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Recent Progress in Solar Cell Physics: Materials, Efficiency, and Emerging Trends

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Abstract

This review paper provides a concise review of the recent developments in the physics of solar cells, in materials, efficiency enhancement, and technological trends. The paper discusses the working principle and historical evolution of the photovoltaic technology, as well as the various kinds of solar cells, including crystalline silicon, thin-film, perovskite, and organic photovoltaics. Notable gains in efficiency and performance have also been achieved through significant advances in material science and the device architecture, including PERC technology, tandem cells, and multi-junction designs. In the review, the significance of nanotechnology and improved fabrication strategies in improving the performance of solar cells is also mentioned. Even with these developments, issues like stability, cost, scalability and environmental impact are critical issues. This paper gives an insight into future prospects of developing efficient, cost-effective, and sustainable solar energy system by identifying research gaps and analyzing the current trends.

Keywords; Tandem Cells; Solar Energy Systems; Solar Cells; Photovoltaic (PV); Perovskite Solar Cells

INTRODUCTION

The increasing demands on energy solutions which are sustainable and renewable, have been escalated due to the rapid growth in global energy demand and the growing environmental concerns and depletion of fossil fuel reserves. One of the most promising and widely available resources has become one of the most available alternatives, solar energy. Because of their potential to generate pure, efficient, and scalable power, photovoltaic (PV) devices, also known as solar cells, are devices that directly transform sunlight into electricity [1]. The sustained developments in the physics of solar cell in the last few decades have been important in increasing the performance of the devices, lowering the cost and increasing their applicability in a variety of fields. Solar cell research is not a new concept; it has evolved over time and is now a diverse body of advanced materials and device architectures [2]. High-efficiency levels have been achieved with crystalline silicon solar cells, which are predominant in the current market, due to the advancements in manufacturing techniques and surface passivation methods. However, problems including high manufacturing costs and material limitations have prompted research into alternative materials, such as "tandem structures, thin-film technologies, perovskite solar cells, and organic photovoltaics" [3]. The benefits of these emerging materials include the ability to manufacture them at a lower cost, flexibility, and the possibility of greater efficiency due to new light absorption and charge transport mechanisms. In addition to material advancements, significant progress has been made in comprehending the basic physical mechanisms that control the operation of solar cells, such as "photon absorption, exciton production, charge separation, and recombination dynamics" [4]. Further techniques of characterization and simulation tools have assisted researchers to optimize the performance of the devices at the microscopic and macroscopic levels. Moreover, with the recent developments like multi-junction solar cells, bi-facial modules and integrating nanotechnology, new avenues of overcoming traditional efficiency limits have been created [5].

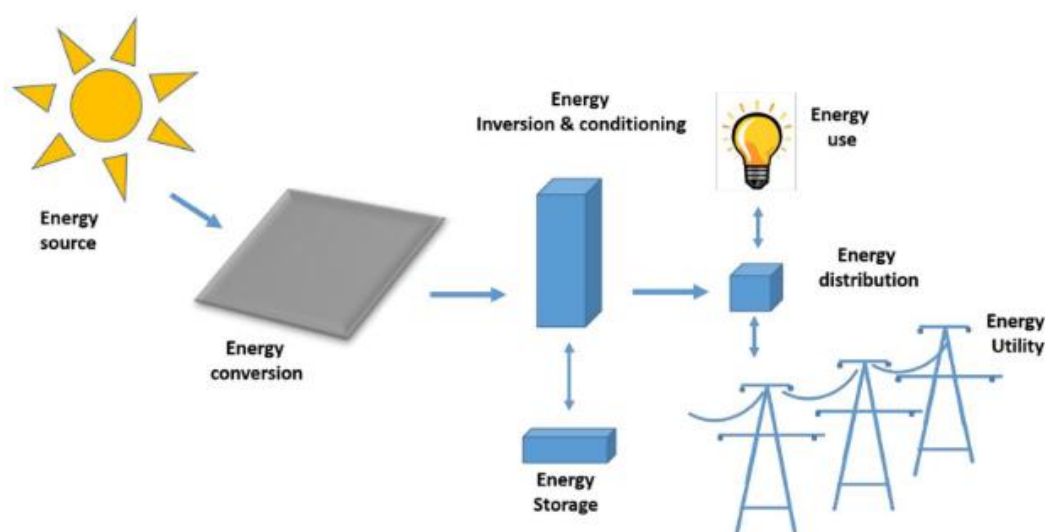


Figure 1: Schematic diagram of the solar photovoltaic systems [5]

Working of Solar Cells

PN junctions are the result of the diffusion technique, which involves the integration of two layers of P and N semiconductors in a solar cell. This electron fills holes, and in the vicinity of the junction, holes and electrons combine to become neutral, creating a depletion area. The junction is characterised by an internal electric field (or potential barrier) of 0.5 to 0.7 volts, which is achieved by the presence of negative ions (anions) on the P-side and positive ions (cations) on the N-side. The solar cell block diagram shown in Figure 2

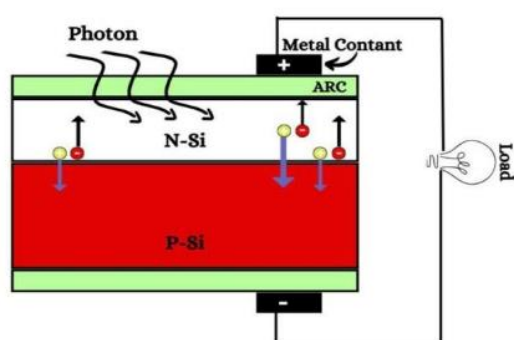


Figure 2: Block diagram of solar cells [6]

Three interdependent parts make up a photovoltaic (PV) cell. Electron-hole (e-h) pairs are created, opposite-type charge carriers are divided, and the carrier is extracted in the external circuit as a result of light absorption. The silicon

atom in the solar cell loses its electrons when photons from the sun strike it, leaving holes in their place. After that, electron-hole pairs are created. When there is an internal electric field, the electrons in the depletion zone are drawn to the P-section by the opposing polarity of the electric field, while the holes in the depletion region move in that direction [7]. The electrons and holes move in the direction of the terminals that correspond to them. When a metal wire or load connects these devices, an electric current flows. Short circuit current (I_{sc}) is the maximum current that may pass through a zero-resistance wire, whereas open circuit voltage (V_{oc}) is the potential across the terminals when no current is drawn. Figure 3 shows the I-V characteristics curve.

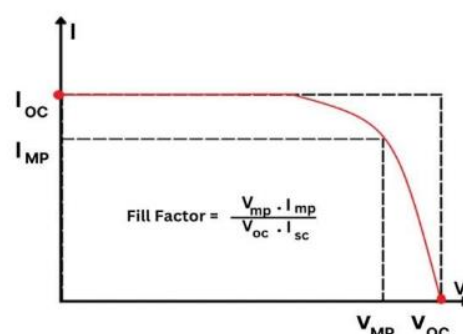


Figure 3: I-V Characteristics curve of solar cells [6]

Historical development of photovoltaic technology

The discovery of the photovoltaic effect by French scientist Alexandre Edmond Becquerel in 1839 marked the

beginning of the development of photovoltaic technology. The transformation of light into electricity is a phenomena that laid the groundwork for later developments. However, the development of useful solar cells did not occur until the middle of the 20th century [8]. In 1954, Bell Laboratories made a significant innovation by developing the "first silicon solar cell". Despite their inefficiency, these precursor cells paved the way for later developments. In the decades that followed, efficiency and cost-cutting witnessed constant improvements, driven by increased energy demands and novel technology. The 1970s oil crisis increased interest in researching and developing renewable energy, particularly solar power [9]. A number of PV cell types, such as thin-film solar cells, became more popular during this time, and PV technology was used for purposes other than space travel. PV technology reached a mature level by the late 20th century, marked by a decrease in cost and an increase in efficiency. This made it easier for solar energy to be widely used for utility-scale, commercial, and household uses. The photovoltaic industry has advanced even more quickly in the twenty-first century due to advancements in materials, device designs, and manufacturing techniques that drive the industry toward better sustainability, reduced costs, and more efficiency [10]

Types of Solar Cells

The materials and technology employed in their production can be used to categorise solar cells. The most widely used types of solar cells are crystalline silicon, organic and perovskite, and thin-film

Crystalline Silicon Solar Cells

For many years, "crystalline silicon (c-Si) solar cells" have ruled the solar industry due to their well-established production methods and comparatively high efficiency. "Monocrystalline and polycrystalline silicon cells" are two other classifications for these cells. As a consequence of their single continuous crystal structure, monocrystalline cells exhibit superior electron mobility and, consequently, a higher efficiency (typically between 18% and 22%). Although they are more economical to manufacture, polycrystalline cells, which are composed of many silicon crystals, have a lower efficiency (15%–18%). Energy output and efficacy have been enhanced by recent developments in silicon solar cell technology, including bifacial solar cells and "passivated emitter and rear contact (PERC) cells". By enhancing the surface, PERC technology lowers recombination losses and raises the cell's total efficiency.

Thin-Film Solar Cells

Photovoltaic materials are deposited in thin layers onto a substrate to create thin-film solar cells. These substances include "amorphous silicon (a-Si), copper indium gallium selenide (CIGS), and cadmium telluride (CdTe)". Thin-film technology offers several benefits over "crystalline silicon solar cells", including lower manufacturing expenses, more flexibility, and less weight. They are therefore appropriate for uses like portable and flexible solar systems. However, with average efficiencies ranging from 10% to 22%, thin-film solar cells are often less effective than crystalline silicon cells. In particular, the efficiency and cost-effectiveness of CdTe-based solar cells have shown promising results. CdTe cells have been successfully commercialised by firms like First Solar, and over time, their cost per watt has drastically decreased. On the other hand, thin-film cells based on CIGS are more expensive to produce but provide higher efficiency. Even though thin-film solar cells are less efficient than silicon-based cells, they are often seen as a more cost-effective choice, particularly in large-scale utility applications [11].

Table 1: Comparison of Thin-Film and Crystalline Silicon Solar Cells

Feature	Thin-Film	Crystalline Silicon
Material	Thin layers of semiconductor materials	Thick silicon wafers
Appearance	Flexible, various colors	Rigid, blue-black or dark blue
Temperature Coefficient	-0.25 %/°C to -0.35 %/°C	-0.35 %/°C (Monocrystalline)
Durability	Generally, less durable	High, long lifespan
Cost	Lower initial cost	Higher initial cost
Efficiency	Lower (typically 8–15 %)	Higher (typically 15–22 %)
Light sensitivity	Improved performance in low-light environments	Excellent performance under various light circumstances
Environmental impact	In general, more ecologically friendly	Less environmentally favourable as a result of various production processes and materials

Perovskite Solar Cells

Perovskite solar cells are a novel technology that has garnered significant interest due to their high efficiency and ease of production. Perovskites are a family of materials that can be designed to effectively absorb sunlight and transform it into electrical energy because they have the same crystal structure as the mineral calcium titanium oxide. With experimental efficiencies above 25%, perovskite solar cells

have made impressive efficiency gains. This is comparable to the efficacy of industrial silicon solar cells, with the additional benefits of reduced manufacturing costs and simplified production processes. Despite its promising performance, "perovskite solar cells" have problems with toxicity and long-term durability. Perovskite materials can degrade over time and reduce the usable life of solar cells due to their susceptibility to moisture, temperature fluctuations, and UV radiation. Additionally, a lot of these cells use lead-based perovskites, which are dangerous for both human health and the environment. However, current research on lead-free perovskites may allay this worry [12].

Organic Photovoltaics (OPVs)

Organic materials that may be utilised to capture sunlight, such as conjugated polymers or tiny molecules, are

the foundation of organic photovoltaics (OPVs). Lightweight, flexible devices, inexpensive manufacture, and the possibility of large-scale roll-to-roll fabrication are just a few benefits of OPVs. However, with typical efficiencies between 10% and 15%, OPVs are currently less efficient than "silicon-based or perovskite solar cells". Recent advancements in OPVs have mostly focused on the stability and effectiveness of organic materials. The development of novel donor-acceptor materials and improvements in device architecture have allowed researchers to achieve efficiency levels of up to 18% in lab conditions. OPVs have great promise for flexible solar applications, including portable electronics and building-integrated photovoltaics (BIPV) [13]

Table 2: Comparison of the Three Most Recent Photovoltaic Materials.

Feature	Perovskite Solar Cells	Organic Photovoltaic Cells
Efficiency (Recent Record)	26.1% was attained under typical test settings; the theoretical maximum is around 32.5%. Tandem structures allow for even greater efficiency gains.	Recorded at 19.5% with non-fullerene acceptor materials; significant advancements have been made recently, particularly with novel material designs to improve charge transfer..
Material Costs	Utilising abundant materials such as lead and halide compounds, the cost is relatively low. However, toxicity concerns are motivating studies into safer, alternative materials.	Low, as they employ readily accessible and reasonably priced organic molecules; current advancements concentrate on lowering the cost of electrode and encapsulating materials.
Flexibility and Application	Limited flexibility because of the stiffness of the material; flexible substrates are being investigated for wider uses, such as wearable and portable electronics.	High flexibility; lightweight and versatile design options; appropriate for incorporation into flexible, semi-transparent, and even wearable electronics.
Stability and Longevity	Long-term performance is limited by deterioration from moisture, UV exposure, and thermal stress; stability is also a major problem. Enhancements in encapsulation are essential.	Restricted by susceptibility to environmental factors (such as moisture and oxygen); current research attempts to improve stability through novel polymer and small molecule compounds.
Commercial Viability	Steadily improving, with continuous attempts to address toxicity and stability issues; the possibility of tandem structures that are affordable is encouraging.	Widespread adoption is impeded by difficulties in increasing stability and scaling up production processes, despite the technology's potential for low-cost, large-area applications.

Advances in Materials

The subject has been greatly influenced by recent developments in "solar photovoltaic (PV) technology", especially through material breakthroughs. Important developments include quantum dot solar cells, organic photovoltaics (OPVs), and perovskite solar cells. The unique advantages and challenges that each of these technologies presents facilitate the development of solar energy applications. Perovskite solar cells have become a very appealing technology because of its remarkable efficiency and extremely low production costs [14]. The material composition of perovskite solar cells frequently uses a hybrid organic-inorganic lead or tin halide compound that mimics the crystal structure of the mineral perovskite. These materials have great charge-carrier mobility and remarkable

light absorption capabilities, which result in high power conversion efficiencies. Recent developments have produced efficiencies that are close to that of conventional silicon-based solar cells, surpassing 25%. Stability is still a major problem for perovskite solar cells, though. Long-term performance may be impacted by perovskites' susceptibility to light, heat, and moisture. By creating encapsulation techniques and investigating other perovskite compositions that provide higher environmental resistance, researchers are tackling these stability problems. The manufacturing of perovskite solar cells has also advanced significantly. Thin films of perovskite materials are produced on substrates using methods including spin-coating and vapour deposition, which may be scaled up for commercial manufacturing. Because these techniques are less costly than

those for silicon-based cells, cost concerns are advantageous. The primary objectives of present research are the stability and scalability of perovskite solar cells, and one of the possible future uses is integration into transparent and flexible solar panels [15].

Another notable development in PV materials is Organic Photovoltaics (OPVs). OPVs make use of organic materials that may be manufactured into thin films, such as polymers and tiny molecules. These materials are flexible, lightweight, and visually appealing, among other benefits. Organic materials used in OPVs include "conjugated polymers like poly(3-hexylthiophene) (P3HT) and fullerene derivatives like [6,6]-phenyl-C61-butyric acid methyl ester". Because of their versatility, OPVs may be used in a variety of form factors, such as roll-to-roll manufacturing on large-area substrates, which is perfect for incorporating solar cells into unusual surfaces like wearable technology or building facades. Despite these advantages, OPVs have typically suffered from lower efficiency when compared to inorganic solar cells. Efficiencies have risen from below 10% to over 18% thanks to recent advancements in material design and device architecture. These developments are made possible by new donor-acceptor polymer combinations and enhanced processing methods. Commercial goods like flexible solar panels and integrated photovoltaic materials for textiles are becoming increasingly common, demonstrating the growing practical applications of OPVs [16].

One innovative method for enhancing solar energy conversion is quantum dot solar cells. Because of quantum confinement phenomena, semiconductor nanocrystals known as quantum dots have special electrical characteristics. In order to improve light absorption and conversion efficiency, the technology incorporates these nanocrystals into a photovoltaic device. Benefits of quantum dot solar cells include adjustable bandgaps, which improve solar spectrum absorption optimisation. Compared to conventional PV materials, this tunability makes it possible to develop devices that can absorb a wider variety of wavelengths. To further increase efficiency, quantum dots can be designed to have excellent photoluminescence and charge-carrier mobility. Despite these benefits, there are still a number of development obstacles to overcome, such as problems with the consistency of quantum dot films, manufacturing scalability, and possible health and environmental risks linked with some quantum dot materials. New developments in quantum dot solar cell research seek to improve both performance and stability of these devices by exploring new quantum dot compositions

and applying state-of-the-art nanostructuring techniques [17].

In conclusion, the efficiency, affordability, and uses of solar energy have been greatly affected by recent developments in materials for solar photovoltaic technology. Although perovskite solar cells have shown great promise due to their high efficiency and cheap production costs, stability and environmental issues remain significant research areas. Organic photovoltaics are lightweight and flexible, and their efficiency and usefulness are constantly being improved. With their distinct advantages in light absorption and conversion efficiency, quantum dot solar cells offer a promising frontier in photovoltaic technology. However, they have difficulties with material stability and scalability. For solar energy technology to advance and play a bigger part in sustainable energy solutions, these materials must continue to be developed.

Efficiency Improvements and Materials Innovations

A solar cell's total performance is largely determined by its efficiency, particularly in large-scale and commercial applications. Optimising material characteristics, device designs, and manufacturing processes have been the main goals of efforts to increase solar cell efficiency.

Crystalline Silicon Improvements

Advances such as "passivated emitter and rear contact (PERC) technology" have significantly improved the efficiency of crystalline silicon cells by reducing recombination losses and boosting charge carrier mobility. Another effective method for boosting efficiency is tandem solar cells, which combine several silicon layers with additional photovoltaic components. By using the complimentary absorption spectra of several materials, these tandem cells can increase overall efficiencies.

Tandem Solar Cells and Multi-Junction Technology

Tandem solar cells have showed great potential in increasing efficiency since they stack many layers of various photovoltaic materials. Consider the possibility of combining perovskite solar cells with silicon or other high-efficiency materials to produce a composite structure that incorporates a broader spectrum of the solar spectrum. Laboratory efficiencies exceeding 30% have already been attained with this technology, indicating the possibility of much greater performance in the future. In laboratory environments, multi-junction solar cells have exceeded 40% efficiency by incorporating multiple semiconductor layers with varying bandgaps. Even though these cells are mostly utilised in specialised applications, such as space missions,

they have a lot of promise for terrestrial uses as well, provided that production methods can be scaled up and costs can be lowered.

Challenges and Limitations

Numerous obstacles continue to impede the widespread adoption of solar cell technologies, despite their substantial progress.

- **Cost and Scalability:** While silicon-based solar cells have become more affordable, emerging technologies such as tandem solar cells, OPVs, and perovskites find it difficult to scale up production without sacrificing price. Large-scale commercialisation of these technologies is still hampered by high material prices and intricate production procedures. Any solar technology's ability to lower production costs while preserving or increasing efficiency is essential to its success.
- **Stability and Durability:** Long-term stability is a problem for many new solar cell technologies, especially perovskite and OPV devices. The materials may deteriorate as a result of exposure to external elements including heat, moisture, and UV radiation, shortening their lifespan and efficiency. For these technologies to be successfully commercialised, these stability difficulties must be resolved.
- **Recycling and Sustainability:** Effective recycling techniques are needed to recover important elements like silicon, silver, and indium due to the growing use of solar panels. The development of appropriate methods for recycling obsolete solar panels is necessary to ensure "the long-term sustainability of solar energy systems" and reduce the environmental impact.

LITERATURE REVIEW

(Ogundipe et al., 2024) [18] gives a summary of these developments and how they will affect solar energy in the future. In addition, the efficiency of conventional silicon-based PV cells has been enhanced by advancements in "passivated emitter rear cell (PERC) technology and bifacial solar cells", which absorb light from both surfaces. New materials, such as perovskite solar cells, have revolutionised the industry by promising high efficiency and low production costs. Lightweight and flexible solar panels are made possible by perovskite materials' flexibility and simplicity of manufacture. Additionally, developments in quantum dot solar cells and organic photovoltaics (OPVs) are helping to create flexible, semi-transparent, and

aesthetically beautiful PV panels, broadening their range of uses. In addition, the efficiency and dependability of solar energy consumption are being enhanced by advancements in energy storage technologies, including high-capacity batteries and hybrid systems, which render it a viable option for residential, industrial, and commercial applications. Together, these developments lower the price of solar energy, make it more accessible, and encourage its use globally.

(Dada & Popoola, 2023) [5] gives a summary of current developments in solar photovoltaic material research and development. This study examines recent advancements in the field of materials for solar photovoltaic devices. Scalability, stability, and economic viability are among the potential and difficulties related to these materials that are examined. The subject of renewable energy might undergo a significant transformation if new materials for solar photovoltaic systems are developed. The continuous research and technical advancements of scientists and engineers have enabled the development of materials with superior qualities, such as better strength, reduced cost, and increased efficiency. These materials can be utilised to create new, more efficient photovoltaic devices and improve the performance of current solar panels. The use of these materials might have a big impact on the shift to a more ecologically friendly and sustainable energy system. However, problems with scalability, stability, potential environmental effects, and economic viability must be solved before these materials may be utilised widely. Ongoing research on the creation of materials for solar photovoltaic systems is crucial to achieving a sustainable future, despite hopeful advancements in this field.

(Y. Li et al., 2022) [19] The advantages of organic solar cells (OSCs), such as their low cost, flexibility, semitransparency, non-toxicity, and suitability for large-scale roll-to-roll production, have garnered significant attention in recent decades. With cutting-edge device designs and high-performance active layer materials, electrodes, and interlayers, the field of OSCs has made great strides. In particular, the development of active layer materials, such as new donors and acceptors, has greatly enhanced OSCs' power conversion efficiency (PCE). This study delves further into high-performance acceptors, which include polymeric non-fullerene acceptors (NFAs), small molecules, and fullerene derivatives. In the meanwhile, very effective donor materials for OSCs based on fullerene and NFA are also introduced. Recent discoveries in the realm of ternary and tandem OSCs are also covered, driven by the ongoing advancements in donor and acceptor materials.

(Shevaleevskiy, 2020) [20] Nanotechnologies and nanostructured materials are attracting significant attention as the most promising candidates for improving the efficiency of solar energy conversion in "the development of next-generation nanostructured-based perovskite solar cells (PSCs)". Among the recent advancements in perovskite solar photovoltaics that we highlight in this review are the creation of "high-performance perovskite-silicon tandem solar cells, inorganic PSCs with stabilised efficiency, and a new generation of PSCs for low lighting conditions that opens great possibilities for indoor applications". The creation of novel, effective photoelectrodes for PSCs based on metal oxides with extremely high band gaps is also given specific consideration.

(Almosni et al., 2018) [21] Over the past 10 years, photovoltaic output has expanded from being an outsider to one of the major actors in the global energy revolution, with 1.7% of the world's power coming from solar cells. This progress has been greatly aided by advancements in production techniques and materials. Nevertheless, many challenges remain before photovoltaics can generate inexpensive, abundant, and clean energy. Here, we examine this line of inquiry, concentrating on the findings from NextPV, a collaboration between France and Japan that focuses on potential solar cell technology. The focus of the partnership was on efficient photovoltaic technologies such as "multijunction, ultrathin, intermediate band, and hot-carrier solar cells", as well as printable solar cell materials such as colloidal quantum dots.

RESEARCH GAP

Although considerable advancement has been made in solar cell technologies, a number of research gaps are still in line with the objectives stated. Although the working principles of solar cells have been established well, there is minimal integration of the advanced physical models with real time performance optimization. Historical study gives general overviews but does not readily compare and contrast past and current innovations and efficiency trends. Moreover, despite extensive research on different types of solar cells, there lacks unified assessment of their long-term performance, scalability, and environmental impact. The studies on efficiency enhancement are mainly concentrated on the laboratory scale outcomes with little focus on the large scale real world application. Other issues which lack a comprehensive treatment across all material systems include stability, recyclability, and cost-effectiveness, which point to a lack of more holistic and application-oriented studies.

OBJECTIVE

1. To study the solar cell and its working.
2. To study the Historical development of photovoltaic technology.
3. To study the type of solar cell based on material and technology.
4. To study the Efficiency Improvements and Materials Innovations.
5. To study the Challenges and Limitations in solar cell.

RESEARCH METHODOLOGY

In order to analyse the latest advancements in solar cell physics, including materials, efficiency, and trends, this review study will employ a methodical literature-based approach. The relevant research articles, review papers, and technical reports were found in reputed scientific databases, including Scopus, Web of Science, and Google Scholar. To gain insight into the working principle, history, solar cell types, material developments, efficiency increases and challenges that accompany these developments, the selected studies were critically analyzed. To compare products of various photovoltaic technologies, comparative analysis was conducted to assess the efficiency, costs, stability and scalability of the technologies. It also focused on determining the technological trends and research gaps. The methodology guarantees a thorough and current synthesis of progress and innovation in solar photovoltaic systems.

DISCUSSION

The review of recent progress in solar cell physics is a clear indication of a shift in conventional technologies based on silicon to innovative materials that include perovskites, organic photovoltaics and quantum dots. Although crystalline silicon has remained the dominant type of silicon due to its reliability, cost-efficiency and simplicity to fabricate, emerging technologies have offered certain advantages in terms of flexibility, cost-effectiveness, and ease of manufacture. Innovations like PERC technology, tandem structures, and multi-junction cells have made significant improvements in efficiency as they have made better use of the solar spectrum. But, issues to do with long-term stability, environmental impact, and scalability remain, especially in more recent material classes such as perovskites and OPVs. Nanotechnology and advanced fabrication techniques have also improved performance, but there is still a barrier to commercialization. All in all, the discussion has shown that despite the promising prospects of technological advancements, there is a need to balance between efficiency, durability and cost to enable the widespread adoption of solar energy systems.

CONCLUSION

Finally, the review demonstrates a significant advancement in the field of solar cell physics, especially in the contexts of material innovations, efficiency improvement, and new technological trends. Conventional crystalline silicon solar cells remain a dominant force in the market due to their maturity and reliability whereas next-generation technologies like perovskite, organic, and quantum dot solar cells have a lot of potential in their future applications. Such innovations as the architecture of devices, such as tandem and multi-junction cells, have extended efficiency limits beyond conventional limits. Nevertheless, a number of issues such as stability, scalability, environmental issues, and cost will have to be resolved to make large-scale deployment and make it sustainable. It is necessary that more studies be conducted to improve the durability of materials, come up with cost-effective manufacturing procedures and improve on the recycling process. All in all, solar energy will continue to be a significant solution in meeting global energy demands and continued development of solar cell physics will be vital in ensuring a sustainable energy future

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