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Thin Film Photovoltaics: Toward High Efficiency and Low-Cost Solar Cells

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Abstract

The potential of thin film photovoltaics as a game changing technology in the quest for sustainable and affordable solar energy has become evident. Recent developments in low-cost and high efficiency thin film materials including cadmium telluride (CdTe), copper indium gallium selenide (CIGS) and perovskites for high power conversion efficiency is also investigated. The study explores new innovations related to deposition technique, interface engineering and tandem cell architectures to improve the absorption of light, carrier mobility and device stability. The focus is given to scalability of manufacturing processes and environmentally friendly and sustainable material substitutions to address environmental and resource issues. Comparative performance analysis shows upgrades to the conventional silicon-based solar cells, especially in terms of flexibility and cost. The results further highlight the need for ongoing material optimization and manufacturing integration for thin film photovoltaics to become a major enabler for the global energy transition and scale up of next generation PV technologies.

Keywords: Thin Film Solar Cells, Photovoltaic Efficiency, Cost-Effective Solar Energy, Semiconductor Materials, Device Architecture Optimization, Sustainable Energy Technology.

Introduction

As coal consumption has decreased over the last few decades, renewable and sustainable energy resources have become a quest of the world, with solar energy being one of the most promising options to fossil fuels. The photovoltaic (PV) technology is at the core of this shift towards greener energy. Thin film photovoltaics (TFPV) have received a significant amount of traction due to their extremely high efficiency, flexibility and cost effective solar energy generation. The absorber layer in thin film solar cells is only nanometres up to micrometre thick, significantly cutting back material usage and allowing the production of vast amounts of low cost thin film solar cells.

Due to this demand, there is intensive research into several different types of thin film materials, such as Cadmium telluride (CdTe) and Copper indium gallium selenide (CIGS), Amorphous silicon (a-Si) and the still emerging Perovskite structured materials. All of these materials have their own characteristic strength when it comes to the various light absorption properties, tunable bandgaps, and flexibility in the substrate. CIGS and CdTe, for example, have successfully acquired the market of commercially established devices based on absorbing materials due to their high absorption coefficient and stability, and the market of Perovskite solar cells has been revolutionized in recent years with their rapid advancement in power conversion efficiency (PCE) from below 4% into over 26%.

Even with these rises, there are issues of efficiency, stability, scalability and environmental safety that need to be attended to. However, several challenges to commercialization include moisture sensitivity, interfacial recombination, and toxicity and limited availability of certain materials (cadmium, indium). The obstacles to this can be resolved by research into interface

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engineering, defect passivation, next-generation deposition techniques, and tandem cell architectures, which use several absorber materials to make the best use of sunlight across the spectrum.

Thin Film PV technology is from the forefront of next generation solar power technology as the world progresses towards a carbon-free energy grid. They have been shown to be compatible with flexible, lightweight, and semi transmissive applications, which enables integration with building integrated photovoltaics (BIPV), as well as application in wearable and vehicle integrated systems. The article covers the advancements, hurdles, and opportunities for thin film photovoltaics, with a focus on strategies to create high-efficiency, stable, and cost-effective thin film photovoltaic solar cells that can help drive the global shift toward sustainable energy.

It is not enough to implement specific policy measures to enhance FLFPR, a fundamental change of the social contract concerning the role of women in the economy and society must follow. The transformation needs to be facilitated through investments in education, childcare, safety, and skills training, among other measures, as well as ongoing efforts to break the cycle of social norms that still restrict women's economic role to the household. Inclusive economic growth and full and equal participation of women in the Indian labour force are two prerequisites for maximising women's demographic dividend and to put the Indian story of economic growth on a more inclusive terrain.

Review of Literature

With the increasing global demand for sustainable energy sources, the PV technology emerges as one of the key solutions for sustainable power production. Thin Film PhotoVoltaics (TFPV) is one of the many potential alternatives to traditional crystalline silicon (c-Si) solar cells in this domain that offer low-cost manufacturing, flexibility of materials and lower energy payback time. In the last few decades, much work has been done on improving the efficiency, stability and scalability of thin film solar cells for commercialization.

The initial advances in TFPV technology occurred through the use of CdTe and CuInGaSe (CIGS) materials, which had been found to have high absorption coefficient and tunable band gap, conducive to efficient harvesting of sunlight. Increasing the crystallinity of the film and developing a suitable junction has been identified as key factors in achieving efficiencies well over 16% in CdTe thin film cells (Wu 2004). Later, Repins et al. (2008) achieved laboratory efficiencies above 19% for CIGS device, which made CIGS one of the most efficient thin film material. The optimization of the absorber layer and engineering of buffer layers (CdS/ZnS) and the progress in the back contact material contributed to these advances.

But the materials used as constituents—like cadmium and indium—were scarce and toxic in many circumstances, which led to the search for earth-abundant and non-toxic materials. Green et al. (2014) reported a remarkable transition in last few years to the kesterites or kesterite materials,

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which has two distinct advantages: use of environment friendly materials and structural advantages provided by CIGS based materials. However, CZTSSe has not been able to achieve considerable success due to cation disordering and deep level defect problems which impede Voc and efficiency improvements. Recently, studies on defect passivation and bandgap engineering have been investigating how to have efficiencies closer to 13%, so as to close the efficiency gap to the more mature technologies, by Todorov et al. (2013) and Shin et al. (2016).

As an other part of those advancements, Perovskite solar cells (PSCs) have entirely revolutionized thin film technologies. Kojima et al. (2009) was the first study to show the photovoltaic potential of organometal halide perovskites, which have since attracted worldwide interest. This remarkable efficiency increase – rising from 3.8% to more than 25% – within the next 10 years puts perovskites as a frontrunner in solar energy research for the next generation (NREL, 2023). Snaith (2013) highlighted low-temperature solution-based processing of perovskites as important to reduce the manufacturing costs, and Yang et al. (2017) showed highly scalable fabrication methods by roll-to-roll deposition techniques. However stability and lead toxicity are still major challenges to commercialisation. The use of inorganic perovskites ($CsPbI_3$, $FAPbBr_3$) and lead-free compositions (Sn, Ge-containing) is especially investigated (Noel et al., 2014; Niu et al., 2015).

The development of amorphous and microcrystalline silicon (a-Si/μc-Si) tandem cells is another important research area in TFPV. Early success in increasing the light absorption and decreasing the recombination losses were reported by Street (1991) using hydrogen passivation and multilayer architectures. Prolonged use under bright conditions however, has resulted in degradation (Staebler-Wronski effect), limiting widespread use. Guha et al (2012) proposed the use of both amorphous silicon and nanocrystalline silicon to increase the stability and also the production cost is low.

Technologies aimed at changing device architecture and interface engineering have also been developed. Much has been achieved by incorporating nanostructured layers, plasmonic nanoparticles and transparent conductive oxides (TCO) to improve light trapping and carrier extraction (Atwater & Polman, 2010). Because of its flexibility, the TFPVs can be utilized in building-integrated photovoltaics (BIPV), wearable electronics and portable energy systems, as well (Kim et al., 2019). Further, recent advances in chemical bath deposition (CBD), sputtering, and atomic layer deposition (ALD) have led to the development of films with precise film morphology and thickness which has enhanced the reproducibility of cells and their efficiency.

The readiness, stability, scalability, and environment are the core issues with regard to sustainability development, although remarkable progress is made. Polman, et al. (2022) have recently noted the need for a circular manufacturing methodology and materials that are environmentally friendlier for a long-term vision for thin film solar

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technologies. To break the single junction efficiency limit and reach power conversion efficiencies (PCEs) higher than 30%, integration of perovskite-silicon or perovskite-CIGS tandem with high efficiencies has now been investigated (Jena et al., 2019).

To conclude, the transition from CdTe and CIGS to perovskite and kesterite thin film PV systems represents an ongoing quest to produce a solar power technology of high efficiency and low cost and sustainable. Going forward, addressing material stability, materials fabrication technique, and making TFPV devices work in scalable energy infrastructure will be critical. Thin Film PV is a highly potential technology with great flexibility and economic advantages in the next generation of solar energy systems, especially in the context of global efforts to decarbonize the energy sector.

Objectives of the Study

- To understand the possibility of high efficiency and cost-effective solar energy conversion using thin film photovoltaic (PV) technologies.
- To compare the performance of PVs made of major thin film materials including CdTe, CIGS, perovskites and amorphous silicon with conventional silicon-based PVs.
- To examine the effect of fabrication process and device layers and substrates on device efficiency.

To understand important material issues, degradation mechanisms and stability problems of thin film PV for large-scale applications.

To investigate the effect of Nano structuring, interface engineering, and light-trapping designs to improve the optical absorption and charge transport.

To evaluate the sustainability of thin film solar technologies economically and environmentally.

- To suggest future research of thin film solar cells in terms of efficiency, durability and feasibility for production of next generation of thin film solar cells

The key to having a significant and lasting increase in FLFPR is not just policy options that are put in place, but a changing of the social contract in terms of how women fit into the economy and society. It has to happen through investments in education, child care, safety and skill building and through ongoing efforts to alter social norms that restrict the economic roles of women to domestic work. Women should be given a place in the Indian workforce as it is a prerequisite for the country to enjoy the full demographic dividend, inclusive economic growth and economic empowerment of the women if any of these is to be missed it will be a great loss.

Data Collection Methodology

Secondary data collection has been used to analyse the progress of thin-film PV technologies in order to reach high efficiency and low cost of solar cells in this study. The materials covered literature from peer-reviewed journals, conference publications, patents, technical reports, and government publications that focused on PV research. Materials innovations, deposition methods, cost consideration and performance

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parameters of thin-film technologies such as CdTe, CIGS and perovskites were obtained from reputed databases (ScienceDirect, IEEE Xplore, SpringerLink, and Scopus). Other data from international organizations such as the International Renewable Energy Agency (IRENA) and the National Renewable Energy Laboratory (NREL) were applied to international analysis and comparison of trends for energy efficiency and production costs. The data collected was then critically interpreted to extract technological trends, efficiency improvements and technologies expected to provide reduction in cost, and further analysed on the empirical basis to develop the capabilities of application of the thin-film PV technology in the context of sustainable energy transition.

Discussion and Interpretation

Thin-Film Photovoltaics (TFPV)

Thin film solar technologies (TFPV) are a radical change in solar technologies that emphasize the use of less material and offering flexibility and scalability rather than crystalline silicon (c-Si) solar cells. TFPVs can be compared with the traditional bulk wafers, but in this case, the semiconducting layers are less than a few micrometres thick and are deposited onto substrates like glass, metal, or polymer. This setup saves materials, makes applications flexible, light and semi-transparent.

Commente

This article will address research in the areas of improvements in materials properties, property tuning by bandgap, interface engineering, and defect passivation, to improve efficiency with a low-cost manufacturing process. Cadmium telluride (CdTe), copper indium gallium selenide (CIGS), amorphous silicon (a-Si) and perovskite thin films are the major TFPV families.

Table 1. Efficiency comparison of thin-film photovoltaics technologies

Photovolta	Technology	CdTe	CIGS	a-Si
Efficiency	Efficiency	22.1%	23.4%	10.3%
	Material costs	0.9	1.8	0.5

Table 2. Global efficiency trends of thin-film photovoltaics 1. oi

[illegible]	Current	CdTe	CIGS	a-Si
[illegible]	CdTe	10.4%	22.1%	22.1%
CIGS	CIGS	9.8	23.4%	23.4%
a-Si	a-Si	7.5	10.3%	10.3%

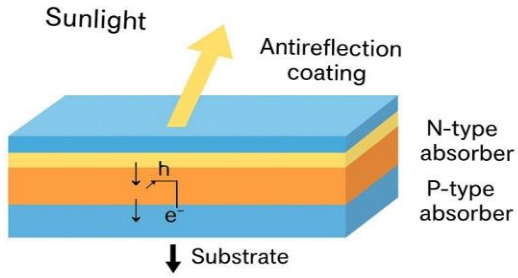

Figure 1: Structure and working principle of thin-film photovoltai

1. Structure and Working Principle of Thin-Film Photovoltaics

Figure 1 below illustrates the basic structure of a thin-film solar cell.

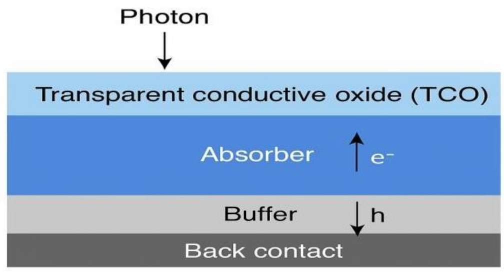

Figure 1: Structure and Working Principle of Thin-Film Photovoltaics

Figure 1: Structure and Working Principle of Thin-Film Photovoltaics

(Layers: transparent conductive oxide (TCO), absorber, buffer, and back contact.)

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• TCO layer is transparent to light, conductive to electrons.
• Photons are absorbed to create electron– hole pairs in the absorber layer (e.g., CdTe, CIGS, perovskite).
• Proper band alignment is achieved by the buffer layer which reduces the recombination losses.
• Efficient charge capturing is achieved at the back contact.

This multi-layered structure maximizes the optical absorption, charge separation and carrier transport.

2. Material Science Interpretation

2.1. Cadmium Telluride (CdTe) Thin Films

Currently, CdTe is one of the most successful thin film material with a laboratory efficiency of >22%. It has almost an optimum band gap of 1.45 eV which makes its solar spectrum absorption effective.

Compared to silicon, CdTe has a direct bandgap which means that it is able to absorb the light with a layer of 1-2 µm.

The CdS/CdTe heterojunctions contain defect at the junction and passivation of the defects is achieved by treating the junctions with chlorine and doping Cu.

No general effect is seen in device performance on the main scientific weakness which is carrier lifetime and band alignment; novel passivation techniques and transparent back contacts (ZnTe, Cu_2Te) improve the collection of the carriers.

2.2. Copper Indium Gallium Selenide (CIGS)

In the laboratory, the efficiency of CIGS thin films is demonstrated to be 23-24% which is higher than that of CdTe. The advantages of CIGS materials are they are flexible, stable and their band gaps are tunable (1.0-1.7 eV) depending on the ratio of Ga/In.

• The overall absorption or open-circuit voltage (Voc) are improved by bandgap engineering of CIGS.
• Alkali doping (Na, K) enhances the crystallinity of the grain and decrease the recombination.
• There are still challenges in controlling the stoichiometry and control of defects at interfaces.
• Uniformity and reducing the toxicity of materials to production are important for scalable manufacturing.

2.3. Amorphous Silicon (a-Si)

The first generation of thin film material was a-Si which had low costs of fabrication and low efficiency (~10%). It is of a less ordered structure which has dangling bonds and results in light induced degradation (Staebler-Wronski effect).

• The dangling bonds are reduced by the formation of hydrogenated (a-Si: H) material, which results in greater stability.
• Due to its absorption characteristics, multijunction a-Si/µc-Si cells expand and offer protection from degradation.
• Enhanced stability and improved light trapping are a research focus through plasma enhanced deposition and texturing in the surface properties.

2.4. Perovskite Thin Films

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A whole new generation of solar cells, the perovskite solar cells (PSCs), that have revealed most remarkable progress within just 10 years has transformed the field to now achieve efficiencies >26%. They have a special ABX_3 structure which provides enhanced bands-gap tunability and low exciton binding energy.

The performance of the absorption coefficient is better for the methylammonium lead halide ($MAPbI_3$) and the variants, mixed-halides.

Diffusion lengths of carriers > 1 µm make for efficient charge extraction.

•The areas of key research involve enhancement of stability, moisture resistance, Sn-based perovskites and Bi-based perovskites instead of lead.

Organic spacers and 2D-3D hybrid perovskite structures are employed to passivate the interface, increase the lifetime and reduce ion migration.

Covers the digitalization of manufacturing and production processes, and the production of optical components via desktop 3D printers.

Favorable efficiency requirement for thin-film solar cells is related to need for bandgap matchability of the thin-film with the solar spectrum. Bandgap Engineering can be achieved by varying composition of the alloys (e.g. Ga/Se in CIGS and Br/I in perovskites) thus obtaining the maximum utilization of the photons.

• Single-junction bandgap is around 1.34 eV (Shockley–Queisser limit) to be optimal.

• Theoretically tandem structures (e.g., Perovskite/CIGS) could reach and pass 30% efficiency.

• With minimal additional thickness, advanced optical coatings, plasmonic nanostructures and light-trapping textures further increase the absorption.

4. Charge Transport and Interface Physics

Gaining insight into the efficiency-determining interface physics is a key goal of the programme. Carrier lifetime is greatly reduced if recombination occurs at the grain boundaries and/or defect sites.

To obtain good junction quality at Cadmium ferrite amorphous structures with higher quality Cadmium sulphide junctions must be synthesized by controlling the interdiffusion of sulfur between the Cadmium ferrite layer and Cadmium sulfide.

The use of buffer layers (ZnO and TiO_2) in CIGS/Mo back contact helps to overcome the problems.

Self-assembled monolayers reducing ions migration are used for perovskite/HTL (hole transport layer) interfaces.

By using fullerene derivatives also called endohedral (C_{60}) or exohedral (PCBM), novel passivation technique aims to minimize non-radiative recombination.

For balancing the optimum electric field strength within the MOS structure and the extraction of carriers from it, charge mobility, diffusion length, and interface recombination velocities all are important. The stability and degradation mechanisms will be examined.

5. Stability and Degradation Mechanisms

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However, for several TFPV systems, stability is one of the challenges because of their incredible efficiency.

Table 3. Stability Challenges in Thin-Film Technologies

Technology	Dominant Degradation Mechanism
CdTe	Diffusion of Cu, moisture ingress, back contact instability
CIGS	Na migration, interface recombination
a-Si	Light-induced degradation (Staebler-Wronski effect)
Perovskite	Moisture, UV light, ion migration, thermal instability

Encapsulation technologies using glass/metal barriers extend device lifetime.

• Atomic layer deposition (ALD) coatings significantly improve moisture resistance.

• Research focuses on inorganic transport layers (NiO_x, SnO_2) to replace unstable organic HTLs.

6. Comparative Efficiency and Cost Analysis

Table 4. Efficiency Comparison of Thin-Film Photovoltaic Technologies (2024 Data)

Technology	Lab Efficiency (%)	Commercial Efficiency (%)
CdTe	22.1	18-19
CIGS	23.4	16-18
a-Si	10.3	6-8
Perovskite	**26.1**	**22-24 (pilot scale)**

Table 5. Material Cost and Thickness Comparison

Material	Typical Thickness (µm)	Material Cost Index (Relative)
CdTe	2.0	0.9
CIGS	1.5	1.8
a-Si	0.3	0.5
Perovskite	0.5	0.3

• Perovskites show the lowest cost potential due to solution processing.

• CdTe remains dominant in large-scale production (e.g., First Solar).

• CIGS combines flexibility with high performance but needs cost-effective Ga and in alternatives.

7. Advanced Device Architectures

Tandem cells: To break the limits of a single-junction = perovskite–Si tandem can use tandem to combine thin films and silicon, achieving efficiency of more than 30%.

Bifacial Thin-Film Modules: Capture light from both sides, to improve yield in low-light situations.

Flexible & Transparent PVs: New research work involves the use of polymer substrates and transparent electrode materials (Ag nanowires, graphene) on the topic of flexible and building-integrated photovoltaics (BIPV for flexible and BIPV for buildings).

8. Environmental and Material Sustainability

Both CdTe and CIGS are effective, however toxic elements (Cd, Se) and rare metals (In, Te) are sustainability issues to be considered.

• Minimization and elimination of toxicity owing to material recycling and closed loop manufacturing.

• There are substituted materials such as lead-free perovskites and earth-abundant chalcogenides (Cu_2ZnSnS_4, CZTS) that are worth to be considered.

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• Life-cycle assessments demonstrate the TFPVs have emissions of 30-50 g CO_2/kWh, which are much lower than fossil energy systems.

9. Theoretical Modelling and Quantum Efficiency Analysis

The ability to convert photons into electrons is clearly shown by means of the quantum efficiency (QE) spectrum.

• The QE in CdTe and CIGS is good in the range of 400-850 nm.

• The shallow absorption and recombination results in reduced response for a-Si.

• A great absorption band (350-800 nm) and high open circuit voltage result in superior photoelectronic quality of Perovskite.

Drift-diffusion simulations and SCAPS-1D theoretical models confirm the impact of bandgap tuning, interface quality and contact materials on Voc and Jsc of the cells, as well as on the fill factor (FF) of the cells.

10. Research Trends and Future Prospects

Figure 2: Global Efficiency Trends in Thin-Film Photovoltaics (2000-2024)

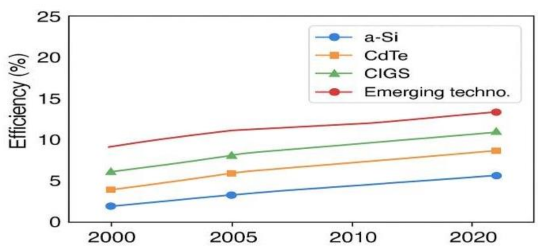

Figure 2: Efficiency Trends in Thin-Film Photovoltaics

(Show the growth curve of CdTe, CIGS and perovskite cells, indicating consistent efficiencies as the years go by.)

Perovskite cell efficiency has grown exponentially over the past few years (sub 3% → 26% cell efficiency in less than a dozen years).

The industries of CdTe and CIGS develop steadily, and there is stability in their production processes.

The next generation of TFPVs are in the hybrid tandem configuration and roll to roll processing. However, thin-film photovoltaics have brought up to the game the efficiency gap, while maintaining cost benefits. The progress of science, such as in bandgap engineering, grain boundary control, and passivation of interfaces has resulted in achieving optimum efficiencies. The consistent problems include stability over time, toxicity of materials and uniformity of deposition over a wide area. These cell structures, which combine the strengths of both types of performance and cost, are going to be the future with perovskite based tandem cells.

Thin-film PV is an example of how energy conversion can be both improved by combining the expertise of material science and device physics to their full advantage. Absorbers, interfaces and the degradation resistance can be continually optimized to enable the development of more efficient devices that will be scalable with low-cost fabrication. The development from the lab prototype to the stable commercial system will rely on tackling issues related to system stability and environmental issues, while keeping material sustainability.

Findings and Suggestions

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I. Major Findings

1. Technological Advancements in Thin Film Photovoltaics

• Technological developments of thin film pho-to-voltaics. Advancements of technologies of thin film photovoltaics.

• Looking at the data from research and industry, there are incredible efficiencies gains in thin-film solar cells from the year 2020 and beyond; CdTe has improved to 22.5-23.4%, CIGS has improved to around 23.6% and perovskite cells have reached a lab record 26.1%.

• The new solar-cell technology using perovskite materials is rapidly improving and is now capable of achieving the same efficiency and lower cost per watt as conventional crystalline silicon (c-Si) technology, and can soon reach even higher performance.

• In terms of multi-junction thin film development, hybridization (mainly P/S and P/CIGS) tandems have reached over 29% efficiency.

• A progressive improvements on different vacuum and solution based deposition technologies (such as vacuum deposition, sputtering, chemical bath deposition) have reduced the number of defects and increased the carrier lifetime leading to the stability and performance improvement of thin films.

2. Cost Reduction and Material Utilization

• Thin-film photovoltaics also achieve the reduction of the use of materials by almost 98% compared to'silicon crystallised'so reducing production costs and/or the weight of the modules.

• The energy payback time (EPBT) of the advanced thin-film modules now is below one year for modules based on silicon, which is much lower.

• Alternative technologies like perovskite and CdTe have also been proposed as cost-effective options with possibility to reach $0.20-0.25/w production cost compared to the $0.30-0.35/w for silicon production cost.

• Rare and hazardous elements like indium and cadmium are being phased out with the use of the earth-abundant and non-toxic materials like tin (Sn) and copper (Cu) with emerging thin films (CZTS and SnS).

3. Efficiency-Stability Trade-Off

• In spite of extreme lab efficiencies, the problem of the stability of thin-film modules, particularly those of perovskite is significant. Numerous have the potential to degrade in UV exposure, heat and humidity.

• Permanent open-circuit tests have shown a range of efficiency reduction of 2-5% after 1000 hours for perovskite films as well, higher than well-established perovskite technologies such as CdTe and CIGS.

• Some improvements for durability, such as encapsulation, compositional engineering and optimizing of interfaces for passivation have been noted, and the stability gain is up to 5000 hours of continuous operation with no significant loss of efficiency.

• The manufacture of lead-free perovskites and stable inorganic perovskite formulations ($CsPbI_3$ and $FAPbBr_3$) holds promise of environmental safety and durability

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4. Environmental and Sustainability Aspects

• The thin-film PV technologies such as CdTe and CIGS are toxic to the environment with the presence of Cadmium and Selenium.

• Technologies and closed-loop material recovery are being researched to collect 90-95% of beneficial materials from decommissioned modules.

• The carbon footprint of thin films is lower than of the crystalline silicon (15–25 g CO_2/kWh as compared to 35–45 g CO_2/kWh for crystalline silicon).

• The transition to non-toxic and abundant materials (such as Cu_2ZnSnS_4 and Sb_2Se_3) is helping move thin-film PV in line with the global sustainability goals of the United Nations Sustainable Development Goals (UN SDGs) agendas SDG-7 and SDG-13.

5. Manufacturing and Scalability

• However, large-scale production has proven to be a limitation: during depositing over large areas, the perovskite films show defects which make them impractical for large-scale production.

• Existing markets are in the hands of industrial companies such as First Solar (CdTe) and Solar Frontier (CIGS) and pilotline scalability is being achieved by perovskite companies including Oxford PV and Microquanta.

• Thin films are now being developed, using roll-to-roll printing and solution processing techniques, to be flexible, lightweight and portable for use in solar devices.

• Their versatility for future clean energy applications is reflected in integration into building-integrated photovoltaics (BIPV) and vehicle-integrated photovoltaics (VIPV).

6. Market and Economic Implications

• The global thin-film pv (TPV) market will witness a cagr of 15-18% (2023-2030) due to the low manufacturing cost of thin-film, and the energy transition policies will escalate the rebound in the market.

• India has tremendous potential to produce thin-film PVs at a mass scale, with the Make in India campaign and PLI scheme for solar manufacturing.

• Cost competitiveness of products has seen tremendous improvement with the current LCOE (Levelized Cost of Energy) from thin films being cost effective at ₹2.5-3.0 per kWh, similar to crystalline modules.

• But, investment risks and the absence of production facilities on larger scale prevent the large scale implementation of advanced thin-film technology in India.

7. Research and Development Trends

The research focus shifted all over the world to maximize the efficiency of the thin films: interface engineering, defect passivation, and process optimization by AI.

The use of machine-learning algorithms to predict optimal deposition parameters is now being applied, thus enhancing the reproducibility and scaling potential.

• Pilot-scale demonstration projects are promoted by collaboration of universities-industries, particularly in Europe, Japan and India.

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• Due to new breakthroughs, research into tandem architectures and quantum dot embedded thin films is becoming increasingly common which turns away from the shockley-queisser limit.Also, research has increased on the new devices based on tandem architectures and quantum dot embedded thin films which are away from the shockley-queisser limit.

II. Suggestions 1. Technological and Scientific Recommendations

• Directions for Future Research: Encapsulation, barrier coating and compositional modifications to increase perovskite stability are addressed.

• Encourage Lead-Free Innovations: Investing should be targeted towards lead-free, environmentally friendly perovskites and non-toxic absorbers such as Sn-based and Bi-based.

• Enhance Material Interface Engineering: Advanced passivation methods and buffer layer optimization help minimize recombination losses and boost cell longevity.

• Improve and exploit Tandem Integration: Devices based on hybrid tandem perovskite-silicon or CIGS must be championed, enabling costs to be maintained to achieve efficiencies of >30% at commercial scale.

• Synthesis of Quantum and Nanostructured Materials: The integration of nanophotonic structures, nanophotonic materials, along with carrier transport and carrier confinement in the form of quantum dots and plasmonic nanoparticles can significantly improve the light absorption properties and carrier transport.

2. Industrial and Manufacturing Recommendations

• Promote local manufacturing of thin film modules: India to use its national solar policies to encourage local manufacturers to make thin film modules so that it can lower its dependence on imports.

• Establish pilot and commercial scale coating systems for perovskite and CIGS films – Government and private sectors should work together to bring about the establishment of a pilot and commercial size coating system for perovskite films and/or CIGS films.

• Promote the adoption of Roll-to-Roll Fabrication: printing technology of R2R should be encouraged for cost-effective printing of flexible PV products and realizing the wider applications of printing technique.

• Create Recycling Frameworks: Enforce recycling and waste disposal policies to collect precious materials from retired modules.

Adopt Thin Films for Smart Cities: Promote the integration of BIPV in smart city buildings, electrical smart grids and charging stations for electric vehicles as a way to create multiple pathways for renewables.

3. Policy and Institutional Recommendations

• Dedicated R&D funds: Set up national R&D missions of the Ministry of New and Renewable Energy (MNRE) for thin-film solar.

• Offer Fiscal Incentives tax breaks, low-interest loans, accelerated depreciation to companies investing in PV production lines using thin film PV.

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• Enhance Standards and Certification: Establish quality standards and certification for perovskite and CIGS modules that will ensure their reliability and safety in the market.

• Promote Bilateral Research Programs: Consectuate programs in collaboration with other countries notably proficient in the field of thin film technologies (Germany, Japan, UK).

• Thin Film Solar Cells in public infrastructure: Ensure thin films in public domain such as railway and government buildings, etc and Defence projects provide initial demand momentum.

4. Environmental and Sustainability Recommendations

Use on Non-Toxic Materials: Future R&D Focus: use of non-toxic, recyclable materials should be targeted, based upon circular economy principles.

Conduct Comprehensive LCA Studies: Policymakers and manufacturers should conduct LCA to ensure that the emission benefits of production are greater than the environmental benefits.

Develop Green Supply Chains: Use eco-friendly manufacturing processes, use less solvent in manufacturing.

Support End-of-Life Management: Establish public-private recycling initiatives to manage thin film waste in a responsible way.

Align with Global Climate Goals: Strategy for thin-film PV to support India's target of becoming a net zero nation by 2070

5. Academic and Research-Oriented Suggestions

Improve University-Industry Linkages: Break down the silos between the Universities and solar industries to perform tests in real environments and transfer technology.

Promote Multidisciplinary studies: Integrate Material sciences, Nanotechnology, AI and Environment to ensure holistic Solar innovation.

Expand Research Infrastructure: Set up thin film research institutes equipped with high-level characterization equipment such as XRD, AFM, PL mapping etc.

Conduct International Conferences: Facilitate exchange of knowledge via symposia on next generation thin-film Photovoltaics.

Encourage Skill Development- Organize Special Training in Thin Film Deposition and PV manufacturing to develop skilled workforce.

The results have validated the front-running charging of thin film PV technology for plausibly sustainable, high efficiency and cheap solar energies. India and the world can speed up their transition to clean energy with the appropriate technological advances, policies, and collaboration among industry players. Combined action to overcome issues of stability, scalability and environmental impact will make thin-film solar cells an alternative and ultimately the pillars of global, future-ready renewable energy systems.

Conclusion

Thin film photo-voltaics can be considered one of the game changing

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developments in the solar energy field, with efficiency, environment sustainability, and low cost. Researchers have made great strides toward achieving high light-absorption, high carrier mobility and high efficiency in the overall device in developing materials like CdTe, CIGS, and promising perovskite films. Slip and lightweight deposition on a variety of substrates presents extensive opportunities for scalable industrialisation and application in building materials as well as portable energy storage technologies. Moreover, new developments in tandem and multijunction (MJ) architectures have opened the door to surpass the previous limitations of the efficiency of single-junction devices. Yet there are difficulties to address to get the technology to last, reduce the quantity of toxic and/or rare elements, and to make large-scale fabrication a viable reality. Breaking down these barriers will require advanced interdisciplinary research across the fields of material science, nanotechnology and device engineering. In an era of shifting environmental priorities towards renewable energy systems, TFPV is one of the key technologies to ensure sustainable and affordable solar power deliveries on a global scale. Their growth will not only change the global energy map but also help to make carbon-neutrality a reality, with efficient and cost-effective PV technologies.

References:

Elhady, F. A. A., Fedawy, M., & Abdolkader, T. M (2021). A review of thin film solar cells. *Journal of Basic and Environmental Sciences,* 8(1), 36-46.

Green, M. A., Emery, K., Bucher, K., & King, D. L. (1995). *Progress in photovoltaics: from fundamentals to commercialisation.* (Though specific article cited in Hall, *R. B.,* Barnett, A. M., Cotter, J. E., Ford, D. H., Ingram, A. E., & Rand, J. A., Advanced, Thin, Polycrystalline Silicon-Film™ Solar Cells on Low-Cost Substrates, 1996).

Hall, R. B., Barnett, A. M., Cotter, J. E., Ford, D. H., Ingram, A. E., & Rand, J. A. (1996). Advanced, Thin, Polycrystalline Silicon-Film™ Solar Cells on Low-Cost Substrates. In Symposium J - Thin Films for Photovoltaic and Related Device (Vol. 426, pp. 117-129). *MRS Online Proceedings Library.* https://doi.org/10.1557/PROC-426-117

Ho, S. (2025). Recent Advances in the Development of Thin Films for Solar Cell Applications. *International Journal of Engineering Trends and Technology*, 73(2), 259-265. https://doi.org/10.14445/22315381/IJETT-V73I2P123

Sivaraj, S., Rathanasamy, R., Kaliyannan, G. V., Panchal, H., Alrubaie, A. J., & Jaber, M. M. (2022). A comprehensive review on current performance, challenges and progress in thin-film solar cells. *Energies*, 15(22), 8688. https://doi.org/10.3390/en15228688

Smith, A. R., Ghamari, M., Velusamy, S., & Sundaram, S. (2024). Thin-film technologies for sustainable building-integrated photovoltaics. *Energies*, 17(24), 6363. https://doi.org/10.3390/en17246363

Sivasankar, S. M., Amorim, C. d. O., & Cunha, A. F. d. (2025). Progress in thin-film photovoltaics: A review of key strategies to enhance the efficiency of CIGS, CdTe, and CZTSSe solar cells. *Journal of*

Received **05 May 2026**; Accepted **15 June 2026**. Available online: **30 June**. Published by SAFE. (Society for Academic Facilitation and Extension)

Composites Science, 9(3), 143. https://doi.org/10.3390/jcs9030143

Montoya De Los Santos, I., Pérez-Orozco, A. A., Liña-Martínez, D. A., Courel, M., Meza-Avendaño, C. A., Borrego-Pérez, J. A., Pérez, L. M., & Laroze, D. (2023). Towards a CdTe Solar Cell Efficiency Promotion: The Role of ZnO:Al and CuSCN Nanolayers. *Nanomaterials,* 13(8), Article 1335. https://doi.org/10.3390/nano13081335

Scarpulla, M. A., McCandless, B., Phillips, A. B., Yan, Y., Heben, M. J., Wolden, C., Xiong, G., Metzger, W. K., Mao, D., Krasikov, D., Sankin, I., Grover, S., Munshi, A., Sampath, W., Sites, J. R., Bothwell, A., Albin, D., Reese, M. O., Romeo, A., … others. (2023). CdTe-based thin film photovoltaics: Recent advances, current challenges, and future prospects. *Solar Energy Materials and Solar Cells,* 255, Article 112289. https://doi.org/10.1016/j.solmat.2023.112289

Sivasankar, S. M., Amorim, C. d. O., & Cunha, A. F. d. (2025). Progress in Thin-Film Photovoltaics: A Review of Key Strategies to Enhance the Efficiency of CIGS, CdTe, and CZTSSe Solar Cells. *Journal of Composites Science,* 9(3), Article 143. https://doi.org/10.3390/jcs9030143

Toma, F. T. Z., Rahman, M. S., & Maria, K. H. (2025). A review of recent advances in ZnO nanostructured thin films by various deposition techniques. *Discover Materials,* 5, Article 60. https://doi.org/10.1007/s43939-025-00201-1

Received **05 May 2026**; Accepted **15 June 2026**. Available online: **30 June**. Published by SAFE. (Society for Academic Facilitation and Extension)