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Comparative Assessment of Polymers and Composites for Solar Panels: Fundamentals, Performance Metrics, Manufacturing, and Sustainability

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Abstract

This paper presents a comprehensive review of the main types of Photo Voltaic polymers and composites such as crystalline silicon (both mono- and poly-Si), thin-film tech (CdTe, CIGS, a-Si), perovskites, and organic/dye-sensitized cells and analyses the parameters such as efficiency, fill factor, open-circuit voltage, temperature response, and degradation. The analysis focusses on polymers and composites and manufacturing techniques like vapor deposition, roll-to-roll printing, and both solution and vapor techniques for perovskites. This paper deals with performance analysis and a comparative assessment of different architectures, lead-free perovskites, greener absorber polymers and composites, and more nonconventional types. Silicon is still leading material because of proven technology, economical perspective but perovskite–silicon type modules and new thin-film technologies are advanced technologies with higher efficiency. This paper gives a detailed review of recent technologically advanced polymers and composites for manufacturing the solar panels. The presented comprehensive assessment of these polymers and composites can be a helpful framework for researchers and academicians working on solar photovoltaic polymers and composites and and their mythologies. The review also highlights emerging research trends, environmental considerations, and long-term stability challenges, offering insights into future directions for material innovation and scalable fabrication. These added perspectives support broader understanding of the sustainable energy development achieved by the next-generation PV materials.

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Keywords: Crystalline silicon; thin-film; perovskite; OPV; DSSC; life cycle assessment; tandem cells; recycling

INTRODUCTION

Renewable energy sources are new sources of technological revolution. Globally solar power resources are leading the non-conventional sources because of least carbon emissions, advance technology, and economically viable option. Cheaper panels and polymers and composites by virtue of newer process engineering, higher efficiency and large manufacturing levels have made solar photo voltaic energy sources a main contributor among all renewables energy resources. But the type of material, different fabrication methodologies and advanced engineering is making the solar cell a leader in all type of energy sources. This study is focusing on these type of polymers and composites and different fabrication techniques. This paper also focusses the photo-voltaic behaviour, covering the optoelectronic specification of the polymers and composites and presented a comparative analysis of different fabrication techniques such as wafer-based, thin-film, or new solution-processed systems. But on the other hand this paper is also presenting the records of the energy usage, in designing of solar panels , their life cycles, the environmental effects and at last the decomposition methods or policies essential for achieving sustainable development goal. This manuscript is bringing altogether different range of material groups, parameters responsible for sustainability and gives a clear view about the future scope of the research. Outcomes of the presented study focus on the efficiency, economic considerations, technical advancements and sustainability contributions of newer polymers and composites. In this manner the presented comprehensive assessment of these polymers and composites can be a helpful framework for researchers and academicians working on future PV technologies, polymers and composites and technologies.

LITERATURE SURVEY

The PV market is governed by silicon (Si) solar cells (92%) and after that by amorphous silicon (a-Si:H, ~1%), copper indium gallium selenide (CuInGaSe2 or CIGS, 2%), and cadmium telluride (CdTe, 5%). The conventional material used for panel fabrication is silicon wafer, which has reached a substantial phase of development at the industrial level and has a thickness of about 180 µm. One of the main issues with utilization of energy is the cost of manufacturing. The Si substrate is responsible for around half of the cost of producing Si solar cells, while device and module manufacturing make up 20% and 30% of the total [1].

Global energy consumption is currently 10 terawatts (TW) annually, and it is expected to reach roughly 30 TW by 2050. By the middle of the century, the globe will require roughly 20 TW of non-CO2 energy to maintain the level of CO2 in the environment. Using photovoltaics (PV) and other forms of sustainable energy for electricity (10 TW), hydrogen for vehicles (10 TW), and fossil fuels for home and industrial heating (10 TW) is the most straightforward scenario to stabilize CO2 by the middle of the century [2–3]. PV will therefore be crucial in supplying the world's future energy needs [3].

In 1839, Becquerel made the discovery of the PV effect while researching how light affected electrolytic cells. It took a while to get to a high enough level of efficiency. Space initiatives and the usage of crystalline Si or c-Si solar cells, which have an efficiency of 6–10%, caused solar cells to advance quickly in the 1950s. Research and development (R&D) for PV was significantly accelerated by the energy crisis in the 1970s [4–5].

Solar energy is one efficient and viable alternative in the area for ecologically friendly energy sources. Numerous technologies have been created, demonstrating the versatility of solar energy in addressing a range of energy requirements, such as water desalination, dryers, heaters, cooling, and power. One excellent option in the pursuit of sustainable energy is solar photovoltaic (PV) technology. Using semiconducting polymers and composites that exhibit the PV effect, it uses the power of sunshine to create electricity [6–7].

Compound semiconductor-based solar cells (III–V and II–VI) were initially studied in the 1960s. Simultaneously, technologies for thin-film and polycrystalline Si (pc-Si) solar cells were invented to offer substantial capacity for production at lower energy and material requirements during fabrication, integration in module structure through the deposition process, and ultimately lower costs for large-scale terrestrial applications [8–9].

Because of their high power conversion efficiency (PCE), organic–inorganic lead halide perovskites have been a popular choice for solar polymers and composites in recent decades. High absorption coefficients, extended carrier lifetimes, long diffusion lengths, and high charge carrier mobilities are some of the beneficial and intriguing characteristics of these semiconducting polymers and composites

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that are responsible for their excellent efficiency nevertheless lead halide perovskites' instability and toxicity prevent them from being widely used.

In this regard, to provide a solution to mentioned contingencies, following different types of polymers and composites lead (Pb) free Ga and In based halide perovskites ($(AM)_3(Ga_{0.50}In_{0.50})_2I_9$, $(MA)_3(Ga_{0.50}In_{0.50})_2I_9$, $(DMA)_3(Ga_{0.50}In_{0.50})_2I_9$, $(TMA)_3(Ga_{0.50}In_{0.50})_2I_9$, and $(TTMA)_3(Ga_{0.50}In_{0.50})_2I_9$) having the general formula $A_3B_2X_9$are designed. The trivalent metal cation based $A_3B_2X_9$ type perovskite polymers and composites exhibit non-toxicity and more ambient stability compared to the conventional ABX_3 type perovskite polymers and composites [10].

In this paper, we review the current status of the PV market and recent results on several leading types of solar cells, such as c-Si, pc-Si, and amorphous-Si (a-Si), and III–V, II–VI, and I–III–VI_2 semiconductors and their alloys and nano-PV [11].

From an initial efficiency of 6% in 1954, the efficiency of PV technology has advanced significantly in recent years. Researchers are now making significant strides in the development of solar cells, which will result in high efficiency levels and an approach to the Shockley-Queisser limit, a theoretical limit. These accomplishments are noteworthy because this field has shown a exponential growth.

Based on their traits and technological developments, solar cells are separated into three generations. Both single and multi-crystal varieties of the first generation of solar cells are known to be the most common. However, these cells have a significant drawback in that they are more expensive and have very low efficiency. Thin-film technology, which comes in a variety of forms such a-Si, CdTe, and CIGS, is the primary component of the second generation. Second-generation cells are thought to be more economical even if their efficiency is lower than that of first-generation cells [12]. On the basis of advanced technology, the third generation is the most recent developments. Nanostructured solar cells, hybrid, organic, and inorganic semiconductors are among the many technologies of advanced generation [13–14].

MATERIAL CATEGORIES FOR SOLAR PANELS

Crystalline Silicon (c-Si)

Monocrystalline Silicon (mono-Si)

Monocrystalline silicon panels exhibit the higher efficiency among the popular solar panels. The efficiency of mono-Si panels lie between 22 and 26%. Their uniform crystal like architecture shown in Figure 1, make them a best choice for advanced architectural designs such as Passivated Emitter and Rear Cell (PERC), Hetero-junction Technology (HJT), and Inter digitated Back Contact (IBC) But these are the costlier ones, and the designing process is bit technically complex and exhibiting a higher energy consumption. Scientists, and researchers are designing the thinner wafers and new techniques for the usage of silicon without wastages for bridging its demand, efficiency and cost are depicted in Figure 2.

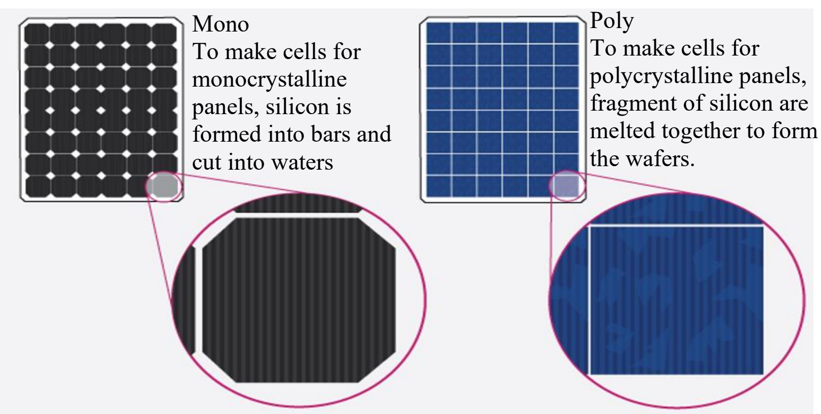

Figure 1. Microstructure comparison of mono- vs. poly-crystalline silicon with grain boundary effects.

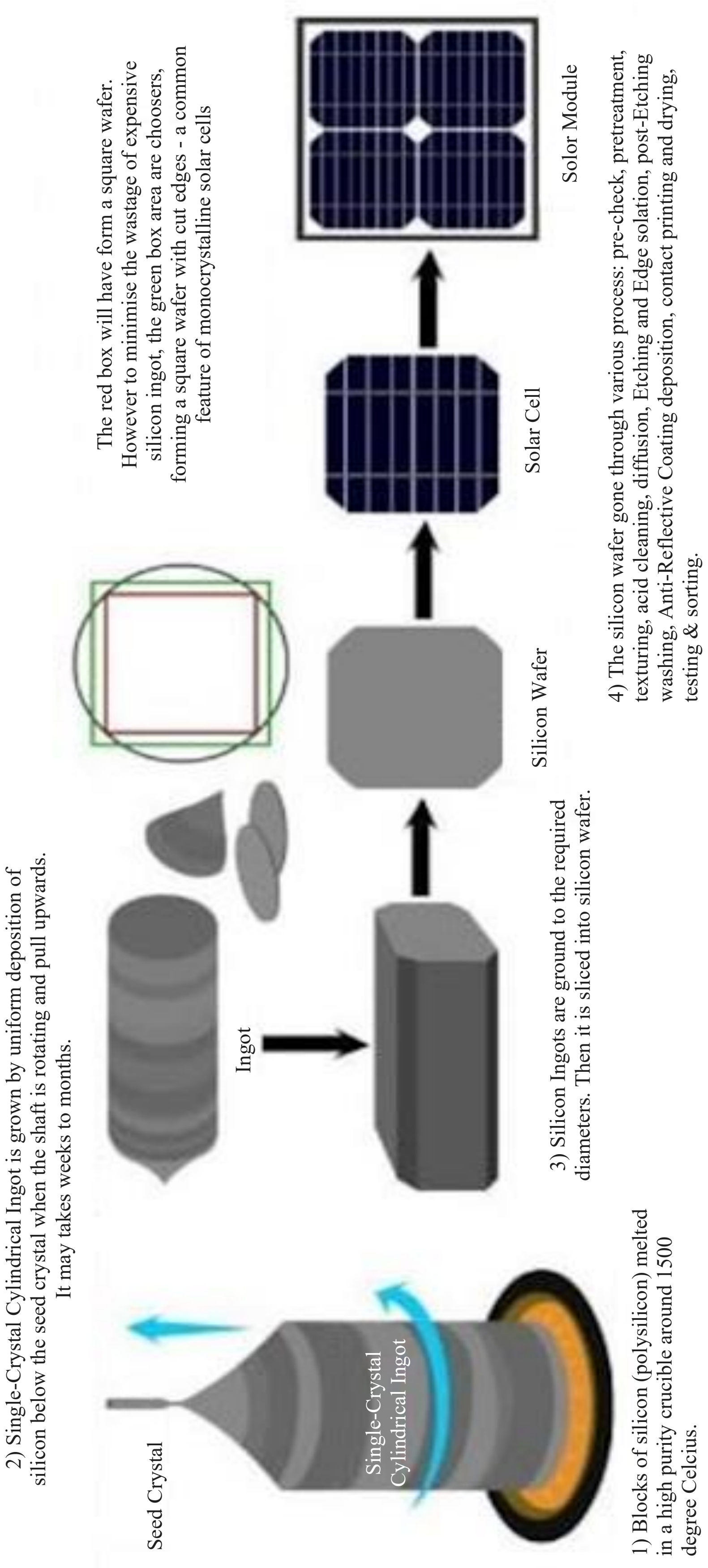

Figure 2. Silicon wafer-based solar module manufacturing process.

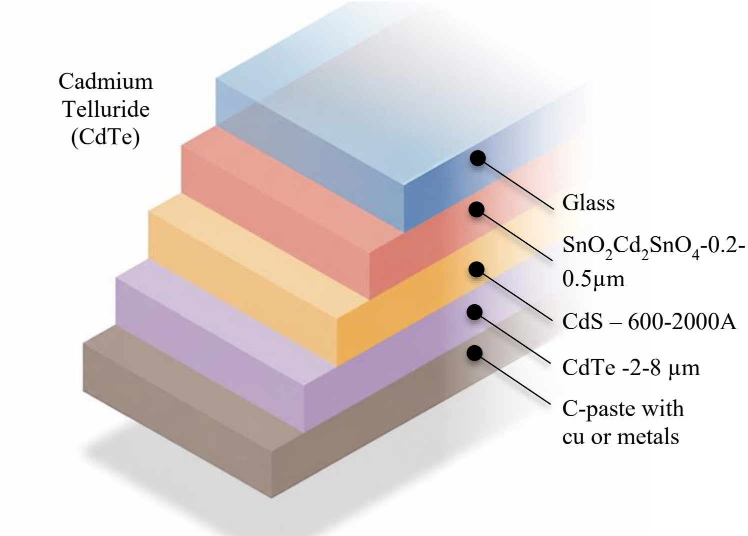

Figure 3. Cadmium telluride (CdTe) thin-film photovoltaic cell.

Polycrystalline Silicon (poly-Si)

Polycrystalline silicon are more affordable than mono-Si, but exhibit the lower efficiency. The efficiency of poly-Si panels lie between 15 and 20%. The efficiency becomes lesser than mono-Si panels because of the presence of grain boundaries in the material. Even though poly-Si panels are popular globally because they are technically sound and proven technology. The limitations of such polymers and composites lie in making of the ingots and designing them into wafers. In these processes a lot of energy and polymers and composites is wasted, which leads to higher cost.

Thin-Film Photovoltaics

Cadmium Telluride (CdTe)

Cadmium Telluride featuring in Figure 3, are cheaper in case of cost per watt is calculated and they exhibit best performance in low-light conditions and hot and humid atmospheric conditions. Their absorption coefficient is very strong and it makes them an ideal choice in adverse environmental conditions but because of the poisonous nature of Cd, its decomposition requires typical methodology.

Copper Indium Gallium Selenide (CIGS)

A CIGS solar cells are the typically specified PVs and it can be manufactured on flexible polymers and composites. They absorb sunlight really well, and their efficiency is comparable to standard silicon (c-Si) panels. But there are limitations also like indium and gallium are not abundantly available, and uniform fabrication of these cells at a large scale is still a contingency.

Amorphous Silicon (a-Si)

a-Si is cheaper, flexible, and fits perfectly into building-integrated PV or wearable technologies. Their limitaions are lower efficiency, and highly sensitive to light because of the Staebler–Wronski effect, which makes it degrading over the time.

Perovskite Solar Cells

Perovskites are the new advanced PV panels shown in Figure 4. Their efficiency is grown from about 3% to over 25% in less than ten years. They are simple to process (so, low-cost manufacturing), easily tuned bandgaps, and simply paired well in tandem with other types. Still, having limitations such as heat and moisture can weaken them, the interfaces break down, and the lead content is a problem. The main polymers and composites here are hybrid organic–inorganic lead halides like CH3NH3PbI3 and its FA or Cs versions.

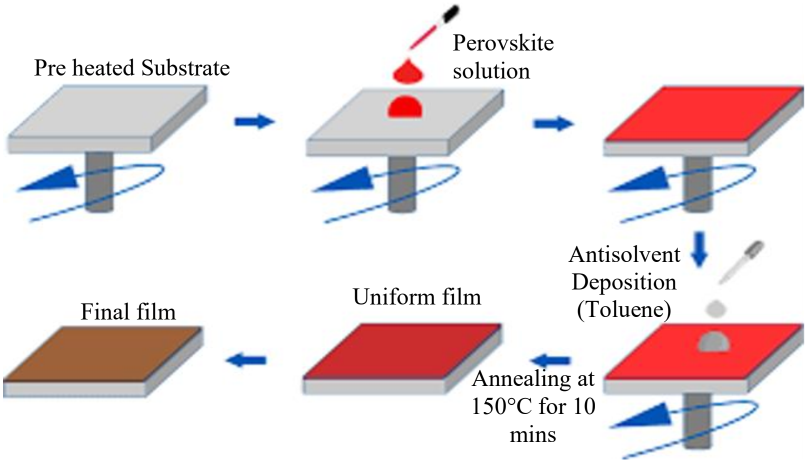

Figure 4. Perovskite solar cells.

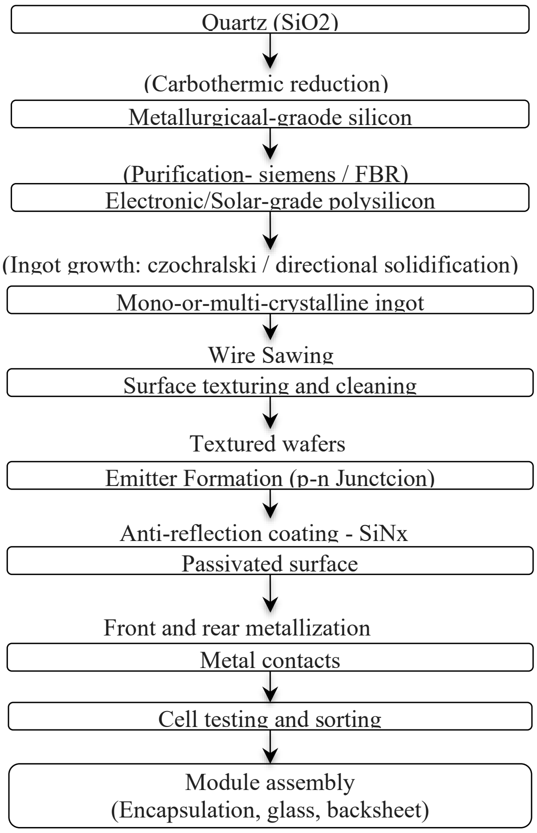

Figure 5. Flowchart for wafer-based manufacturing methodology.

Organic Photovoltaics (OPVs) and Dye-Sensitized Solar Cells (DSSCs)

OPVs use flexible, lightweight polymers or small molecules, and it can be printed using roll-to-roll techniques. It's fabrication is very simple .DSSCs work differently as usage in dye molecules designing on TiO2 scaffolds, This configuration enables efficient light absorption and electron injection, allowing DSSCs to effectively harvest energy even under indoor illumination or low-light conditions.

MANUFACTURING AND FABRICATION TECHNIQUES

Wafer-Based Manufacturing

Outline ingot growth (Czochralski method), wafer slicing and kerf loss, doping and junction formation, surface texturing, passivation, and contact metallization. Mention bifacial modules and trends toward thinner wafers and whole process in the Figure 5.

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Thin-Film Deposition

Figure 6 summarize the physical vapor deposition (PVD), chemical vapor deposition (CVD), chemical bath deposition (CBD), and annealing. Include printing and roll-to-roll processes for flexible PVs.

Perovskite Deposition

Figure 7 describe solution casting (spin, blade, slot-die), vapor deposition (co-evaporation), and hybrid approaches. Discuss scalability challenges, defect control, uniformity, and in-line metrology.

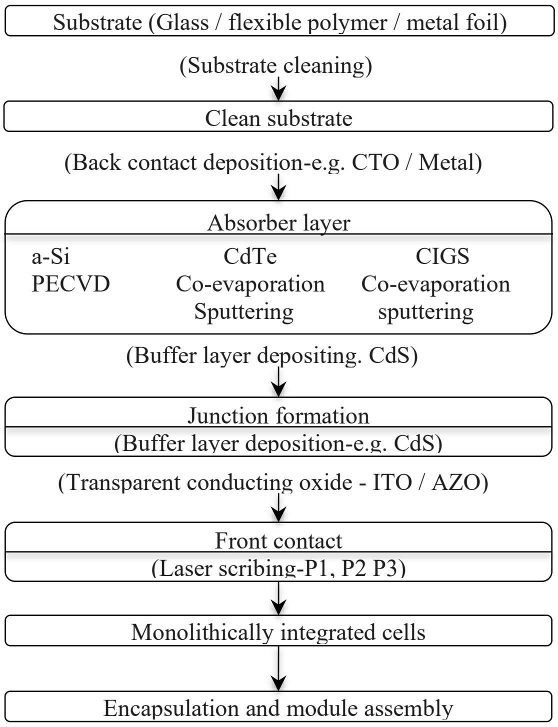

Figure 6. Flowchart for thin-film solar cell manufacturing (a-Si, CdTe, CIGS).

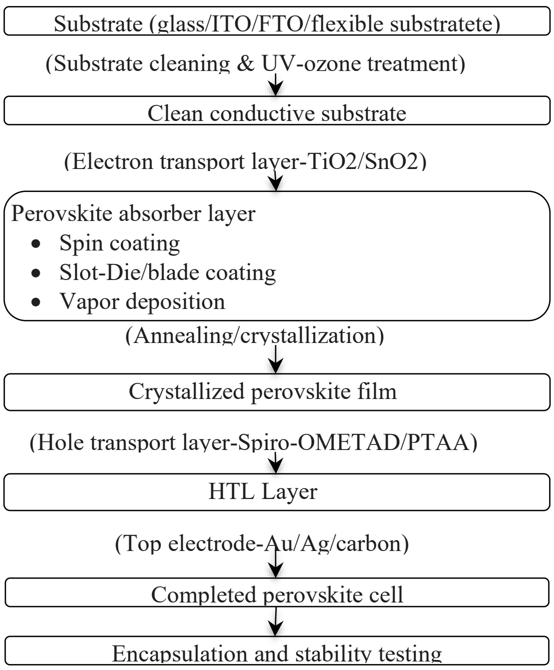

Figure 7. Flowchart for perovskite solar cell deposition process.

COMPARATIVE STUDY AND ANALYSIS

In this section comparative analysis material Properties is presented based on the parameters such as efficiency, cost, stability, and environmental impact varied between these technologies. Table 1 sums up the key differences.

The presented assessment evaluate the main solar photovoltaic polymers and composites and gives a clear view of each material exhibiting different parameters like efficiency, cost, stability, and environmental impact. These factors are the deciding factors for the usage and technical advancements. Monocrystalline silicon (Mono Si) continues to dominate because of higher efficiency, lying between 22 to 26 percent and exhibiting greater lifespan as well. This makes them a popular choice of panels for designing big solar farms. But the manufacturing process is expensive and it is its biggest limitation. Polycrystalline silicon (Poly Si) is a balanced option because it is having a lower efficiency of about 15 to 20 percent, but it is cheaper to design. It becomes a better option of having solid performance, decent price, still pretty stable over time. Thin film options shows different behavior such as Cadmium telluride (CdTe) cells are the cheaper options with greater efficiency but cadmium is toxic in nature. Table 2 sums up the key Life-Cycle Assessment (LCA) parameters for different types of Polymers and Composite Materials for designing of PV panels

Table 1. Comparative material properties across PV technologies.

Material / component	Band gap (eV)	Typical commercial efficiency	Absorption coefficient	Typical uses	Key strengths	Key limitations
Monocrystalline silicon (mono-Si)	1.12	~22 – 26 % cell; ~20 – 22 % module	High	Mainstream PV cells	High efficiency, mature tech	High material/processing cost
Polycrystalline Silicon (poly-Si)	1.11	~15 – 20 %	High	Standard PV panels	Lower cost than mono-Si	Lower efficiency than mono-Si
CdTe (Cadmium Telluride)	~1.45 – 1.48	~15 – 19 % module	Very high	Thin-film PV	Lower cost, good performance	Cd toxicity concerns
CIGS ($Cu(In,Ga)Se_2$)	~1.0 – 1.7 (adjustable)	~14 – 17 %	High	Thin-film PV	Good absorption & flexibility	Material scarcity (In, Ga)
Amorphous silicon (a-Si)	~1.7 – 1.8	~6 – 10 %	Moderate	Low cost thin-film	Low cost & flexible	Low efficiency, Staebler-Wronski effect
Perovskites (Hybrid, e.g., $MAPbI_3$)	~1.5 – tunable	Lab >25 %	Very high	Emerging PV / tandems	Very high efficiency potential	Stability & Pb toxicity issues
Organic photovoltaics (OPV)	~1.8 – 2.3	~10 – 15 % (lab)	Moderate	Flexible / low-cost PV	Flexible, lightweight	Lower efficiency / lifetime
Transparent conductive oxides (e.g., ITO, AZO)	—	N/A	High	Front contact layer	High conductivity/transparency	Cost / brittleness
Anti-reflective coatings (Si_3N_4, MgF_2)	—	N/A	Reduces reflection	Enhances light absorption	Improves output	Adds process steps

Table 2. Life-cycle assessment indicators for polymers and composite materials used in solar panels.

Material type	Energy (MJ/kg)	Carbon content (kg CO_2/kg)	Life span (Years)	Key environmental considerations
EVA (Ethylene Vinyl Acetate)	70–90	2.5–3.5	20–25	Medium recyclability properties
PET (Polyethylene Terephthalate)	80–100	3.0–4.0	20–25	Good mech. strength and higher recyclability
Glass Fiber Reinforced Polymer (GFRP) Composite	45–60	1.5–2.5	25–30	High durability but limited recyclability
Carbon Fiber Reinforced Polymer (CFRP) Composite	180–250	8–12	25–30	High strength and lightweight but and difficult to recycle.

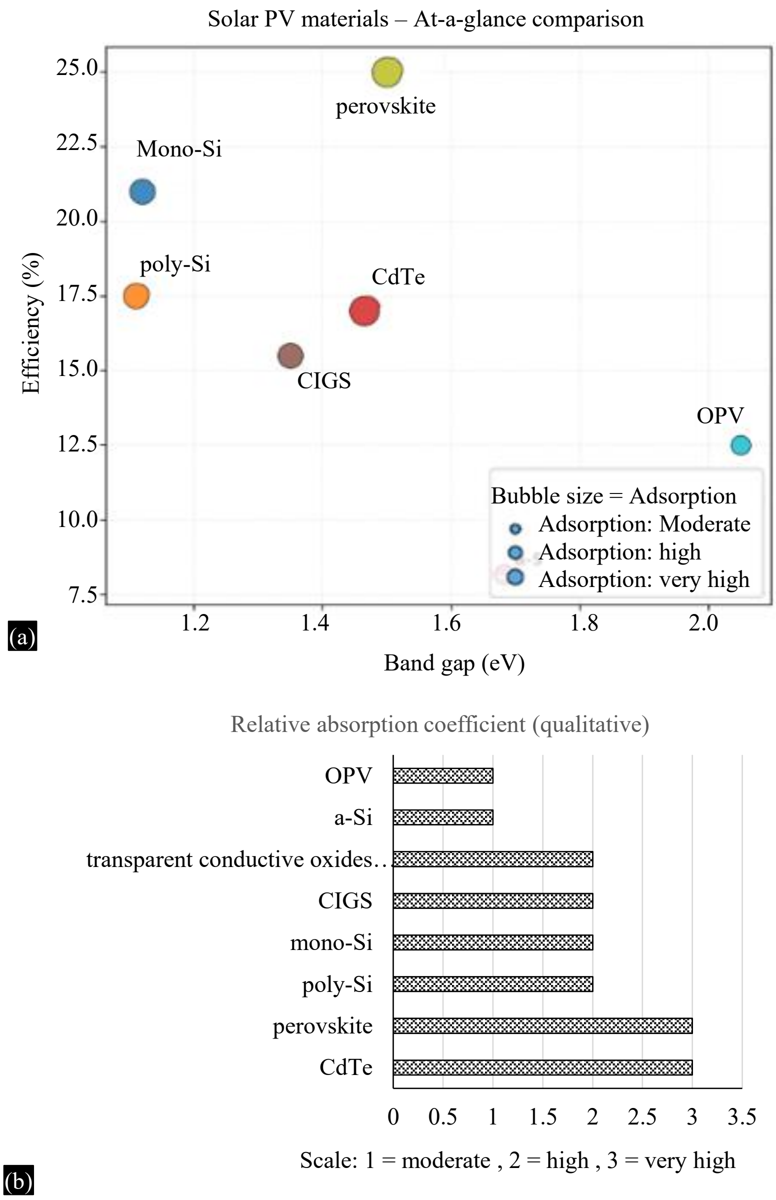

Figure 8. (a, b) Solar PV polymers and composites-at a glance comparison.

Therefore a careful approach is adopted during the tossing of these panels out otherwise real environmental risk can occur. CIGS cells those use copper, indium, gallium, and selenide can hit medium to high efficiencies and stay stable, but indium and gallium aren't exactly easy to find. The mass manufacturing is little because of these limitations. Perovskite solar cells are the new entrants in the field of solar technologies, and they've made a splash exhibiting higher efficiencies (20–25 percent) at a fraction of the cost of manufacturing [15]. But they've still got issues with staying power, and the use of lead in some designs adds environmental headaches. Then there's organic photovoltaics (OPVs) and dye-sensitized solar cells (DSSCs). They are cheap and flexible, so these can be used in places where, the rigid panels won't work. But the downside is clear: lower efficiency and a much shorter lifespan. As Figure 8 suggests, silicon-based panels still lead the pack because they're proven, tested, and reliable. But keep an eye on next-gen technologies like perovskites, advanced thin films and bifacial solar panels and its economic considerations [16]. If researchers can crack the problems with durability and environmental safety, these new polymers and composites will be a flag bearer in the field of solar technologies.

CONCLUSION

This study has summarized the fundamental physics, performance parameters, fabrication technologies, and sustainability impacts of old and modern photovoltaic technologies, considering different factors such as efficiency, cost, reliability, and environmental impact. Polymers and composites possessing advanced architectures and higher efficiency often exhibit limitations in long-term stability, scalability, environmental impacts, whereas conventional and proven technologies focusses on reliability and economical consideration with absolute performance. Crystalline silicon continues to lead the global PV market due to its proven durability, robust manufacturing ecosystem, reasonable energy payback time, and comparatively established recycling infrastructure. On the other hand, thin-film and emerging photovoltaic polymers and composites like perovskites and perovskite–silicon tandem architectures exhibit new opportunities having higher efficiencies and marginalized cost of electricity because of low-temperature processing and material-efficient fabrication. However, their large-scale implementation is still limited because of critical issues related to long-term operational stability, degradation, toxicity management, and the scalability, eco-friendly manufacturing and decomposition policies. Bridging these compelling factors are becoming crucial to the recent development of photovoltaic polymers and composites, where technological advancement must align with reliability, sustainability, and economical considerations to enable widespread and reliable deployment.

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