

Advancement in Solar Energy: A Comprehensive Study

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Abstract—This paper seeks to explore the recent advancements made in solar power technology in detail. The last couple of decades have seen solar energy rise to popularity as one of the most promising renewable sources which can meet the demands for energy globally in a green way. The review investigates the improvements in photovoltaic cells, advancements in concentrated solar power systems and covering emerging trends such as solar paint and fabrics. It discusses the progress of each modality, how the devices work, factors that can cause efficiency improvement, and the fields where it can be employed. Furthermore, the paper discusses the challenges garnered by these technologies as well the prospects of such technologies in aiding the transition towards greener energy sources.

Keywords—solar, energy, renewable energy, sustainable development.

I. INTRODUCTION

Background: The Sun has long been revered as a source of life on Earth since ancient times. With the advent of the industrial age, we began to recognize sunlight as a viable energy source. India is blessed with significant solar energy potential, with around 5,000 trillion kWh of solar energy falling on the country each year, and most regions receiving 4-7 kWh per square meter daily [1]. Solar photovoltaic power can be efficiently harnessed, offering vast scalability across India. Solar energy also allows for distributed power generation and enables quick capacity expansion with shorter lead times. Off-grid, decentralized, and low-temperature applications are particularly beneficial for rural areas, supporting power, heating, and cooling needs in both rural and urban settings. From the perspective of energy security, solar energy is the most reliable source due to its abundant availability. In theory, capturing just a small portion of the total incident solar energy could fulfill the entire nation's power demand. In recent years, solar energy has made a noticeable impact on India's energy landscape. Decentralized and distributed solar applications have improved the lives of millions in Indian villages by addressing their cooking, lighting, and other energy needs in an eco-friendly way. The social and economic advantages include reducing the burden on rural women and girls who collect firewood over long distances and cook in smoky kitchens, lowering the risk of lung and eye diseases, creating jobs at the village level, and enhancing the overall standard of living while fostering economic activities in rural areas. Additionally, the solar energy sector has become a key contributor to grid-connected power generation in India. It aligns with the government's focus on sustainable development, playing a crucial role in meeting the country's energy demands and ensuring energy

security. The National Institute of Solar Energy (NISE) has estimated India's solar potential to be around 748 GW, based on the assumption that 3% of the country's wasteland could be covered with solar PV modules. Solar energy holds a prominent position in India's National Action Plan on Climate Change, with the National Solar Mission (NSM) being one of its key initiatives. Launched on January 11, 2010, the NSM represents a significant effort by the Government of India, with active involvement from the states, to promote ecologically sustainable growth while addressing the country's energy security challenges. It also plays a crucial role in India's contribution to global efforts to combat climate change. The mission's goal is to position India as a global leader in solar energy by rapidly creating favorable policy conditions for the widespread adoption of solar technology across the nation. This aligns with India's Nationally Determined Contributions (NDCs), aiming to achieve about 50% of its total installed electric power capacity from non-fossil fuel sources and to reduce the emission intensity of its GDP by 45% from 2005 levels by 2030.

II. SOLAR PHOTOVOLTAIC CELL

Solar photovoltaic (PV) cells are devices that directly convert sunlight into electricity. This process is known as the photovoltaic effect. When sunlight strikes the surface of a PV cell, it dislodges electrons, creating a flow of electrical current.

Components of a Solar Photovoltaic Cell:

Semiconductor Material: This is typically made of silicon; this material is the heart of the cell. It is doped with impurities to create a p-n junction.

Anti-Reflective Coating: This coating reduces light reflection, increasing the amount of sunlight absorbed by the cell.

Contact Layers: These layers collect the generated electricity and transport it to the external circuit.

Encapsulation: A protective layer that shields the cell from the environment.

In this section, we will explore four, main types of solar PV cells.

Traditional Silicon Solar Cells: Traditional silicon solar cells are the most widely used type of photovoltaic (PV) cell, accounting for most of the global solar market. These cells are made from silicon, a semiconductor material that is abundant and relatively inexpensive. There are mainly two types of traditional silicon solar cell. Monocrystalline Silicon are made from a single crystal of silicon, resulting in high efficiency and long lifespan. Polycrystalline Silicon are made from multiple silicon crystals, which can be less efficient but also less expensive to produce. These cells operate based on

the photovoltaic effect, where sunlight excites electrons in the silicon semiconductor, generating an electric current.

Thin-Film Solar cell: Thin-film solar cells are like the lightweight, flexible cousins of traditional solar cells. They're made from super-thin layers of materials, making them easier to install in different places. Thin-film technologies offer advantages in terms of lower manufacturing costs and potential for large-scale production, although they generally exhibit lower efficiency compared to silicon-based cells [3].

Perovskite solar cells: Perovskite solar cells are a relatively new type of solar cell that have gained significant attention due to their rapid efficiency improvements and low manufacturing costs. These cells are made from perovskite materials, a class of crystalline compounds with a specific atomic structure. Perovskite compounds, such as methylammonium lead iodide ($\text{CH}_3\text{NH}_3\text{PbI}_3$), exhibit excellent light-absorption properties and can be solution-processed at low temperatures. Perovskite compounds, such as methylammonium lead iodide ($\text{CH}_3\text{NH}_3\text{PbI}_3$), exhibit excellent light-absorption properties and can be solution-processed at low temperatures. While perovskite solar cells have shown remarkable progress in laboratory settings, challenges remain in terms of stability, scalability, and toxicity of lead-based materials.

Tandem solar cells: Tandem solar cells are a type of photovoltaic (PV) cell that combines multiple layers of different materials, each absorbing a specific range of sunlight wavelengths. This stacking allows them to capture a wider spectrum of sunlight, leading to higher overall efficiency. Tandem solar cells, also known as multijunction or stacked cells. By combining materials with complementary absorption properties, tandem cells can achieve higher efficiencies than single-junction cells. Emerging tandem cell configurations, such as silicon-perovskite tandems, offer the potential for further efficiency improvements while leveraging the manufacturing infrastructure of traditional silicon technology [4].

TABLE I. COMPARISON OF KEY CHARACTERISTICS OF DIFFERENT SOLAR CELL TECHNOLOGIES

Characteristics	Traditional Silicon	Thin-Film	Perovskite	Tandem
Efficiency (%)	15-22	10-15	20-25	25-30
Cost (\$ per watt)	0.30-0.50	0.20-0.40	0.10-0.20	0.40-0.60
Material	Silicon	Various (CIGS, CdTe, a-Si, etc.)	Perovskite Compounds	Combination of different materials
Process	Energy-intensive	Less energy-intensive	Low-cost solution processing	Complex fabrication process

III. CONCENTRATING SOLAR POWER SYSTEMS

Concentrating Solar Power (CSP) systems are a type of solar technology that efficiently harnesses the sun's energy to generate electricity. By utilizing mirrors or lenses to concentrate sunlight onto a receiver, CSP systems can achieve high temperatures and generate electricity on a large scale. CSP systems offer a promising solution for large-scale, renewable electricity generation. As technology advances and costs decrease, CSP is expected to play a crucial role in the transition to a sustainable energy future.

Parabolic Trough Systems: Parabolic trough systems are a type of concentrating solar power (CSP) technology that use parabolic mirrors to focus sunlight onto a receiver tube. This concentrated sunlight heats a working fluid, which is then used to generate steam to drive a turbine. It can achieve high energy conversion rates. It is less affected by cloud cover compared to photovoltaic systems and it is suitable for large-scale electricity production. Parabolic trough systems are among the most mature CSP technologies and have been deployed in various commercial-scale power plants worldwide [5].

Solar Power Tower: Solar power towers are a type of concentrating solar power (CSP) technology that use a field of mirrors to focus sunlight onto a central receiver tower. This concentrated sunlight heats a fluid within the tower, which is then used to generate steam to drive a turbine. Solar power towers offer higher operating temperatures compared to parabolic trough systems, enabling higher efficiency and thermal storage capacity. This technology has been deployed in several utility-scale power plants, demonstrating its potential for large-scale electricity generation. Solar power towers are a promising technology for large-scale renewable electricity generation. They offer the potential for high efficiency, continuous power generation, and thermal energy storage. However, the high capital costs and technical complexity associated with solar power towers remain significant challenges.

Dish Stirling Systems: Dish Stirling systems are a type of concentrating solar power (CSP) technology that use a parabolic dish to focus sunlight onto a Stirling engine. The concentrated sunlight heats a working fluid within the Stirling engine, which converts the heat into mechanical energy to drive a generator. Dish Stirling systems offer high efficiency and the ability to track the sun's movement throughout the day, making them suitable for distributed power generation in remote areas.

TABLE II. COMPARATIVE ANALYSIS OF CONCENTRATED SOLAR POWER TECHNOLOGIES [7]

Characteristics	Parabolic Trough	Solar Power Tower	Dish Stirling Systems
Efficiency (%)	15-20	20-25	25-30
Storage Capability	Thermal energy storage	Thermal energy storage	Limited or no storage
Scalability	Moderate	High	Low
Land Requirement	Moderate	Moderate	Low

Cost-effectiveness	Moderate	Moderate high	Moderate high
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Concentrating Solar Power (CSP) technology has made significant strides in recent years, driven by advancements in various areas:

1. Enhanced Receiver Technologies:

Advanced Materials: The use of high-temperature materials such as ceramics and alloys has improved receiver efficiency and durability.

Improved Heat Transfer: Innovative designs have enhanced heat transfer within receivers, leading to higher energy conversion rates.

2. Advanced Solar Fields:

Precise Tracking Systems: More accurate tracking systems ensure mirrors or lenses follow the sun's movement precisely, maximizing energy capture.

Modular Design: Modular solar fields facilitate easier installation, maintenance, and scalability.

3. Improved Thermal Energy Storage:

Advanced Materials: New materials and technologies have enhanced the efficiency and durability of thermal energy storage systems.

Integrated Storage: The integration of thermal storage systems directly into CSP plants has reduced costs and increased flexibility.

4. Hybrid Systems:

CSP-PV Integration: Combining CSP with photovoltaic (PV) systems can provide a more stable and reliable power supply.

CSP-Biomass Integration: Integrating biomass into CSP plants can enhance energy security and reduce carbon emissions.

5. Cost Reduction:

Economies of Scale: As CSP technology becomes more widespread, economies of scale are driving down costs.

Manufacturing Innovations: Advancements in manufacturing processes have reduced the cost of components and overall system construction.

6. Increased Efficiency:

Higher Concentration Ratios: Improved mirror and lens technologies have allowed for higher concentration ratios, leading to increased efficiency.

Advanced Working Fluids: The development of new working fluids with higher heat transfer capabilities has boosted efficiency.

7. Cybersecurity:

Enhanced Security Measures: The increasing reliance on digital technologies in CSP systems has necessitated stronger cybersecurity measures to protect against cyber threats.

8. Integration with Grid:

Advanced Grid Integration: CSP systems are becoming better integrated with existing power grids, improving their reliability and stability.

These advancements have made CSP a more competitive and attractive option for renewable energy generation. As technology continues to evolve, CSP is poised to play a significant role in meeting the world's growing energy demands while reducing greenhouse gas emissions.

IV. SOLAR PAINT AND SOLAR FABRICS

Solar paint and solar fabrics represent innovative approaches to integrating solar energy harvesting into everyday objects and surfaces. These technologies offer the potential to revolutionize urban infrastructure and reduce reliance on centralized power grids.

Solar Paint: Solar paint is a special type of paint that contains tiny solar cells embedded within its pigment. When sunlight strikes the painted surface, the solar cells convert the light into electricity. This technology can be applied to a wide range of surfaces, including walls, roofs, and even vehicles.

Solar Fabrics: Solar fabrics are textiles that incorporate solar cells into their fibers. These fabrics can be used to create solar-powered clothing, awnings, and other applications. Solar fabrics offer a unique and portable way to harness solar energy [8].

Solar Paint: Concept and Development: Solar paint, also known as photovoltaic paint or solar ink, is a coating applied to various surfaces to harness solar energy and convert it into electricity. The concept involves incorporating photovoltaic materials, such as nanoparticles of semiconductor materials, into a liquid or sprayable form that can be easily applied like traditional paint. When exposed to sunlight, the photovoltaic particles generate electricity through the photovoltaic effect. Research and development efforts in solar paint technology have focused on improving the efficiency, durability, and scalability of the coating. Innovations such as printable organic solar cells, quantum dot-based paints, and perovskite-based formulations have shown promise in enhancing the performance of solar paint while reducing manufacturing costs. Additionally, advancements in nanotechnology and material science have enabled the development of transparent or translucent coatings, allowing solar paint to be applied to windows, facades, and other architectural elements without obstructing light transmission.

Solar Fabric Technology: Solar fabric technology involves embedding photovoltaic elements into textiles, fabrics, or fibers to create solar-powered clothing, accessories, and flexible solar panels. These fabrics can harvest solar energy from ambient light sources, such as sunlight or indoor lighting, and convert it into electricity. Solar fabrics are typically composed of conductive fibers or coatings, such as conductive polymers or thin-film solar cells, integrated into the fabric structure. Advancements in textile engineering and materials science have led to the development of lightweight, flexible, and breathable solar fabrics that can be incorporated into a wide range of applications. These include solar-powered clothing for outdoor activities, portable solar chargers for electronic devices, and building-integrated photovoltaic systems. Solar fabrics offer the advantage of mobility and versatility,

allowing users to generate electricity on the go and in off-grid environments.

Challenges of Solar Paint and Fabrics: Solar paint and fabrics, while promising technologies, face several challenges that need to be addressed for widespread adoption:

1. Efficiency:

- **Lower Efficiency:** Compared to traditional solar panels, solar paint and fabrics often have lower energy conversion efficiencies.
- **Wavelength Absorption:** The materials used in these technologies may not absorb the full spectrum of sunlight as efficiently as traditional solar cells.

2. Durability:

- **Weathering:** Exposure to harsh weather conditions, such as rain, wind, and UV radiation, can degrade the performance and lifespan of solar paint and fabrics.
- **Mechanical Stress:** These materials may be susceptible to mechanical damage, especially when applied to flexible surfaces.

3. Cost:

- **Manufacturing Costs:** The production of solar paint and fabrics can be more expensive than traditional solar panels due to the integration of solar cells into the materials.
- **Scalability:** Achieving large-scale production of these materials at a competitive cost remains a challenge.

4. Integration:

- **Compatibility:** Ensuring compatibility with existing building materials and infrastructure can be complex.
- **Aesthetics:** Maintaining aesthetic appeal while incorporating solar paint or fabrics into various applications can be challenging.

5. Performance Degradation:

- **Long-Term Performance:** Over time, the efficiency and output of solar paint and fabrics may decline due to factors such as degradation of the solar cells or changes in the material properties.

Addressing these challenges will be crucial for the continued development and commercialization of solar paint and fabrics. Researchers and manufacturers are actively working to improve the efficiency, durability, and cost-effectiveness of these technologies to make them more viable alternatives to traditional solar panels.

Overcoming these challenges will require continued research, collaboration among interdisciplinary teams, and investment in innovation and technology development. With ongoing advancements and investment in solar paint and solar fabric technology, these innovative solutions have the potential to play a significant role in the transition to a sustainable and renewable energy future.

V. EFFICIENCY ENHANCEMENT TECHNIQUES

Efficiency enhancement techniques play a crucial role in improving the performance of solar photovoltaic (PV) cells, maximizing energy conversion rates, and optimizing power output. In this section, we will discuss four prominent

techniques used to enhance the efficiency of solar PV systems:

Anti-reflective Coatings: Anti-reflective coatings are thin films added to solar panels to capture more sunlight. These coatings reduce the amount of light that bounces off the panel, allowing more to be absorbed and converted into electricity. They work by using materials that match the solar panel's material, which helps to trap and absorb light effectively.

Passivation Layers: Passivation layers are protective coatings on solar panels that help them work better. They stop electrons and holes from recombining, which means they can produce more electricity. These coatings make the surface of the panel smoother and stronger, which helps to prevent energy loss. This improves the overall efficiency of the solar panel.

Tandem Cell Configurations: Tandem cells are like layered solar panels that use different materials to capture more sunlight. Each layer absorbs a different color of light, so they can use more of the sun's energy. This makes them more efficient than regular solar panels. Scientists are working on new types of tandem cells, like those using silicon and perovskite, to make solar panels even better in the future.

Bifacial Solar Panels: Bifacial solar panels are special panels that can collect sunlight from both sides. This means they can produce more electricity than regular panels that only use sunlight from one side. They have a clear back that lets light in, and they can also use light that bounces off the ground or other things around them. This makes them more efficient and can produce more energy.

These new ways of improving solar panels are helping them work better and produce more energy. By using special coatings, different materials, and new designs, solar panels can become more efficient, cheaper, and produce more electricity. This will make solar energy a popular and sustainable choice for power.

VI. ECONOMIC AND ENVIRONMENTAL IMPACT

Solar energy is a clean and renewable energy source that offers significant economic and environmental benefits. It creates jobs, reduces energy costs, stimulates economic development, and promotes energy independence. Additionally, solar energy helps reduce greenhouse gas emissions, improves air quality, conserves water, and minimizes land use impacts. As technology advances and costs decrease, solar energy is becoming a more attractive and sustainable option for energy generation.

Cost Reduction Trends: The cost of solar energy has significantly decreased in recent years due to technological advancements, economies of scale, and supportive policies.

Technological advancements have led to increased efficiency, reduced manufacturing costs, and improved materials, resulting in lower production costs and higher energy yields.

Economies of scale have driven down costs as the solar industry has expanded and production volumes have increased.

Supportive policies, such as incentives, tax credits, and mandates, have incentivized investment in solar energy projects and reduced upfront costs for consumers.

Financing options have also played a role, with access to low-cost financing and innovative financial models making solar energy more affordable.

These factors have collectively made solar energy a more competitive and accessible energy source, contributing to its rapid growth and adoption.

Life Cycle Assessment: Life Cycle Assessment (LCA) is a tool used to evaluate the environmental impact of a product or technology from cradle to grave. For solar energy, LCA assesses factors like energy payback time, greenhouse gas emissions, and resource depletion.

Energy payback time measures how long it takes a solar panel to produce enough energy to offset the energy used to make it.

Greenhouse gas emissions occur primarily during the manufacturing and installation of solar panels, but not during their operation.

Resource depletion is a concern due to the materials used in solar panel production.

LCA helps policymakers, businesses, and consumers make informed decisions about the environmental sustainability of solar energy [10].

Environmental Benefits and Challenges: Solar energy offers a compelling combination of environmental benefits and economic advantages. It significantly reduces greenhouse gas emissions, conserves resources, and minimizes water consumption, making it a crucial component of a sustainable energy future.

While challenges such as land use and waste management exist, proactive measures, including responsible siting practices, efficient waste management, and investment in recycling infrastructure, can mitigate these impacts.

As solar energy continues to become more cost-effective and efficient, it is poised to play a pivotal role in the transition to a clean energy economy.

VII. FUTURE PROSPECTS AND CHALLENGES

The future of solar energy is promising, but it faces several challenges. Emerging technologies, such as perovskite solar cells and tandem cells, offer potential for increased efficiency and reduced costs.

Market trends include continued cost reduction, the growth of utility-scale projects and distributed generation, and the integration of energy storage.

Policy and regulatory frameworks are essential for shaping the future of solar energy by providing incentives, setting standards, and supporting grid modernization.

Addressing these challenges will require a concerted effort involving technological advancements, supportive policies, and international cooperation to ensure the successful and sustainable growth of solar energy.

VIII. SOME CASE STUDIES

Solar energy projects are diverse and impactful, ranging from large-scale solar farms to off-grid systems and community initiatives.

Large-scale projects like Ivanpah in the USA and Kurnool in India demonstrate the potential for solar energy to generate significant amounts of clean electricity.

Off-grid systems in Sub-Saharan Africa provide access to clean energy for millions of people who lack grid connection.

Community solar projects offer a way for individuals and communities to participate in solar energy without owning their own panels.

These projects showcase the versatility and benefits of solar energy in meeting diverse energy needs and promoting sustainable development.

Success Stories: Solar energy has achieved significant success in various applications.

Germany's Energiewende demonstrates the potential of government policies to drive large-scale solar adoption.

SolarCity showcases the success of a business model focused on residential solar installations.

Solar-powered disaster relief highlights the ability of solar energy to provide essential services in emergency situations.

Solar-powered desalination addresses water scarcity in regions with limited freshwater resources.

These examples illustrate the transformative impact of solar energy on individuals, communities, and industries.

Solar energy has a lot of potential, but it needs the right things in place to be successful. We need clear and consistent rules and plans, and we need to involve communities in the process. We also need to keep investing in research to make solar energy better and cheaper. By working together, we can make solar energy a big part of a clean and sustainable future.

IX. CONCLUSION

Solar energy is a crucial component of the transition to a clean energy future. It offers significant environmental benefits, such as reduced greenhouse gas emissions, resource conservation, and water savings, while also contributing to energy security and economic development.

The rapid growth of the solar energy industry is driven by technological advancements, supportive policies, and increasing market acceptance. However, challenges such as grid integration, land use, and end-of-life management must be addressed to ensure the long-term sustainability of solar energy deployment.

By investing in research and development, implementing effective policies, and fostering collaboration among stakeholders, we can overcome these challenges and unlock the full potential of solar energy. This will enable us to create a cleaner, more sustainable, and more equitable world powered by the sun.

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