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A Review on Advancements in Solar Cell Technology for Sustainable Energy in India @2047"

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Abstract

The growing demand for energy around the world and worries about the environment mean that we need to switch to more sustainable energy sources. Solar energy is becoming a key part of India's India @2047 vision. This review offers a thorough examination of progress in photovoltaic technologies, encompassing silicon, thin-film, and novel perovskite solar cells. Conventional silicon solar cells are the most common type on the market. They work 18–22% of the time. Thin-film technologies like cadmium telluride (CdTe) and copper indium gallium selenide (CIGS) work 15–20% of the time, but they are more flexible materials. Perovskite solar cells have made a lot of progress in a short amount of time. Their efficiencies are over 25%, and their tandem configurations are over 30%. This shows that they could be useful in the next generation applications. Solar capacity in India has grown a lot, reaching over 70 GW, and the cost of electricity has dropped to ₹2–3 per kWh, making solar one of the cheapest sources of energy. Solar energy is also good for the environment because it cuts down on CO_2 emissions by 0.8–1.0 kg for every kWh of electricity it makes. There are still problems, though, like high installation costs (₹40,000–₹60,000 per kW), limited energy storage (150–300 USD per kWh), and material degradation (0.5–0.8% per year). Future advancements such as tandem cells, nanotechnology, smart grids, and electric vehicle integration are anticipated to improve efficiency and scalability. In general, solar energy is likely to be very important for India to reach its goal of sustainable and energy-secure development by 2047.

Keywords: *Solar Energy, Photovoltaics, Sustainability, Perovskite Solar Cells, Renewable Energy*

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Introduction

The world's energy landscape is changing a lot because of rising energy demand and worries about the environment. The International Energy Agency says that global primary energy use has gone up by more than 25% in the last 20 years and is expected to go up by almost 50% by 2050 if current policies stay in place. Even though this growth has happened, fossil fuels still make up almost 80% of the world's energy use, which releases a lot of greenhouse gases. In the past few years, the amount of CO_2 in the atmosphere has gone over 420 parts per million (ppm). This has caused climate change, global warming, and environmental problems like extreme weather and rising sea levels. India is one of the fastest-growing economies in the world, and it has to deal with two problems at once: meeting rising energy needs and protecting the environment. According to the Ministry of New and Renewable Energy, the demand for electricity is expected to rise by 5–6% each year, which could mean that it will double by 2040. India's installed power capacity is already over 420 GW, and a large part of it still comes from coal-based thermal energy. This raises concerns about carbon emissions and the long-term security of the country's energy supply. Because of this, renewable energy sources are now necessary. Solar energy is one of the best options because of India's good geography. The country gets 4 to 7 kWh/m²/day of solar energy on average and has almost 300 sunny days a year. The National Solar Mission and other government programs aim to reach about 280 GW of solar capacity by 2030. This shows that there is strong policy support for the transition to clean energy. The photovoltaic effect is what makes solar cells operate. It uses semiconductor materials to turn sunlight directly into electricity. Silicon-based solar cells, especially monocrystalline silicon, are the most common type on the market. They work at 18–22% efficiency [1,2]. But high processing temperatures (1000°C) and the expense of materials have made researchers look for other solutions. Cadmium telluride (CdTe), copper indium gallium selenide (CIGS), and new materials like copper zinc tin sulfide (CZTS) are all examples of thin-film materials. They all have benefits, such as using less material, being more flexible, and being 15–22% more efficient. The remarkable optoelectronic capabilities of hybrid organic–inorganic perovskite materials, such formamidinium lead iodide ($FAPbI_3$) and methyl ammonium lead iodide ($CH_3NH_3PbI_3$), have transformed photovoltaic research in recent years.

These materials have tunable band gaps (1.2–2.3 eV), large carrier diffusion lengths (>1 μm), and strong absorption coefficients ($>10^1$ cm^{-1}). As a result, perovskite solar cells' efficiency has rapidly increased, rising from 3.8% in 2009 to over 25% in more recent research. Additionally, tandem solar cells that combine crystalline silicon and perovskites have shown efficiency beyond 30%, which are close to theoretical limitations.

In light of India's long-term development objective, India @2047, the development of photovoltaic technology is both a scientific challenge and a socioeconomic requirement **[3, 4].** By facilitating decentralized power generation, lowering emissions, and supporting applications like solar irrigation systems, rooftop photovoltaics, and electric vehicle integration, solar energy is anticipated to play a key part in accomplishing sustainability goals.

Notwithstanding these developments, issues such material instability, efficiency deterioration, large-scale production limitations, and energy storage integration continue to be crucial. Multidisciplinary efforts in materials research, device engineering **[5]**, and system optimization are needed to address these problems. Thus, the goal of this study is to present a thorough examination of current developments in solar cell technology, concentrating on next-generation materials like perovskites **[6]** and thin-film devices, while assessing their performance, scalability. With an emphasis on next-generation materials like perovskites and thin-film devices, this review seeks to offer a thorough analysis of recent developments in solar cell technologies while assessing their performance, scalability, and contribution to India's 2047 sustainable energy goals.

Discussion

1. Basic Principles of Solar Cells

The direct conversion of solar light into electrical energy is made possible by solar cells, which function on the basis of semiconductor physics and optoelectronic interactions. The photovoltaic effect, in which incoming photons transfer their energy to charge carriers within a semiconductor material, is the fundamental mechanism behind this process. Photons with energy larger than or equal to the material's band gap drive electrons from the valence band to the conduction band when light with enough energy interacts with a solar cell, creating electron–hole pairs **[5]**. An incident photon's energy is determined by:

$$E=h\nu \quad (1)$$

where h is Planck's constant and ν is the frequency of the incident radiation. The range of photons that can be absorbed in practical solar cell materials is largely dependent on the band gap. For example, the market leader in photovoltaics, crystalline silicon, has a band gap of about 1.1 eV, which enables it to absorb a large amount of the solar spectrum. On the other hand, new materials like hybrid perovskites have adjustable band gaps between 1.2 and 2.3 eV, which allow for improved spectrum matching and increased theoretical efficiency. Because photon energies in the sun spectrum range from about 0.5 eV to 3.5 eV, band gap engineering is essential to the design of solar cells.

The p–n junction **[5]**, which is created by combining p-type and n-type semiconductor areas, is a crucial structural element of the majority of solar cells. In silicon, the n-type region is doped with donor impurities like phosphorus, which provide surplus electrons, whereas the p-type region is usually doped with acceptor impurities like boron, which results in a large concentration of holes. The diffusion of charge carriers causes a depletion layer to form at the interface of these two regions, resulting in an internal electric field that is usually in the order of 10^4 to 10^5 V/m across a region that is roughly 0.1 to 1 μm thick. The separation and directed motion of photo-generated carriers depend on this inherent electric field.

Electron-hole pairs are created inside the semiconductor when photons are absorbed. The material's absorption coefficient has a significant impact on how effective this technique is. For instance, silicon has an absorption coefficient between 10^3 and 10^4 cm^{-1}, hence in order to obtain effective absorption, relatively thick wafers (usually 150–200 μm) are needed. On the other hand, materials with greater absorption coefficients, including copper indium gallium selenide (CIGS) and cadmium telluride (CdTe), enable efficient operation in thin-film setups with thicknesses as low as 1-2 μm. With absorption coefficients as high as 10^5 cm^{-1}, perovskite materials like $CH_3NH_3PbI_3$ **[6]** allow for effective light harvesting in layers as thin as 500 nm. Furthermore, a key factor in determining device performance is the diffusion length of charge carriers; silicon usually has diffusion lengths of 100–300 μm, whereas perovskites and CIGS have values in the range of 1–10 μm and 1–5 μm, respectively.

Light absorption is the first step in a solar cell's operation, which is followed by carrier excitation, separation, transport, and collection. Photons are absorbed in the active layer of the cell when sunlight strikes it, producing excited electrons and matching holes. The internal electric field in the depletion area then drives electrons toward the n-type side and holes toward the p-type side, separating these charge carriers. In addition to ensuring that carriers contribute to electrical current, this separation reduces recombination losses. The carriers are then collected at the appropriate electrodes after being moved through the semiconductor by drift and diffusion processes **[7, 8]**. To enable effective charge extraction and lower recombination, further layers like electron transport layers (such as TiO_2 and SnO_2) and hole transport layers are added to advanced solar cell layouts.

Open-circuit voltage (Voc), short-circuit current density (Jsc), and total power conversion efficiency are common metrics used to describe a solar cell's performance. Because of their advantageous electrical characteristics, perovskite solar cells may reach higher voltages of roughly 1.0–1.2 V, whereas conventional silicon solar cells typically have Voc values in the range of 0.5–0.7 V. Similarly, current densities of 30–40 mA/cm^2 can be seen in high-performance devices. Together, these factors determine the device's efficiency; commercial silicon solar cells achieve efficiencies of 18–22%, thin-film methods reach 15–20%, and laboratory-scale perovskite devices surpass 25%. Thus, the overall performance and efficiency of solar cells are determined by the interaction of material qualities, device architecture, and basic physical processes.

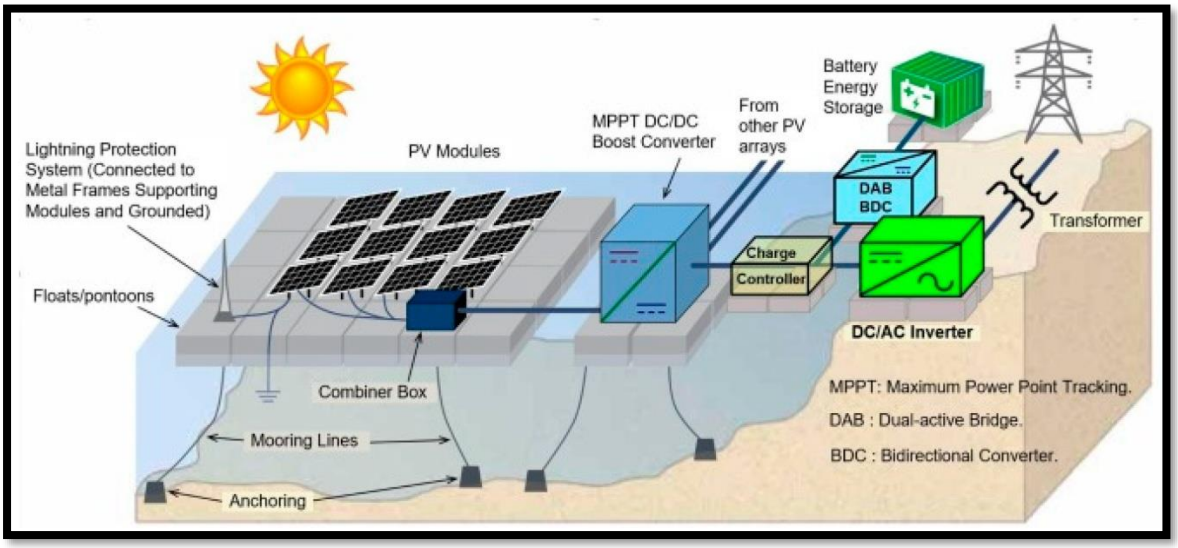

Fig.1: Architectural representation of FPV system. (REF: A Comprehensive Review of Solar Photovoltaic (PV) Technologies, Architecture, and Its Applications to Improved Efficiency).

An architectural representation of a **Floating Photovoltaic (FPV) system** [7, 8], as shown in **Fig. 1**, illustrates the integrated arrangement of solar energy generation and floating infrastructure on a water body, where photovoltaic modules are mounted on buoyant pontoon structures and interconnected through DC cabling to combiner boxes, which aggregate the generated power before feeding it into inverters for DC-to-AC conversion; the system is stabilized using a mooring and anchoring mechanism that secures the floating platform against water movement and level variations, while the converted electrical power is transmitted to the onshore grid via underwater or floating cables, and a monitoring and control unit continuously supervises system performance, ensuring efficient, reliable, and safe operation in the aquatic environment.

2 Types of Solar Cells

Conventional silicon-based solar cells, thin-film solar cells, and newly developed perovskite solar cells are the three main categories into which solar cell technologies can be roughly divided. These three categories differ in terms of material composition, fabrication methods, efficiency, cost, and long-term performance.

Fig.2: Proposed solar cell structure (REF: 10.9734/bpi/rdst/v3/2118B).

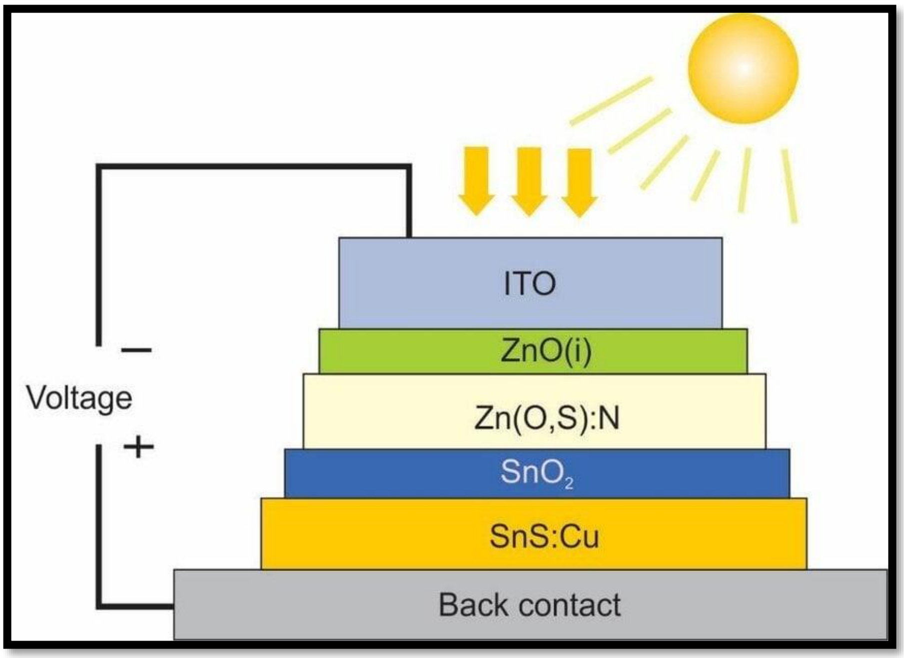

Fig.2 shows layered **thin-film solar cell architecture** designed to efficiently absorb sunlight and convert it into electrical energy through a sequence of functional semiconductor layers. At the top, the **ITO (Indium Tin Oxide)** layer acts as a transparent conducting electrode, allowing sunlight to pass through while collecting charge carriers. Beneath it, the **ZnO(i)** intrinsic layer serves as a buffer to reduce defects and improve interface quality, followed by the **Zn(O,S):N** layer, which functions as a tunable window or absorber interface layer to optimize band alignment. The **SnO_2 layer** operates [9] as an electron transport layer, facilitating efficient movement of electrons while

blocking holes, and below it, the **SnS: Cu layer** acts as the primary absorber where photons generate electron–hole pairs. At the bottom, the **back contact** provides electrical grounding and completes the circuit. As indicated in the figure, incident sunlight enters from the top, generating charge carriers that are separated and driven by the built-in electric field, producing a voltage across the external circuit (shown on the left), thereby enabling power extraction.

1 Silicon Solar Cells

Because of its maturity, stability, and comparatively high efficiency, silicon-based solar cells account for over 90% of installations in the global photovoltaic market. They are primarily divided into two types: monocrystalline and polycrystalline. Because of their highly organized crystal structure, monocrystalline silicon cells made with techniques like the Czochralski process **[10]** have excellent electronic characteristics and efficiencies of 20–24% in commercial modules and more than 26% in experimental settings. Additionally, these cells exhibit longer carrier diffusion lengths (200–500 μm), which enhances charge collection. However, their production requires energy-intensive procedures (1000°C) and high-purity silicon, which results in a higher cost of roughly 0.25–0.35 USD/W. Although polycrystalline silicon cells made using less complicated casting methods are more affordable (0.20–0.30 USD/W), they have grain boundary flaws that raise recombination losses. As a result, their efficiencies are usually between 15 and 18%. In addition to having restrictions on flexibility and material usage, both silicon methods require thick wafers (150–200 μm) and show temperature-related efficiency losses of roughly −0.4 to −0.5% per °C.

2 Thin-Film Solar Cells

Second-generation technology are represented by thin-film solar cells, which use less material and allow for flexible, lightweight designs by depositing semiconductor layers (1-2 μm thick) onto substrates like glass, metal, or flexible polymers. Cadmium telluride (CdTe), copper indium gallium selenide (CIGS), and new substances like amorphous silicon (a-Si) and copper zinc tin sulfide (CZTS) **[9]** are notable materials. CdTe solar cells have a nearly ideal band gap (1.45 eV), commercial efficiency of 17–19%, and experimental values as high as 22%. Their low production costs (0.20 USD/W) and high absorption coefficient ($>10^5$ cm^{-1}) enable effective operation with little thickness. But concerns about tellurium scarcity and cadmium toxicity still exist. With variable band gaps (1.0–1.7 eV), CIGS solar cells have demonstrated efficiencies of 15–18% in commercial settings and 23–24% in experimental conditions. They also function effectively in low light, but they need difficult manufacturing procedures and rare materials like gallium and indium.

With reduced temperature coefficients (−0.2% per °C), thin-film technologies provide advantages such flexibility, lightweight structure, and improved high-temperature performance. Because of these characteristics, they can be used for curved surfaces, portable systems, and building-integrated photovoltaics (BIPV). Long-term stability and reduced efficiency are still problems, though.

3 Perovskite Solar Cells

Perovskite solar cells' remarkable optoelectronic qualities and quick efficiency gains have made them a game-changing technology. The common formula for these materials is ABX_3, where A stands for organic cations like $CH_3NH_3^+$ (MA^+) or formamidinium (FA^+), B is usually Pb^{2+} or Sn^{2+}, and X contains halides like I^-, Br^-, or Cl^-. $CH_3NH_3PbI_3$ and $FAPbI_3$ are typical instances. In recent laboratory-scale systems, the efficiency of perovskite solar cells has increased dramatically from 3.8% in 2009 to over 25–26%. Silicon tandem designs have shown efficiencies over 30%, which are higher than that of single-junction cells. High performance with thin active layers (500 nm) is made possible by these materials' tunable band gaps (1.2–2.3 eV), long carrier diffusion lengths (1–10 μm), and high absorption coefficients ($>10^5$ cm^{-1}).

One of the main benefits of perovskites is that they can be made at low temperatures (<150°C) utilizing solution-based methods such spin coating, printing, or vapour deposition, which lowers prices to about 0.15–0.25 USD/W. However, stability is still a major concern because these materials deteriorate when exposed to heat, moisture, oxygen, and UV light. In ambient settings, un-encapsulated devices might lose efficiency in a matter of weeks. Furthermore, research on lead-free substitutes, such as tin-based perovskites **[11]** (e.g., $FASnI_3$), which presently show lower efficiencies of 10–15%, is prompted by the environmental concerns raised by the presence of lead.

3 Recent Advancements in Solar Cell Technology

Tandem solar cells, nanotechnology, bifacial modules, and artificial intelligence integration are examples of recent developments in photovoltaic technologies that aim to improve performance, lower costs, and surpass efficiency restrictions. These advancements are intended to improve system-level efficiency, charge transport, and light absorption.

A significant advancement in exceeding the Shockley–Queisser limit (33%) **[12]** of single-junction devices is represented by tandem solar cells, especially silicon–perovskite combinations. Low-energy photons are absorbed by the silicon bottom cell (band gap 1.1 eV) in these structures, while high-energy photons are captured by the perovskite top layer (band gap 1.6–1.8 eV), which is made of materials like $FAPbI_3$, $CsPbI_3$, and mixed-halide perovskites (e.g., $FA_{1-x}MA_xPb(I_{1-y}Br_y)_3$). This design enhances spectrum utilization while lowering thermalization losses. Although there are issues with interfacial stability, recent tandem systems have attained efficiencies surpassing 30–33%, with some instances approaching ~35%.

Because nanotechnology **[13]** makes it possible to regulate material properties at the nanoscale, solar cell performance has been greatly improved. Spectral absorption is enhanced by variable band gaps (0.7–2.0 eV) offered by quantum dots like PbS, CdSe, and newly developed perovskite quantum dots ($CsPbBr_3$). Ag, Au, and Al are examples of plasmonic nanoparticles that improve light trapping and can boost absorption by 20–30%. Furthermore, graphene-based layers, TiO_2, ZnO, SnO_2, and other nanostructured materials are frequently employed as conductive

or electron transport layers to increase carrier mobility and lower recombination losses. Although these methods improve productivity and use less material, scalability and long-term stability continue to be major obstacles.
By collecting light from both front and rear surfaces, bifacial solar panels have become an effective substitute for traditional modules. Heterojunction (HJT) structures and technologies like PERC and Topcon are frequently used. Energy benefits from these modules can range from 10% to 20%, and in high-reflectivity situations, they can reach >25%. They are appropriate for large-scale installations because to their increased longevity and endurance. Machine learning and artificial intelligence (AI) are being used more and more to optimize solar energy systems. Maximum power point tracking (MPPT), fault detection, and solar irradiance forecasts all employ AI approaches. While AI-based MPPT systems improve energy extraction by 5–10% under variable conditions, machine learning models can increase power forecast accuracy by 20–30%. All things considered, these developments show a shift toward intelligent, economical, and high-efficiency (>30%) solar energy systems. It is anticipated that the use of cutting-edge materials, creative architectural designs, and digital technologies will boost solar adoption and sustainable energy objectives, especially in light of India's 2047 transition.

Solar Energy in India

With solar energy playing a major role in its sustainable development strategy, India has become a global leader in renewable energy. Solar deployment has been further increased by major government efforts like the Jawaharlal Nehru National Solar Mission. The aim was first set at 20 GW by 2022, but it was then increased to 100 GW, including 40 GW rooftop capacities, and further aligned with a more general target of 280 GW solar capacities by 2030 within a 500 GW non-fossil fuel goal. Adoption has been bolstered by other initiatives including PM-KUSUM, solar parks, and rooftop subsidies, especially in decentralized energy systems and agriculture. India's solar capacity increased at a rate of more than 25% per year, from 2.6 GW in 2014 to over 70 GW by 2023. This rise has been greatly aided by large solar parks in regions like Gujarat and Rajasthan, which frequently have capacities greater than 1 GW. In addition to economies of scale and better production techniques, scientific advancements in photovoltaic materials including monocrystalline silicon, CdTe, CIGS, and upcoming perovskites have caused solar rates to drastically drop from ₹17/kWh in 2010 to less than ₹2.5/kWh **[12].**
Through decentralized systems like solar-powered irrigation pumps, mini-grids (10–500 kW), and solar residential systems, solar energy has also enhanced rural electrification. By installing more than 2 million solar pumps, the PM-KUSUM program seeks to lessen reliance on fuel. In rural and semi-urban regions, rooftop solar systems (1–10 kW) are becoming more and more popular since they improve dispersed generation and lower transmission losses. Despite these successes, a number of obstacles still exist. Land-use disputes arise because large-scale solar installations need a substantial amount of land (4–5 acres per MW). With lithium-ion batteries costing between $150 and $300 USD per kWh, energy storage continues to be a significant constraint, driving up system costs. Smart grid technology and sophisticated infrastructure are also necessary for the grid integration of intermittent solar energy. Economic and supply chain issues are also brought about by rooftop systems' upfront installation costs (between ₹40,000 and ₹60,000 per kW) and reliance on imported components like silicon wafers, silver connections, and EVA wrap. Long-term growth is further impacted by policy uncertainties and performance degradation (0.5–0.8% yearly). In conclusion, strong regulatory support, falling costs, and advances in materials and technology have all contributed to the rapid expansion of solar energy in India. Even while it has greatly improved energy access and sustainability, long-term goals in line with the India @2047 vision will require addressing issues with land, storage, infrastructure, and cost.

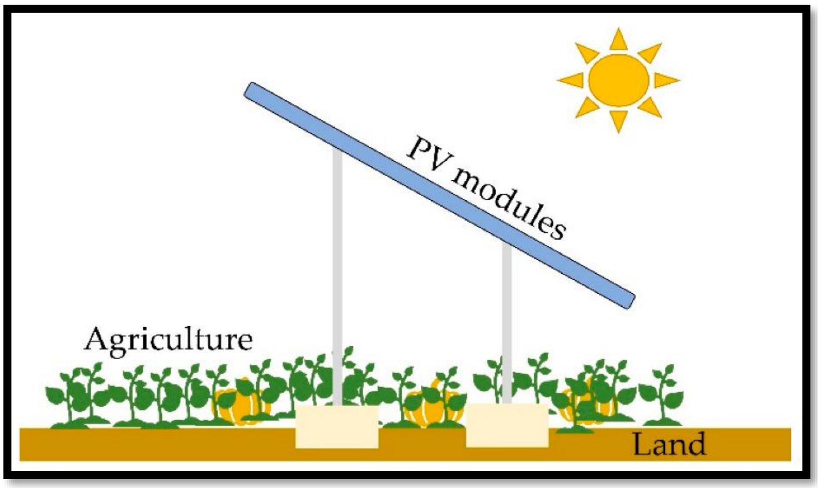

Fig.3: Conceptual representation of Agrivoltaics (REF: A Comprehensive Review of Solar Photovoltaic (PV) Technologies, Architecture, and Its Applications to Improved Efficiency).

Fig.3 presents a conceptual representation of an **agrivoltaic system [14]**, where photovoltaic (PV) modules are installed above agricultural land to enable the simultaneous use of land for both energy generation and crop cultivation. As shown in Fig. 3, the PV panels are mounted on elevated support structures at an inclined angle to maximize solar irradiance capture while allowing sufficient sunlight to reach the crops grown beneath. This dual-use configuration creates a partially shaded microclimate that can reduce water evaporation and protect plants from excessive heat stress, potentially improving crop yield and water efficiency. At the same time, the solar modules generate electricity that can be utilized for farm operations or fed into the grid, thereby enhancing overall land productivity and sustainability.

5 Sustainability Impact

By decreasing reliance on fossil fuels and greenhouse gas emissions, solar energy is essential for fostering environmental sustainability. When compared to coal-based power generation, photovoltaic systems can typically lower 0.8–1.0 kg of CO_2 per kWh; a 1 MW solar plant may offset about 1,200–1,500 tonnes of CO_2 yearly. Solar power is a clean and environmentally beneficial alternative to traditional sources because it doesn't emit any hazardous emissions like SO_2, NO_X, or particulate matter. By increasing energy availability and reducing climate change, solar energy also contributes to international frameworks like the United Nations Sustainable Development Goals (SDGs), especially SDGs 7 and 13. Solar deployment improves rural electricity and lessens environmental deterioration in India. In terms of employment, the industry creates roughly 20–25 jobs per MW during installation and 3–5 jobs per MW during operation and maintenance. Additionally, the levelized cost of power has dropped to ₹2–3 per kWh due to the dropping costs of photovoltaic technologies including silicon, CdTe, CIGS, and perovskites, making solar energy one of the most economical. As a result, solar energy supports both sustainable economic growth and environmental preservation.

6 Challenges and Limitations

Solar energy has a number of technical and financial difficulties despite its benefits. The expensive initial installation cost, rooftop systems cost between ₹40,000 and ₹60,000 per Kw as well as additional costs for inverters, mounting structures, and grid connectivity components are a significant obstacle. Because solar power is intermittent and only produces electricity during the day, energy storage is still a major problem. At 150–300 USD per kWh, battery technologies especially lithium-ion and new alternatives like solid-state and sodium-ion batteries significantly raise system costs.

Because variations in irradiance brought on by clouds, dust, and seasonal changes can lower output by 10–25%, weather dependence also has an impact on system reliability. Furthermore, efficiency losses of 0.3–0.5% per °C are caused by high working temperatures. Material deterioration also affects long-term performance; standard silicon panels deteriorate at a rate of 0.5–0.8% per year, which over a 25-year period results in an efficiency loss of 15–20%. Due to their sensitivity to heat, moisture, and UV light, advanced materials like organic photovoltaics and perovskites (such as $CH_3NH_3PbI_3$ and $FAPbI_3$) have even more stability issues. Developments in encapsulating materials (such as EVA and POE), better device topologies, and reliable energy storage methods are needed to overcome these constraints.

Future Scope (India @2047)

Achieving energy security, sustainability, and technical advancement by 2047 is directly related to the future of solar energy in India. The deployment of smart solar grids, which incorporate digital technology like sensors, real-time monitoring, and automated control systems for effective energy management, is a significant advancement. By using demand-response mechanisms and smart meters, these systems can increase overall efficiency by 10–15% while reducing transmission losses, which are now 15–20%. Furthermore, grid-scale storage options with capacities ranging from 100 MWh to several GWh, such as lithium-ion, sodium-ion, and flow batteries, are crucial for controlling high solar penetration and guaranteeing dependability. Another important development is the integration of solar energy with electric cars (EVs). EV energy requirements of 15–20 kWh per charge can be satisfied by solar-powered charging stations, which are usually supported by 5–20 kW rooftop systems. EVs can operate as dispersed storage units thanks to technologies like vehicle-to-grid (V2G), which improves grid flexibility. By 2047, this integration might cut emissions associated with transportation by 30–40% **[15].**

Efficiency gains will be further fuelled by developments in photovoltaic materials. It is anticipated that next-generation technologies like organic photovoltaics, quantum dot solar cells (such PbS and $CsPbBr_3$), and perovskite–silicon tandem cells would reach efficiencies higher than 30–35%. Although current efficiencies are still only about 10–15%, research into lead-free perovskites like $FASnI_3$ and $CsSnI_3$ is still ongoing. To improve durability and light absorption, graphene layers, nanostructured coatings, and anti-reflective materials (such Si_3N_4) are also being investigated. Applications like wearable technology and building-integrated photovoltaics (BIPV) are made possible by flexible and transparent solar cells. For widespread implementation, policy and regulatory assistance will be essential. The goal of programs like public-private partnerships, subsidies, and production-linked incentives (PLI) is to boost domestic manufacturing and lessen reliance on imports of commodities like silicon wafers and silver contacts. Simplified regulations for storage installations, grid integration, and land usage are also required. India is expected to reach solar capacity of 400–500 GW by 2047 with continued technology and regulatory developments, making solar energy a key component of its energy infrastructure. In conclusion, developments in smart grid integration, EV coupling, next-generation materials, and supportive policy frameworks are critical to the future of solar energy in India. These developments will improve efficiency, dependability, and sustainability in line with the India @2047 goal.

Conclusion

In light of rising worldwide energy demands and India's sustainability objectives, the quick development and expanding importance of solar cell technologies have been thoroughly addressed in this paper. According to the analysis, thin-film technologies like CdTe and CIGS offer advantages like reduced material usage and mechanical flexibility, achieving efficiencies in the range of 15–20%, while conventional silicon solar cells, with commercial efficiencies of 18–22%, continue to dominate the market due to their dependability and technological maturity. On the other hand, newly developed perovskite solar cells have shown impressive progress, with tandem configurations above 30% and efficiencies over 25%, suggesting great promise for next-generation photovoltaic applications. Additionally, it has been demonstrated that solar energy greatly lowers carbon emissions roughly 0.8–1.0 kg of CO_2 are avoided for every kWh of electricity generated thus promoting environmental sustainability. Due to favourable government policies, falling energy prices (as low as ₹2–3 per kWh), and rising usage in both urban and rural areas, solar capacity in India has grown quickly to over 70 GW. Large-scale adoption is still hampered by issues including high initial installation costs (₹40,000–₹60,000 per kW), energy storage restrictions (150–300 USD per kWh), and performance deterioration brought on by environmental factors (0.5–0.8% yearly). Future developments that are anticipated to improve the efficiency, dependability, and scalability of solar systems include tandem solar cells, nanotechnology, smart grid integration, and coupling with electric cars. India has the potential to reach solar capacity surpassing 400–500 GW by 2047 with consistent technology improvements and strong regulatory backing, establishing solar energy as a key component of its future energy infrastructure. To overcome current obstacles and fully achieve the potential of solar energy, ongoing innovation in materials, device engineering, and system integration will be crucial, guaranteeing a clean, sustainable, and energy-secure future for both India and the world community.

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