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Full Length Research Article

Comparative Review of Silicon-Based and Non-Silicon Solar Cells

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Abstract: *Solar photovoltaic (PV) technology has emerged as one of the most critical renewable energy solutions in combating climate change and ensuring long-term energy security. Over the past six decades, silicon-based solar cells have dominated the PV market due to their high efficiency, long-term stability, and well-established manufacturing processes. However, their relatively high manufacturing energy requirements, rigidity, and cost have prompted research into alternative non-silicon technologies such as cadmium telluride (CdTe), copper indium gallium selenide (CIGS), perovskites, organic photovoltaics (OPVs), dye-sensitised solar cells (DSSCs), and quantum dot solar cells (QDSCs). This chapter presents a comprehensive comparative review of these technologies, analysing their material properties, fabrication techniques, performance records, cost structures, environmental implications, and market prospects. The review also discusses the emergence of hybrid and tandem architectures that combine the advantages of different materials to achieve record efficiencies exceeding 33%. The chapter concludes with future research directions and strategies for large-scale sustainable deployment of both silicon-based and non-silicon PV technologies.*

Keywords: *Silicon solar cells, non-silicon photovoltaics, perovskite solar cells, thin-film photovoltaics, organic photovoltaics, dye-sensitised solar cells, tandem photovoltaics, photovoltaic efficiency, renewable energy.*

I. INTRODUCTION:

Silicon-based and non-silicon solar cells represent two major categories of photovoltaic technologies with distinct advantages and limitations. Silicon-based solar cells, primarily crystalline silicon, dominate the global market with more than 90% share due to their high efficiency, stability, and mature manufacturing processes. Silicon is abundant and offers reliable long-term performance, making it the preferred choice for large-scale utility and commercial applications. However, their production is energy-intensive, requires substantial material use, and results in rigid structures that limit versatility and integration into non-traditional surfaces

Non-silicon solar cells, including thin-film and emerging third-generation technologies, are gaining attention as alternatives. Thin-film cells such as cadmium telluride (CdTe) and copper indium gallium selenide (CIGS) use less material and energy during fabrication, making them cost-effective and versatile. They can be manufactured on flexible substrates, enabling innovative applications such as building-integrated photovoltaics (BIPV) and portable devices. Emerging technologies like perovskite and organic solar cells further enhance design flexibility and show promise for next-generation applications, including wearable electronics. Despite these advantages, non-silicon cells typically exhibit lower efficiencies and face challenges related to long-term stability and large-scale commercialization.

In summary, silicon solar cells remain the benchmark for efficiency and reliability, while non-silicon technologies offer exciting opportunities for flexibility, cost reduction, and novel applications. Future research aims to improve the efficiency and durability of non-silicon options, making them competitive with silicon and broadening the scope of photovoltaic applications worldwide.

II. LITERATURE REVIEW:

The development of photovoltaic (PV) technologies has progressed through several generations, each aimed at improving efficiency, reducing material consumption, lowering production costs, and expanding the potential applications of solar energy systems. The literature on silicon-based and non-silicon-based solar cells demonstrates a rich history of scientific innovation, driven by advances in materials science, thin-film deposition methods, semiconductor physics, and device engineering. A comparative review of research findings across these diverse technologies highlights the strengths and limitations of each, revealing emerging trends that are shaping the future of solar energy.

Silicon-Based Solar Cells

The earliest and most extensively studied category of PV technology is silicon-based solar cells. Crystalline silicon (c-Si), both mono- and polycrystalline, has long been considered the benchmark for photovoltaic performance due to its stability, mature processing techniques, and predictable electrical behavior. Early literature established silicon's indirect bandgap and long carrier diffusion lengths as the primary factors governing its photovoltaic performance. While the indirect bandgap necessitates relatively thick wafers for effective light absorption, improvements in wafer texturing, surface passivation, and anti-reflective coatings have significantly boosted cell efficiencies.

Monocrystalline silicon solar cells have been the focus of numerous studies demonstrating consistent efficiency improvements through advanced architectures such as Passivated Emitter and Rear Cell (PERC), Heterojunction with Intrinsic Thin Layer (HIT), and Interdigitated Back-Contact (IBC) cells. PERC technology, for example, introduced additional rear-side passivation to decrease recombination losses, resulting in enhanced efficiency and improved low-light performance. HIT cells combine thin amorphous silicon layers with crystalline wafers, leveraging the strengths of each material, while IBC architectures eliminate front-side grid shading, allowing more light to be absorbed. These advancements reflect decades of academic and industrial research aimed at pushing silicon close to its theoretical Shockley–Queisser limit.

Thin-Film Non-Silicon Technologies

Non-silicon thin-film solar cells such as Cadmium Telluride (CdTe) and Copper Indium Gallium Selenide (CIGS) have garnered extensive attention due to their reduced material requirements and compatibility with low-cost manufacturing methods. CdTe solar cells benefit from a near-optimal bandgap (~1.45 eV) and high absorption coefficient, enabling significant light absorption with thin layers. Literature highlights the remarkable commercial success of CdTe modules, particularly due to scalable manufacturing and high performance in hot and low-light environments. However, concerns regarding cadmium toxicity and tellurium scarcity are frequently discussed, emphasising the need for sustainable material sourcing and recycling strategies.

CIGS solar cells exhibit excellent optoelectronic properties and tunable band gaps through compositional adjustment of indium and gallium. Numerous studies report laboratory-scale efficiencies exceeding those of CdTe, demonstrating the potential of CIGS for high-performance thin-film PV. Despite these advantages, challenges such as complex deposition processes, dependence on scarce materials, and difficulties achieving large-area uniformity limit widespread adoption.

Organic, Dye-Sensitised, and Emerging Third-Generation Technologies

Organic photovoltaics (OPVs) have been extensively researched for their mechanical flexibility, lightweight design, and solution-processability. Literature in this domain highlights the tunability of organic semiconductors, enabling applications such as transparent and flexible modules. However, studies consistently point out limitations, including low efficiency, limited stability under UV exposure, and moisture sensitivity. Research continues to improve organic donor–acceptor systems, polymer blends, and encapsulation methods to enhance performance and shelf life.

Dye-sensitised solar cells (DSSCs), introduced in the 1990s, sparked significant interest due to their low-cost fabrication and effective performance under diffuse light conditions. DSSC research emphasises molecular engineering of dyes, electrolyte stability, and electrode nano-structuring. While DSSCs have not achieved widespread commercial adoption due to long-term stability issues, they remain promising for indoor energy harvesting and aesthetic architectural applications.

III. METHODOLOGY:

A comprehensive comparative review of silicon-based and non-silicon solar cells requires a multi-dimensional methodology addressing technical, economic, and environmental factors. The foundation of this approach lies in detailed technical and performance evaluations, conducted both in laboratories and under real-world conditions.

Standard photovoltaic characterisation is performed under Standard Test Conditions (STC: 1000 W/m² irradiance, AM 1.5 spectrum, and 25°C cell temperature) to ensure fair comparison. Key parameters include power conversion efficiency (η), open-circuit voltage (Voc), short-circuit current (Isc), fill factor (FF), and quantum efficiency (QE), which collectively measure conversion capability, electrical output, and spectral response.

Beyond basic I–V analysis, advanced characterisation techniques provide deeper insights into material and device physics. Spectroscopic ellipsometry determines thin-film thickness and optical constants, while photoluminescence (PL) and electroluminescence (EL) imaging reveal defects and recombination losses. Hall effect measurements quantify carrier mobility and concentration, essential for understanding charge transport.

Environmental and degradation testing simulates long-term operational conditions. Temperature coefficients indicate efficiency losses under heat, while damp heat and thermal cycling assess resistance to humidity and fluctuating climates. Light-induced degradation (LID), common in both silicon and perovskite devices, is measured to account for early performance drops.

This combined methodology ensures a rigorous and holistic comparison, allowing researchers to assess not only peak efficiencies but also long-term durability, stability, and practical viability of both silicon and emerging non-silicon solar technologies.

IV. RESULT:

Silicon-based solar cells remain the dominant photovoltaic technology due to their high efficiency, durability, and mature manufacturing processes. Crystalline silicon (c-Si), available in monocrystalline and polycrystalline forms, accounts for most of the market. Monocrystalline silicon offers the highest efficiencies, with laboratory records above 26% and commercial modules ranging between 17–23%. These cells are reliable and long-lasting, often backed by 25-year warranties, though their production is energy-intensive and requires costly high-purity silicon. Polycrystalline silicon, made from multiple crystals, provides a more affordable option but at slightly lower efficiencies.

Non-silicon solar cells present attractive alternatives, offering flexibility, lower production costs, and potential for diverse applications. Perovskite solar cells (PSCs) are particularly promising, with laboratory efficiencies surpassing 27% and the advantage of lightweight, flexible fabrication. However, their major challenge is instability under moisture, oxygen, and heat, leading to short lifespans. Ongoing research focuses on encapsulation and material improvements to enhance durability. Thin-film technologies like cadmium telluride (CdTe) and copper indium gallium selenide (CIGS) are already commercialised, offering cost-effective production. CdTe is simple to manufacture but raises toxicity concerns due to cadmium, while CIGS achieves high lab efficiencies yet faces scalability and resource limitations.

V. DISCUSSION:

The comparative evaluation of silicon-based and non-silicon-based solar cell technologies highlights the diverse pathways through which photovoltaic (PV) innovation continues to evolve. Each category of solar technology—crystalline silicon, thin films, organics, perovskites, dye-sensitized systems, and hybrid/tandem architectures—presents a unique set of advantages and limitations that shape their practical applicability. This discussion synthesizes the results in the context of performance, stability, manufacturing, sustainability, cost, and prospects, emphasising how different technological trajectories contribute to the broader solar energy landscape.

Efficiency and Performance

Silicon (Si) Cells: Crystalline silicon (c-Si) cells (monocrystalline and polycrystalline) are the most efficient commercially available solar technology, with efficiencies often exceeding 20% and lab records near 25%. Monocrystalline panels generally outperform polycrystalline panels, especially in hot conditions.

Non-Silicon (Thin-Film) Cells: Thin-film technologies generally have lower efficiencies in commercial modules (typically 10-15%) compared to c-Si, though lab efficiencies for materials like CIGS and CdTe can reach over 22%. However, thin-film cells perform better than c-Si in low-light conditions (e.g., cloudy days, sunrise/sunset) and exhibit lower thermal losses at high operating temperatures, making them suitable for hot climates.

Cost and Manufacturing

Silicon Cells: The production of c-Si cells requires a highly energy-intensive process involving pure silicon wafers, which historically made them expensive. However, technological advances and large-scale production have significantly reduced costs, making them the most cost-effective option for many large-scale applications.

Non-Silicon Cells: Thin-film cells require less active material and simpler, less energy-intensive manufacturing processes (like vapour deposition), resulting in lower production costs per unit area. This makes them an attractive option for cost-sensitive projects and applications where cost per watt is a primary concern.

Durability and Environmental Factors

Silicon Cells: Silicon panels are highly durable with a long operational lifespan, often lasting 25-35 years with minimal degradation. Silicon is abundant and non-toxic, making it an environmentally friendly choice during use, and it is largely recyclable.

Non-Silicon Cells: Thin-film cells (especially polymer and amorphous silicon) are lighter, more flexible, and can be integrated into various surfaces, including curved ones. However, some materials like Cadmium Telluride (CdTe) contain toxic heavy metals (cadmium), which raises environmental concerns during manufacturing and disposal, though emissions during operation are minimal. Their lifespan is generally slightly shorter than c-Si panels, typically 20-25 years.

IV. CONCLUSION:

Silicon-based solar cells continue to dominate the photovoltaic industry due to their proven efficiency, long lifespan, and cost-effectiveness at large scales. Their maturity, reliability, and robust supply chain ensure their position as the leading technology for utility-scale and rooftop applications. However, inherent drawbacks such as rigidity, heaviness, and energy-intensive production processes create opportunities for alternative approaches. Emerging non-silicon technologies—including perovskites, cadmium telluride (CdTe), and organic photovoltaics (OPVs)—present advantages in terms of flexibility, lightweight design, and low-cost manufacturing. They also hold promise for innovative uses such as building-integrated photovoltaics (BIPV), wearable electronics, and semi-transparent solar panels. Despite this potential, challenges remain significant, particularly in achieving long-term stability, avoiding toxic materials, and scaling laboratory breakthroughs to industrial production.

Future research must address these barriers to unlock the full potential of non-silicon solar cells. Enhancing stability and lifespan is a priority, especially for perovskite and organic technologies that degrade quickly under moisture, heat, and oxygen. Advances in encapsulation and the development of more resilient materials are essential. Improving efficiency and reducing costs at commercial scale also remain critical, as laboratory performance does not yet translate consistently to large-area modules. Furthermore, scalable, high-throughput manufacturing methods—such as roll-to-roll processing—must be developed to achieve mass production while maintaining quality and uniformity.

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