ranging from 60.1 to 87.3 g.CO_2-eq/kWh and an EPBT ranging from 1.6 to 2.3 years, depending on the installation technique (see Table 4 for details). For example, it was discovered that the production of solar-grade silicon accounts for around 35 % of the energy used in the process and the GHG emissions released. At least 84 % of the energy consumption and GHG emissions were attributable to the PV production process.

Another LCA was carried out by Ludin et al. (2018) to compare the different types of PV modules based on previous research studies. The module made of monocrystalline silicon showed the most energy usage values, EPBT, and GHG emissions among the PV technologies under investigation. Fig. 8 displays the ranges of EPBT for several solar PV technologies beginning in 2000. It can be observed that both types of tandem cells exhibited the lowest EPBT among all the other types.

4. Efficient solar PV technologies

4.1. Bifacial solar panels

There are two primary types of solar panels that are utilized to generate electricity from the sunlight: monofacial and bifacial PV panels (Radwan et al., 2023). Monofacial solar panels have been in use for decades, and they are flat and opaque panels. These panels are produced by a layer of PV cells set in an aluminum frame and protected by tempered glass. They transform sunlight into electricity, but only on the front side. Bifacial solar panels are an innovative new technology that can absorb light from both sides of the module. The light received by the surrounding surfaces and ground partially reflects on the bifacial PV panel's rear side. Therefore, compared to monofacial panels of the same size, bifacial panels may provide higher electrical power. The operating principles of both PV modules are depicted in Fig. 9. To get the most out of sunlight on both sides, bifacial panels could be positioned in multiple methods, including on the ground, on the roof, or on poles. Its efficiency may be decreased by variables including the angle of incidence, shade, albedo, and ground height, requiring specific mounting systems.

Using the same irradiance, measurements are made independently for the panel's front and rear surfaces. A unitless parameter called the bifaciality factor measures the correlation between the front and rear sides' respective efficiencies. The measurement expresses the efficiency with which the panel converts light from both sides into electrical energy. Modern bifacial solar panels typically have a bifaciality factor between 0.75 and 0.95 (Rodrigo et al., 2024). This indicates that they have the capability to produce 70–90 % of the power generated by light on the front side when exposed to light on the back side. Research has shown that bifacial systems can generate up to 12 % more electricity compared to monofacial modules at latitudes below 65°, and up to 71 % more energy than their monofacial modules at higher latitudes (Rodríguez-Gallegos et al., 2018). This is also confirmed by another study, the performance of bifacial cells is greatly improved, with the increase ranging from 20.1 % to 68.1 % (Pal et al., 2020). Another study found that in comparison with monofacial modules, bifacial ones with a fixed tilt would be 20–30 % more efficient, while bifacial tracking on one axis would add another 20–40 % (Khan et al., 2021). Fig. 10 shows the difference between monofacial and bifacial systems at different orientations.

Currently, monofacial technology has the majority of the market share. However, despite attempts to decrease the production process and minimize the use of aluminum, only 25 % of the aluminum required for monofacial cells is needed for bifacial cells. The International Technology Roadmap for Photovoltaic indicates that the transition has already started. Bifacial technology is gaining increasing support, with projections indicating that it will keep dominating the market with a 90 % market share during this decade (ITRPV, 2024). The development of bifacial solar panels is still ongoing. However, several significant projects were implemented in many countries globally because of its ~30 % greater power production and around 2–6 % lower LCOE (Gu et al., 2020). Moreover, a new design for indoor bifacial Perovskite PV was recently created (Singh et al., 2023).

4.2. Tracking systems

PV tracking systems, in contrast to conventional solar panels with a fixed tilt, dynamically adjust the orientation of solar panels in order to track the sun's path across the sky. This maximizes the amount of sunlight that the exposure to the sun receives throughout the day. The ability to follow movement in a dynamic manner greatly improves the efficiency of energy harvesting, thereby making solar PV tracking systems a more favored option for large-scale solar installations.

Single-axis tracking systems precisely reposition solar panels along a single axis, which can be either the horizontal (azimuth) or vertical (elevation) axis. Horizontal single-axis trackers are prevalent, as they rotate the solar panels horizontally from east to west during the day. This motion enables the panels to directly orient towards the sun, hence optimizing solar radiation exposure. However, solar panels are moved in both the horizontal and vertical directions using dual-axis tracking systems. The panels can adapt to changes in the sun's angle throughout the day and track its daily path due to this dual movement. Although dual-axis tracking provides even more efficiency, it is more complicated and expensive. With a dual-axis or single-axis PV tracking system with suitable control mechanisms, the energy output may be enhanced by 22–56 % in comparison to a fixed system (Seme et al., 2020).

Awasthi et al. (2020) explored all types of solar tracking techniques. The authors also make a contribution to the rapidly evolving field of solar energy technology by offering comprehensive explanations of the design, operation, and evaluation of different dual-axis solar tracking systems. According to the authors, solar tracking systems fall into different categories according to the tracking method, the drivers employed, the control system utilized, or the system's degree of movement freedom as shown in Fig. 11.

Multiple studies have demonstrated that both dual and single-axis tracking have yielded improved energy efficiency and production, as observed in Table 5 in different countries and regions. Nevertheless, implementing these systems may require higher initial costs but eventually lead to a reduced LCOE over time.

Table 4
Summary of the LCA of c-Silicon PV (Hou et al., 2016). (With permission, License number: 5,727,581,144,028).

PV module	LS-PV		Distributed PV	
	Polycrystalline Silicon	Monocrystalline Silicon	Polycrystalline Silicon	Monocrystalline Silicon
EPBT (years)	1.6	1.7	2.1	2.3
Energy consumption (kWh/W)	1.9	2.06	1.8	1.95
Energy yield ration	15.8	14.6	11.7	10.8
Greenhouse gas emissions (g.CO_2-eq/kWh)	60.1	65.2	81	87.3

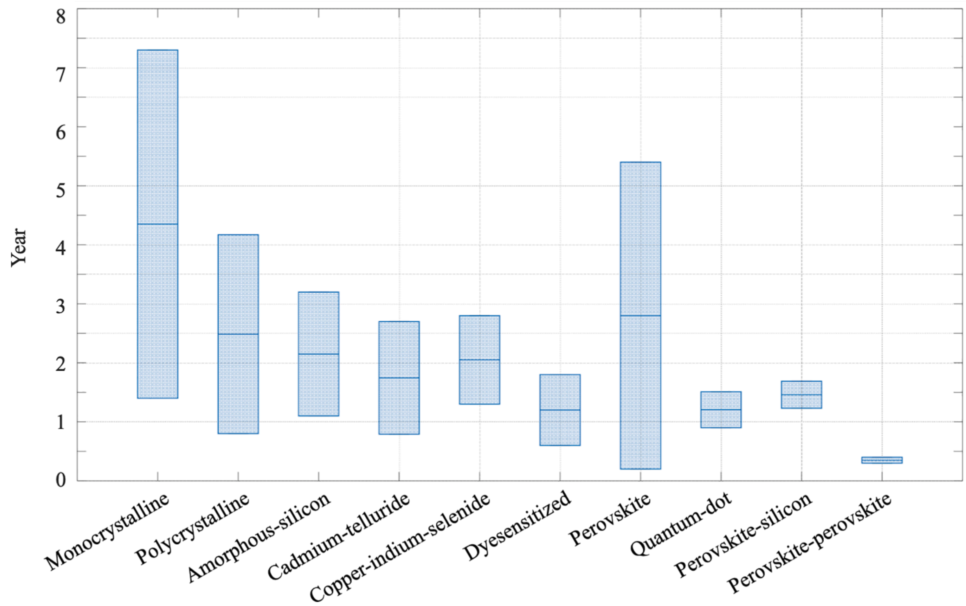

Fig. 8. Comparison between the EPBT of different solar PV technologies.
(Data Obtained from Ludin et al. (2018) and Tian et al. (2020))

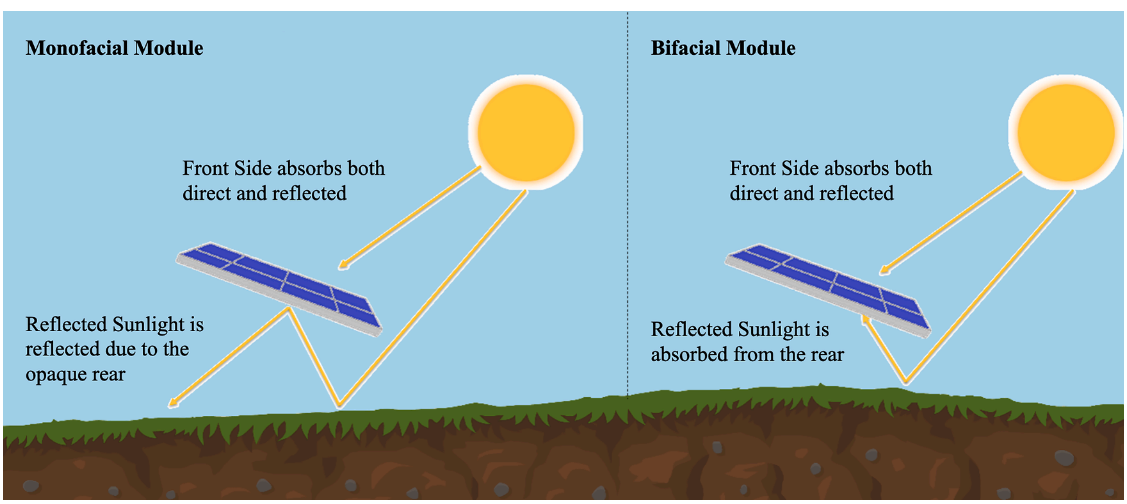

Fig. 9. The operational concept of a monofacial module vs. a bifacial module.

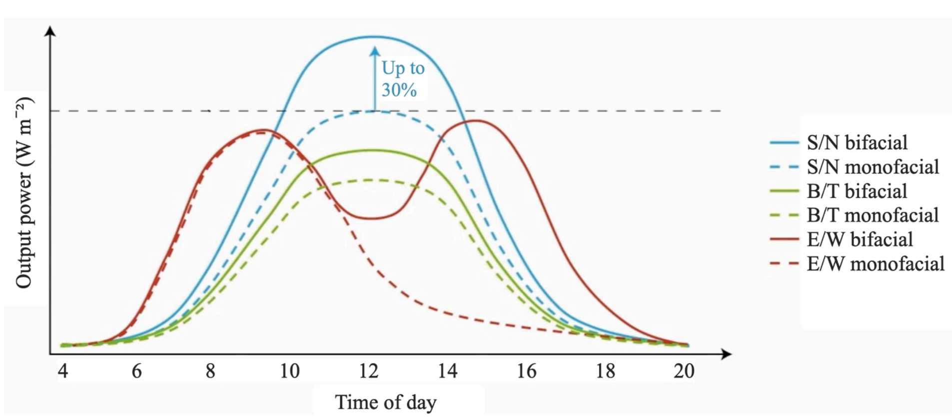

Fig. 10. Power output curves compared for monofacial and bifacial panels mounted at different orientations (Kopecek and Libal, 2018).
(With Permission, License Number: 5,667,580,034,628)

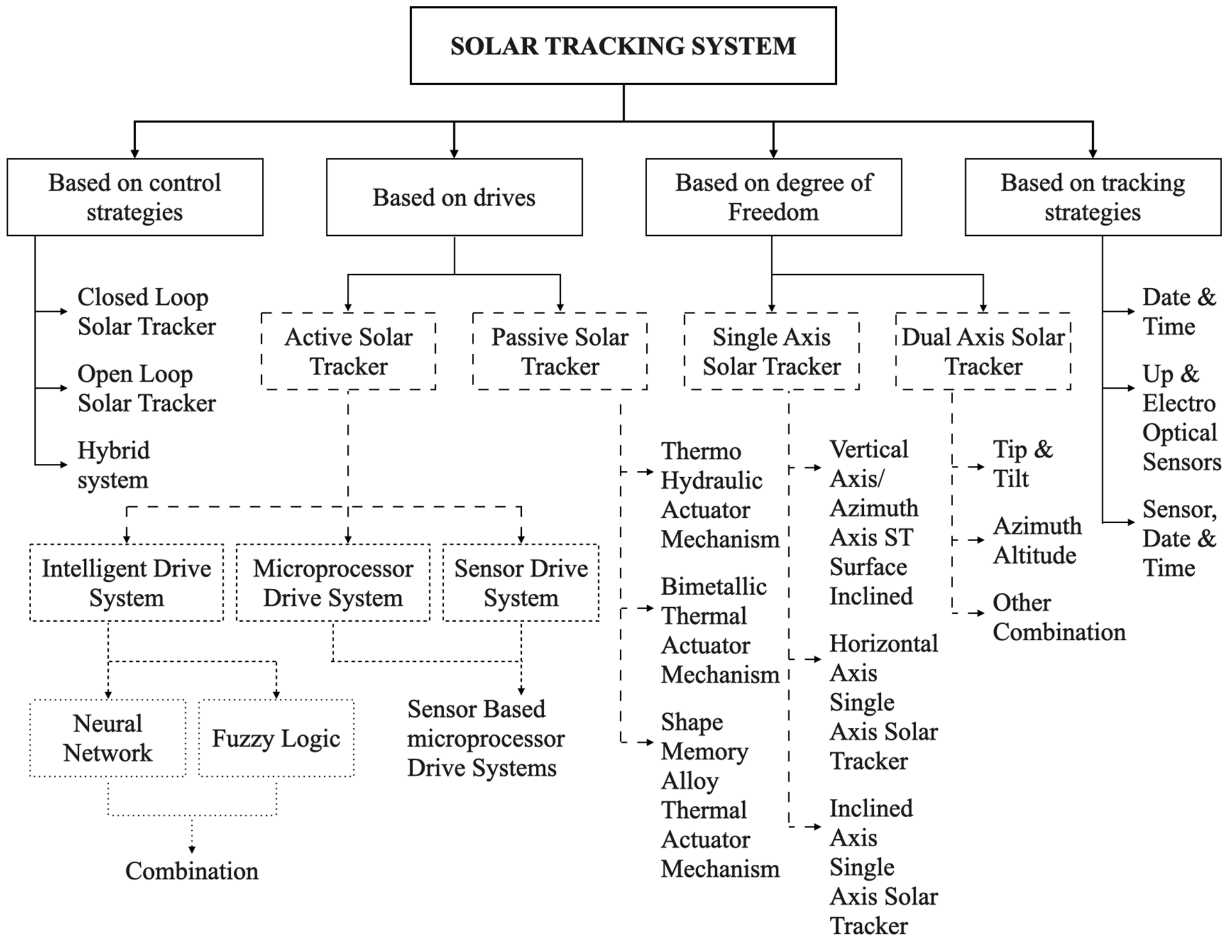

Fig. 11. Solar Tracking Systems Classifications (Awasthi et al., 2020).
(With Permission, License Number: 5,700,641,166,695)

5. Environmental and end-of-life considerations

5.1. Degradation

PV modules may experience decreased performance and efficiency over time due to many variables, depending on the distinctive PV technology and installation climate. The nature of module degradation makes it a problem in many aspects (Ndiaye et al., 2013). To ensure the sustainability and effective operation of solar PV systems, a comprehensive understanding of the factors contributing to degradation is necessary. Early in the design process, it is essential to examine the dynamics of typical degradation and failure modes of significant PV module components.

For instance, the structural framework of a PV module, an essential component, may be susceptible to corrosion. Corrosion accelerates the chance of warping, therefore raising the probability of damage to the module. Corrosion not only endangers the structural integrity of the frame but also poses a substantial risk to the long-term functionality of the entire module. Moreover, glass, an essential component that offers both protection and transparency in PV modules, is prone to corrosion due to the chemical reactions between the glass surface and atmospheric gases. This corrosion is frequently associated with exposure to moisture or vapor due to condensation or contact with an alkaline solution, resulting in breakage, contamination, and abrasion (Corrosion Doctors, 2024). Such degradation reduces the generated current and may even lead to hotspots inside the module. It also weakens the module's physical strength by obstructing light transmission.

Furthermore, the backsheet, exposed to environmental stressors, may experience photooxidation and hydrolysis, resulting in discoloration, delamination, and the development of cracks. These degradations amplify the likelihood of corrosion and isolation failures, contributing to a notable decline in the module's overall reliability (Lyu et al., 2018; Gambogi et al., 2014). The encapsulant, tasked with shielding solar cells from external factors, may undergo photooxidation, manifesting as discoloration and delamination. Such degradation diminishes the encapsulant's ability to protect internal components effectively, resulting in reduced current and an higher susceptibility to corrosion. Nevertheless, the junction box, serving a critical role in facilitating electrical connections, may undergo arcs and delamination. These issues can precipitate electrical faults and detachment, posing a significant risk to the functional integrity of the PV module. Internal circuits, including interconnects and TCO layers, are prone to corrosion-induced fatigue and cracks. These issues contribute to a reduction in current flow, cell isolation, and hotspot formation, collectively compromising the efficiency and durability of the PV module (Aghaei et al., 2022).

Solar cells can experience degradation in the forms of light-induced degradation (LID), potential-induced degradation (PID), and light and elevated temperature-induced degradation (LETID) (Kersten et al., 2015; Gostein and Dunn, 2011; Pingel et al., 2010). These problems result in cracks and the separation of cells, resulting in the module's hotspots growing and its power output decreasing. PID is triggered by elevated system voltages, LID is a result of the boron-oxygen formation when exposed to sunlight, and LETID combines the impacts of light exposure and higher temperatures. These activities collectively lead to the formation of cracks, isolation of cells, and a decrease in power production in solar cells.

Table 5
Summary of recent studies used for estimating the performance of different tracking systems.

References	Experimental/ Simulation	Location	Tracking Systems	Results
Zhu et al. (2020)	Simulation	China	Single Axis Dual Axis	Introduced a unique single-axis tracking design that produced an annual incidence radiation on the tracked panel that was 96.40 % a fraction of that of a dual-axis tracked panel.
Tina and Scavo (2022)	Simulation	Italy & Germany	Fixed Single Axis Dual Axis	Compared to the fixed systems in Italy and Germany, the Horizontal E-W system demonstrated a 16.9 % and 14.4 % gain in energy, while the Horizontal N-S system showed a 27.6 % and 23.3 % increase. The One Axis Vertical system exhibited a 31.3 % and 27.8 % increase, whereas the Dual Axis system achieved a significant 47.4 % and 42.5 % rise in energy production.
Ponce-Jara et al. (2022)	Experimental	Ecuador	Fixed Dual Axis	the dual axis tracking PV system generates an average of 19.62 % more energy output than a fixed PV system.
Gönül et al. (2022)	Simulation	Turkey	Fixed Single Axis Dual Axis	Comparing the Dual Axis tracking system to the fixed tilted system, the results show a 30–35 % improvement in energy production. Likewise, there was a 22.5–24 % rise in the single axis tracking EW system and a 2.5–5 % increase in the single axis tracking SN system.
Jaanaki et al. (2021)	Experimental	–	Fixed Dual Axis	The energy production of the dual axis tracking system was 34.2 % higher than that of the fixed system.
Kuttybay et al. (2020)	Simulation and Experimental	Kazakhstan	Fixed Single Axis	The suggested single-axis tracking system was 57.4 % more efficient than a fixed solar panel set at an optimal tilt angle.
Alktranee et al. (2020)	Simulation	Iraq	Fixed Dual Axis	The two-axis tracking demonstrated a significant increase in solar radiation absorption, outperforming the fixed PV system by around 37.3 %.

A study examined how cracks/fractures and bubble formation impact the functionality of several solar cell technologies, including CIGS, c-Si, a-Si, and organic perovskite cells (Alves dos Santos et al., 2021). The analysis included studying the I-V and P-V curves for each evaluated technology under two degradation situations. PV modules were subjected to mechanical forces in the crack test, leading to visible cracks. After 5 breaks, the c-Si cracking test demonstrated a significant 92.88 % decrease in power. After the initial break, the a-Si cell experienced an immediate 92.77 % power decrease, highlighting the substantial impact that even a minor fracture may have on the technology's performance. CIGS cells showed a 7.84 % power decline after the initial crack, but organic perovskite cells had a 24.1 % power drop after 6 cracks. The experiments showed no clear relationship between the power loss and the number of cracks across various technologies. The study also investigated the influence of temperature conditions on different PV technologies during the formation of bubbles. Organic perovskite cells went through three 15-minute intervals of irradiation exceeding 2200W/m^2, resulting in a surface temperature of 69 °C and noticeable bubble formation. Due to toxicity concerns, the study excluded Cadmium-containing CIGS cells. Following the heat test, there was a reduction in power output by 31.6 % for c-Si cells, 10.4 % for a-Si cells, and a substantial 99.74 % for organic perovskite cells at the conclusion of the third bubble degradation step.

5.2. Environmental impacts

Solar PV is often regarded as an environmentally friendly and renewable energy technology. Compared to fossil fuels, it provides a variety of environmental benefits. The carbon footprints associated with PV systems were calculated to be within the range of 14–73 g.CO_2-eq/kWh, it is far less than those of coal-fired (975.3 g.CO_2-eq/kWh), oil (742.1 g.CO_2-eq/kWh), and gas (607.6 g.CO_2-eq/kWh) power plants (Tawalbeh et al., 2021). Nevertheless, the production, installation, and disposal procedures linked to solar PV systems may still result in some environmental implications. Below are many crucial aspects concerning the environmental effects of solar PV technologies.

Solar panels may be established on many types of terrains, but when it comes to large-scale solar farms, there is a risk of altering land use and disrupting habitats, especially if proper planning and management are not implemented. Solar PV systems utilize a significant quantity of water for their cleaning procedures (Patil et al., 2018). The production of solar panels entails the utilization of many raw materials, including silicon, glass, and metals. The extraction and processing of these minerals can result in the production of waste and possess a negative impact on the environment when it comes to energy use and GHG emissions. The EPBT of the manufacturing process varies according to the characteristics of the solar panel. The EPBT varies from one technology to another and from one region to another, although it usually falls between 1 and 3 years (Lamnatou et al., 2023; Ziemińska-Stolarska et al., 2021; Muteri et al., 2020). It must be considered when evaluating PV systems' overall environmental impact. The manufacturing of silicon wafers results in the creation of silicon tetrachloride and other potentially dangerous byproducts. If not dealt with correctly, these waste products could cause environmental problems (Qi and Zhang, 2017).

Materials like tellurium and cadmium that are used for creating thin-film cells, possess the potential to cause harm to humans and the environment at different stages in their lifespan, from manufacturing to usage to eventual disposal. This raises issues regarding toxicity and pollution. Moreover, the process of obtaining scarce and valuable substances, such are the CIGS cells' utilization of indium and gallium, can lead to the exhaustion of resources and geopolitical conflicts (Stamp et al., 2014). The mining operations involved in this extraction can also cause environmental damage and the destruction of habitats. Although the material footprint of thin-film solar cells is less than that of crystalline silicon cells (Emmott et al., 2014), their end-of-life management can still contribute to electronic waste (e-waste) issues if not properly recycled and disposed of Jariwala and Soni (2021), Prakash et al. (2015). This highlights the need to address e-waste problems.

Soil has an average natural content of about 36 mg/kg of lead, which is a consequence of the widespread utilization of tetraethyl lead in gasoline over an extended period of time. Although a 1 m^2 panel releasing all its lead would result in a 4 mg/kg increase in Pb concentration (Li et al., 2020), the probability of such an occurrence is quite low. The use of Pb-based PSCs for power generation offers a possible environmental benefit compared to coal burning, even when faced with a devastating failure, as the overall leakage of Pb would be much reduced (Schileo and Grancini, 2021). While it is important to limit the leakage of Pb, it is necessary to understand the global lead emissions in perspective. The coal industry releases around 80,000 mt of Pb into the atmosphere every year. However, a solar system with a power output of 1 TW, utilizing solar cells made of Pb with an efficiency of 20 %, would necessitate around 20,000 mt of Pb. The panels would encapsulate this lead, which would not be dispersed into the surroundings (Stranks and Snaith, 2015). In addition, as lithium-air and lithium-sulfur battery technology develops, an increasing number of lead-acid batteries, which can provide enough lead for approximately 700 m^2 of Perovskite-based PV panels per car battery, will not be recycled. This presents an economically viable and environmentally advantageous supply of lead for PSCs (Schileo and Grancini, 2021).

Moreover, the solubility of lead in water might cause it to leak out from compromised panels, leading to the pollution of groundwater and eventual risks to human health. Lead may cause heavy metal poisoning when it enters the human body through the gastrointestinal and respiratory systems (Babayigit et al., 2016). Similarly, the use of arsenic in some solar cells' antireflection coatings may cause this hazardous material to be released into the environment during the manufacture or disposal of these cells, resulting in pollution of the environment (Jomova et al., 2011).

Because of its same electrical configuration and the s orbital's single pair of electrons, Sn starts to emerge as a promising replacement for Pb in PSCs. $MASnI_3$, specifically, demonstrates a reduced energy bandgap and an increased absorption coefficient in comparison to $MAPbI_3$, hence improving its appropriateness for PV applications (Umari et al., 2014). Sn-based Perovskites provide difficulties due to their quick reaction with air and moisture, resulting in undesired changes in semiconductor characteristics and a significant decrease in solar efficiency (Yao et al., 2020). This highlights the necessity of resolving the stability concerns linked to Sn-based PSCs. Chronic lead poisoning, even at levels as low as 5 μg/dL, can cause significant neurological diseases in both children and adults. Such diseases include reduced intelligence levels, behavioral issues such as anxiety, depression, and aggression. It is important to take into account the benefits and challenges related to using alternative materials such as Sn in PSCs in order to progress sustainable and environmentally friendly solar technology (Sanders et al., 2009).

5.3. Recycling

The growing number of solar plant installations has led to more PV panels approaching the end of their lifespan. Research indicates that the estimated global volume of PV waste reached about 870 tons by 2017. According to projections, by 2038, this volume could increase to about 1.96 million tons (Shin et al., 2017; Paiano, 2015). The anticipated rise in PV waste and its possible detrimental impacts on the environment globally have drawn the attention of the worldwide community (Liu et al., 2023). This highlights the importance of recycling, which plays a crucial role in the circular economy of solar PV by minimizing waste and promoting resource recovery (Rabaia et al., 2024; Oteng et al., 2022).

5.3.1. Monocrystalline and polycrystalline

Research on recycling these solar cells has gained traction (Lunardi et al., 2018). A typical Si PV module is composed of different elements, as shown in Table 6. The module surface, made of glass, makes up around 75 % of the overall weight, while silicon accounts for around 5 % of the weight. Furthermore, the interconnectors consist mostly of copper, representing 1 % of the total weight. In addition, the contact lines have a silver content of less than 0.1 %, with the rest amount consisting of other metals such as tin and lead (Olson et al., 2013). Fig. 12 shows the available recycling methodologies.

In principle, the recovery and utilization of materials like glass, aluminum, and semiconductors seem viable (Lunardi et al., 2018). However, concerning Si solar modules, existing recycling techniques involve mechanical, thermal, and chemical processes, which are not deemed environmentally sustainable. An example of such methods is the physical disintegration process (Chowdhury, 2019; Berger et al., 2010), providing an advantage in waste material treatment. This process entails breaking down the modules into smaller fragments or pieces through mechanical means, constituting a crucial part of the overall recycling procedure and often serving as one of the initial stages in the process. This process comes with its drawbacks, such as the fact that other processes are required for the ethylene vinyl acetate removal from the solar module structure, the formation of dust containing heavy metals, and most importantly, the breakage of solar cells.

An alternative method used to eliminate the EVA encapsulant and facilitate the potential recovery of solar cells without breaking the glass incorporates a two-step heating treatment (Wang et al., 2012). This approach is acknowledged as a highly cost-effective and practical process. The method involves subjecting solar modules to a controlled heating procedure comprising two distinct stages. The thermal treatment is precisely engineered to break down the EVA encapsulant and increase its flexibility, thus easing its removal from the solar cells and other components. This ensures the effective separation of substances without compromising the integrity of crucial elements, such as Si with a recycled percentage of 62 %. Other techniques, such as chemical etching, are widely employed for the recovery of high-purity materials; however, they have the disadvantage of relying on chemical processes.

In recent years, a significant amount of research has focused on the adoption of green recycling practices, indicating a growing emphasis on sustainable practices and environmental responsibility. This shift has resulted in a significant transformation in traditional methods of waste management and resource recovery. The recycling process for first-generation solar cells involves the retrieval of valued materials such as aluminum, silicon, and silver, aiming to reduce environmental impact and enhance resource efficiency. Based on research by Kang et al. (2012), the initial stage of the recovery process involves the separation of various layers within the Si wafer. The research procedure utilizes toluene as a solvent to achieve a high-purity (99.999 %) silicon recovery rate of 86 %. This is achieved by potassium hydroxide and nitric acid to

Table 6
Si-solar module composition. (Data obtained from Lunardi et al. (2018)).

Material	Glass	Polymer material (Encapsulant and back-sheet foil)	Aluminum (Frame)	Silicon	Metals (Copper and silver)
Percentage of total weight	75 %	10 %	8 %	5 %	1.1 % ~ (0.1 % silver)

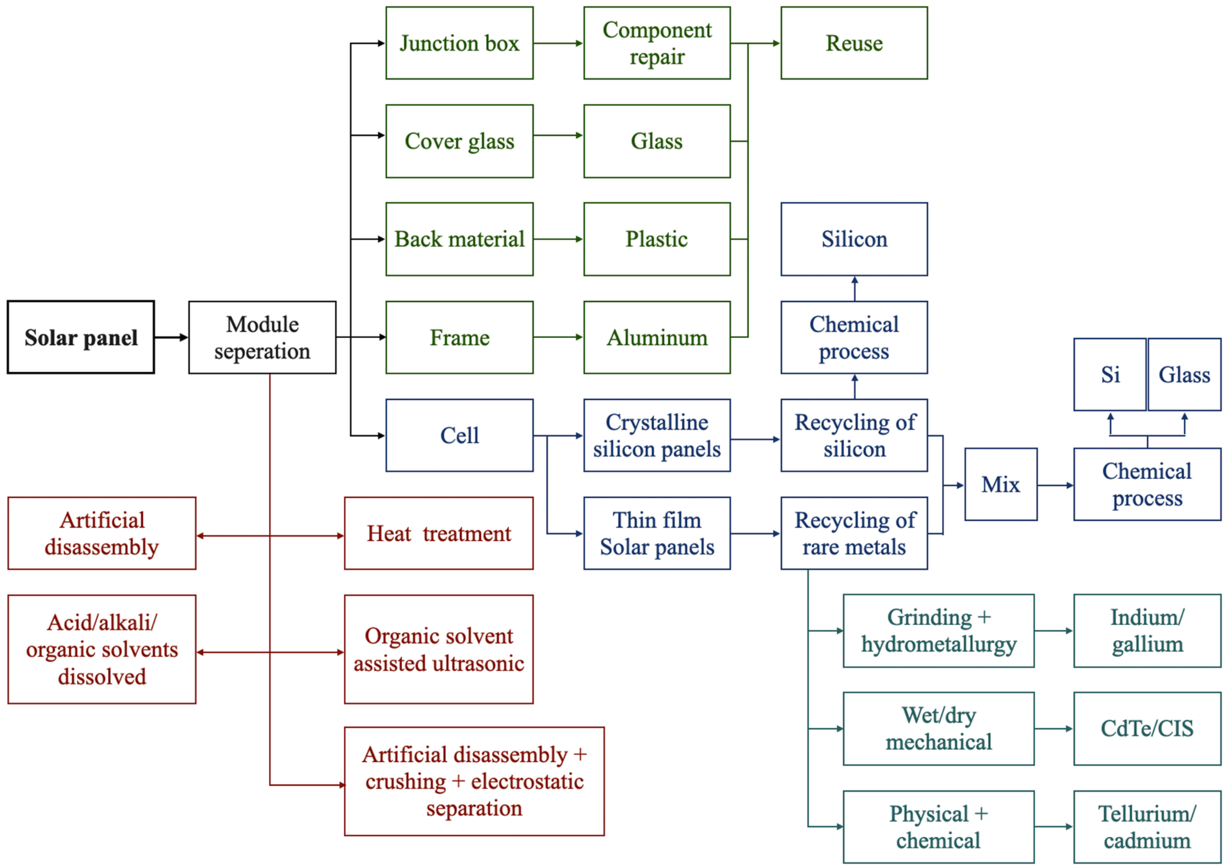

Fig. 12. First Generation Solar PV recycling methodologies (Xu et al., 2018). (With Permission, License Number: 5,700,641,343,307)

dissolve aluminum and silver, respectively. Another study (Jung et al., 2016) was conducted to explore environmentally friendly techniques for the removal and recovery of certain materials. One crucial aspect of the research involves the removal and retrieval of metal impurities, specifically Pb. The investigation revealed Pb was removed with a 93 % removal rate, and Si, Cu, and Ag were recovered with 80 %, 79 %, and 90 % rate of recovery, respectively. These results were obtained through the implementation of neutralization and sulfurization processes.

5.3.2. Thin films

Properly disposing or recycling thin film panels is vital to minimize potential environmental damage, considering their expected significant impact in the future (Berger et al., 2010). A careful examination of processing methods is necessary to responsibly manage panels, given the presence of hazardous substances, including potentially harmful heavy metals.

Several recycling and recovering methods are accessible for thin film modules. The leaching procedure is primarily employed for metal extraction but suffers from the drawback of excessive reliance on chemicals, resulting in the emission of acidic byproducts and necessitating intricate chemical regulation (Marwede et al., 2013). Another method for retrieving intact cells involves employing heat treatment (Berger et al., 2010), facilitating the complete removal of the encapsulant in a straightforward and cost-effective manner. Nevertheless, this approach has its drawbacks, including the emission of hazardous substances, significant energy consumption, and the potential for inducing cell defects and degradation. Fig. 13 demonstrates the different recycling and recovering procedures for thin film PV modules.

Sustainable recycling techniques were investigated in a study (Berger et al., 2010). The exploration covered both small-scale and semi-technical scale assessments for recycling thin-film PV modules, focusing on CdTe and CIS modules. Among the suggested techniques were combined thermal-mechanical approaches and wet-mechanical processing for damaged modules. The primary objective was to develop processes that effectively process and utilize indium (In) and tellurium (Te), which are recovered through wet-mechanical processing, to produce new modules. Another research (Giacchetta et al., 2013) presented an innovative method for thin-film PV modules' end-of-life, which involves mechanical and hydro mechanical treatments. CdTe modules were used on a laboratory scale to test this method. The environmental benefits of the new method were evaluated using LCA, which included a classification/characterization phase and a normalization phase. Before implementing the developed process, the initial step involves removing the wiring from the module. Subsequently, the modules undergo shredding and hammer milling to reduce their size to about 4–5 mm. The process can recycle whole modules, broken modules, or manufacturing scrap due to this size reduction. The next step is hydro-mechanical treatment, which separates valuable materials by using friction and shear. Finally, a flotation process is used to create a solid-liquid separation (See Fig. 14).

5.3.3. Perovskite and organic solar cells

Third-generation photovoltaics seek to enhance solar harvesting devices' efficiency using thin-layer deposition and the integration of innovative materials and processes. Notably, this technique is characterized by its lack of harmful processes and reliance on easily accessible materials, making it very suitable for widespread use in PV solar cells and adding to its recyclability (Iqbal et al., 2022). An environmental impact analysis was undertaken in Krebs-Moberg et al. (2021) to examine the life cycle of Perovskite thin-film, organic thin-film, and polycrystalline silicon panels. Per the study, Perovskite thin-film panels and organic PV exhibited the least environmental effect across all

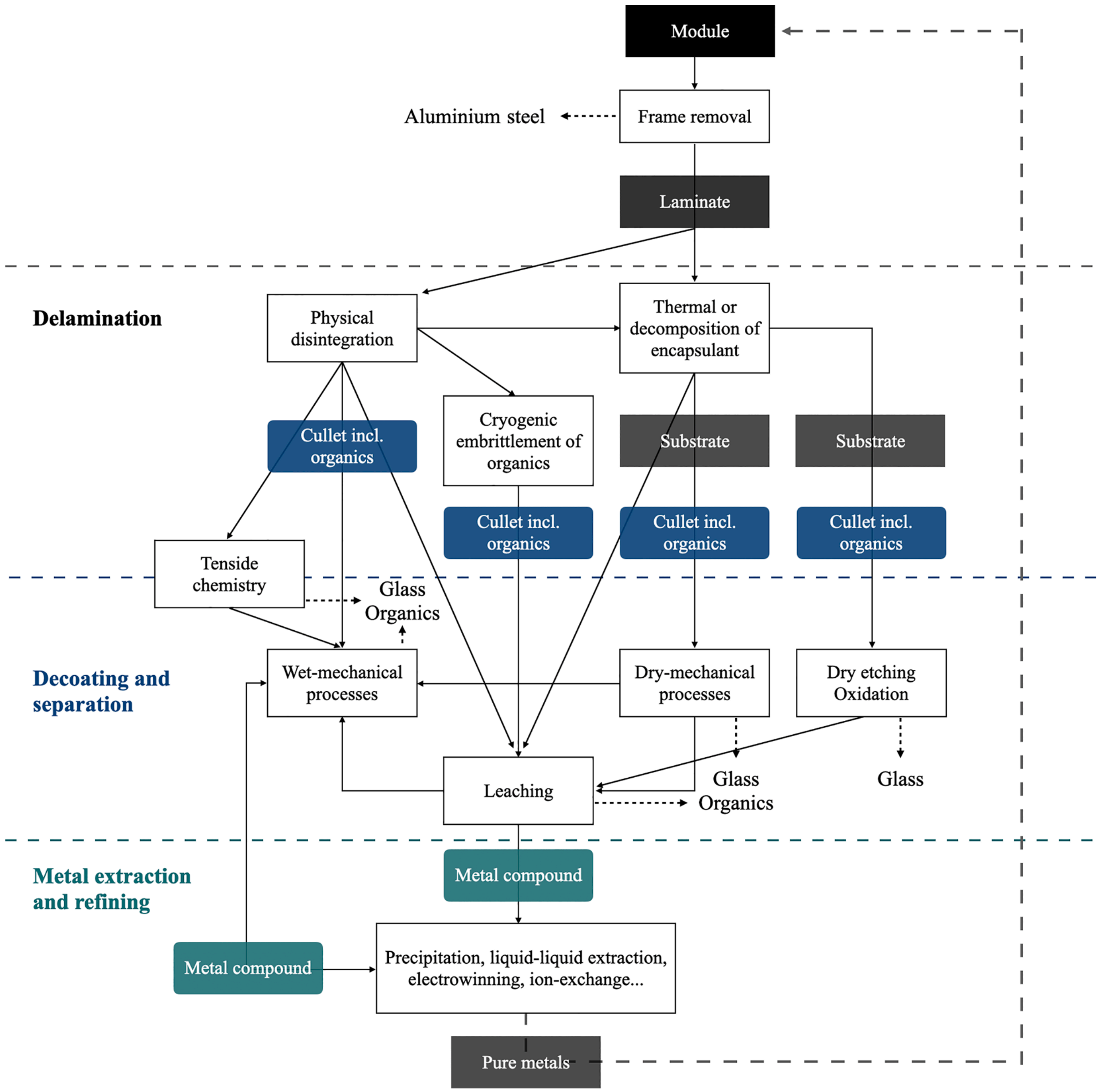

Fig. 13. Thin films PV modules recycling paths (Marwede et al., 2013).
(With Permission, License Number: 5,700,650,063,832)

categories. Based on different disposal scenarios, the study also discovered that the end-of-life implications differed for each kind of panel, with recycling having less of an impact than landfilling. Recycling reduced the global warming potential of organic thin-film solar panels by 67 % and that of perovskite thin-film solar panels by 39 %.

Zhou et al. (2013) proposed a novel organic solar cell developed using optically transparent cellulose nanocrystal substrates. This innovation demonstrates remarkable efficiency and recyclability, achieving a record PCE of 2.7 %. Utilizing renewable cellulose nanocrystal substrates holds a potential for producing energy in a sustainable and eco-friendly manner. The cell disintegrates rapidly in distilled water, forming a recoverable solid residue. Components like the photoactive layer and electrodes separate effortlessly at room temperature, minimizing energy and material requirements for the recycling process.

Perovskite solar cell recycling presents challenges and complexities in the realm of PV device recycling. A prominent issue emerges in the form of instability and toxicity associated with Pb during the waste management of Perovskite solar cells (Jena et al., 2018). Proposed measures involve recycling and reclaiming Perovskite films from discarded devices, encompassing techniques such as the removal of thermally deformed hole transport layers (HTLs) and Perovskite films on degraded devices can be recovered from residual lead iodide (PbI_2). The significant environmental concerns associated with lead poisoning underscore the need to prioritize the recycling of lead from degraded Perovskite cells.

A recycling approach involved systematically dismantling PSCs layer by layer to prevent the introduction of contaminants that could compromise the recycling of Pb (Binek et al., 2016). This process allowed PbI2 and the fluorine-doped tin oxide (FTO) substrate to be reused by converting the Perovskite layer into Methylammonium Iodide (MAI) and PbI_2. While these systems exhibit a slightly lower PCE compared to PSCs employing highly pure PbI_2, they mark crucial initial steps in addressing the issue of Pb in PSCs. Moreover, a notable study presented a novel electrochemical technique that was introduced for recycling Pb in PSCs (Poll et al., 2016). A deep eutectic solvent including ethylene glycol and choline chloride is used to dissolve perovskite

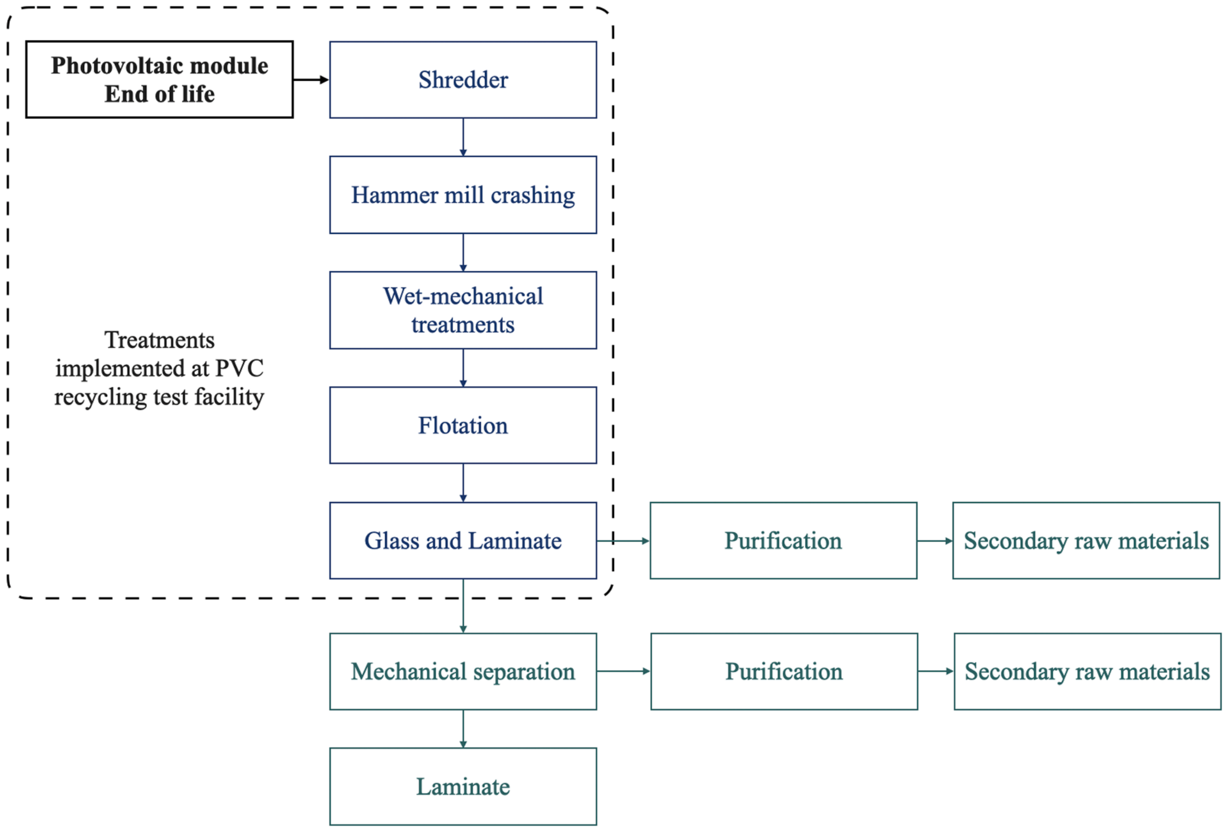

Fig. 14. Proposed recycling method scheme (Giacchetta et al., 2013). (With Permission, License Number: 5,700,650,204,068)

layers. After that, Pb ions were added to and taken out of a Pb working electrode using electrodeposition, resulting in a 99.8 % Pb removal rate. However, challenges remain in the PbI_2 recycling process, including the presence of impurities that may harm PCE. Furthermore, purification methods must be tailored to meet the stringent manufacturing requirements for recovered materials. Previous research investigated these issues (Zhang et al., 2018).

Considering the high cost of these components, it is essential to identify economical solutions to recycle and reuse TCOs from used PSCs (Liu et al., 2021c). Effective PSCs can be created without the need for an Electron Transport Layer (ETL), according to a study (Huang et al., 2016) by recycling old FTO/glass substrates from discarded cells. Subsequent research expanded the scope of recycling to include TiO_2, demonstrating the recovery of FTO/TiO_2 and ITO/glass substrates from different Perovskite solar cell configurations.

5.3.4. Tandem solar cells

Perovskite/silicon tandem cells were examined for their potential impacts on the environment using LCA (Monteiro Lunardi et al., 2017) The results demonstrated that compared to the Perovskite cell, the environmental impacts were substantially decreased when the tandem cell's metal electrodes were replaced with an indium tin oxide/metal grid. The Perovskite/Si tandem with Aluminum as the top electrode outperformed the other tandem designs in terms of environmental consequences, including a shorter energy payback period. Reusing silicon cells from Perovskite-silicon tandem cells was explored in a recent work (Yang et al., 2023) reusing the silicon cells from decommissioned Perovskite/silicon solar cells allows for the production of new cells while preserving their efficiency. Two processes are involved in recycling: heating and cleaning. The Perovskite coating sticks well to the recycled silicon. The recycled tandem device works at 25.7 % efficiency, just a bit less than the new one at 26.3 %.

6. Challenges, perspectives, and future trends

Solar PV technology has experienced significant breakthroughs; however, it still encounters multiple challenges that must be addressed to maximize its potential. The primary challenge to enhancing PV technology is attaining high efficiency while maintaining long-term stability. Although perovskite solar cells have shown considerable enhancements in efficiency, their stability in practical environments continues to be an issue. Factors including humidity exposure, UV radiation, and temperature variations contribute to the degradation of materials such as perovskite and organic materials, thereby reducing device performance over time.

The use of hazardous and limited materials, such as lead in perovskite solar cells and cadmium in thin-film technology, presents environmental and health concerns. These materials may leach into the environment during manufacturing, operation, or disposal, raising concerns over their sustainability. Also, the extraction of limited resources such as indium and gallium for CIGS cells poses geopolitical and environmental concerns.

Producing improved solar cells at scale while maintaining competitive costs is an ongoing problem. Techniques like R2R processing and scalable deposition methods are under development, necessitating optimization to ensure uniformity, efficiency, and cost-effectiveness. The complex manufacturing processes of tandem cells, which include precise layer stacking and material integration, also lead to higher production costs.

In order to tackle stability issues, significant research is being focused on encapsulation and material engineering methods. Interface engineering and enhanced encapsulation can improve resilience to environmental hazards while the development of lead-free perovskite formulations and alternative materials such as tin-based compounds provide practical opportunities to mitigate toxicity. Hybrid tandem cells that integrate both stable and efficient materials may balance performance with reliability.

Adopting circular economy concepts in solar PV production and disposal helps reduce environmental impacts. Recycling technologies are being improved to efficiently recover valuable materials such as silicon, silver, and indium. Innovative electrochemical recycling technologies and dismantling techniques are being investigated for the safe recovery of lead and other components in perovskite solar cells.

Tandem and multijunction solar cells are expected to lead future research due to their ability to capture a wider spectrum of sunlight and attain greater efficiency. Recent innovations in perovskite/silicon and III-V/Si tandem cells have attained efficiencies of 34.6 % and 36.1 %, respectively, indicating the possibility for further progress. Efforts to decrease the expenses associated with these technologies, particularly through the utilization of abundant and non-toxic materials, will be critical for their adoption.

Bifacial solar panels and advanced tracking systems are growing popular for their ability to optimize energy production. By adjusting panel orientation and utilizing reflected sunlight, these technologies provide significant enhancements in energy production. With the reduction of manufacturing costs, the use of solar PV systems is anticipated to increase, therefore further enhancing their competitiveness.

7. Conclusion

The aim of this review is to demonstrate the latest developments in PV solar cell generations and other commercially available technologies designed to improve solar energy capture efficiency. It also examines important factors that need to be considered while assessing the life cycle of newly manufactured solar cells. Additionally, the study investigates the effect of the materials used in production on the environment and outlines different methods for recycling resources. To summarize, the investigation results in the following conclusions:

- Third-generation and tandem solar cells have significant potential to advance solar PV and establish it as the leading commercially used renewable energy technology worldwide in the future. Achieving this potential depends on overcoming problems related to costs, scalability, stability, and durability over time.
- To improve the energy generation of residential and commercial PV systems, one can utilize either bifacial panels, tracking systems, or a combination of both. Although this approach may require a higher initial investment, it can lead to a reduction in the LCOE. Despite producing the most energy, dual-axis tracker installations have an LCOE value that is 4–8 % higher than fixed monofacial installations due to their high costs.
- Both EPBT and LCOE are significant parameters to consider when assessing the environmental sustainability and economic feasibility of solar cells. Compared to the commercialized solar cells, Perovskite and Tandem cells showed a great potential in achieving significant reduction in EPBT and LCOE.
- Compared to conventional thermal power plants, PV power plants generate lower carbon emissions. However, there are a few environmental concerns related to the use of Pb, Sn, Cd, and Te that may pose harmful effects on human health.
- The recycling of solar panels during their decommissioning phase is an essential strategy for promoting a sustainable process. Several recycling techniques have been investigated, demonstrating the possibility of a significant recovery rate of silicon. The recycled tandem cells exhibit a negligible efficiency reduction of about 0.6 % in comparison to a newly produced cell.

The combination of 3rd Generation solar cells with tandem cell designs shows significant potential for attaining greater overall efficiency in converting solar energy. However, to bring these technologies to a level with more established solar technologies on the market, researchers are trying to optimize them, enhance their stability to extend their lifespan and improve their energy output.

CRediT authorship contribution statement

Ayman Mdallal: Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Conceptualization. **Ahmad Yasin:** Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **Montaser Mahmoud:** Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **Mohammad Ali Abdelkareem:** Writing – review & editing, Writing – original draft, Visualization, Supervision. **Abdul Hai Alami:** Writing – review & editing, Writing – original draft, Visualization, Conceptualization. **Abdul Ghani Olabi:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization.

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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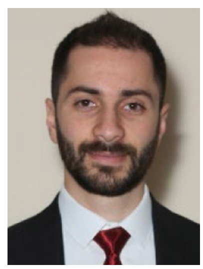

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