



Advancements In Photovoltaic (Pv) Technology for Solar Energy Generation

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Received:05 June 2023; Revised: 23 June 2023; Accepted: 01 July 2023; Available online: 10 July 2023

Abstract: Photovoltaic (PV) technology has witnessed remarkable advancements, revolutionizing solar energy generation. This article provides a comprehensive overview of the recent developments in PV technology, highlighting its improved efficiency, affordability, and accessibility. The discussion begins with an introduction to PV technology, explaining its role in solar energy generation. It then delves into the efficiency improvements achieved through novel materials, cell architectures, and manufacturing techniques, emphasizing their impact on performance and cost-effectiveness. The article explores emerging PV technologies, including perovskite, tandem, and organic solar cells, discussing their potential advantages, challenges, and progress in terms of efficiency, stability, and scalability. Innovative manufacturing techniques like roll-to-roll printing and thin-film deposition are examined for their contributions to scalability and cost reduction. The integration of energy storage technologies with solar PV systems is addressed, highlighting advancements in batteries and energy management systems. Solar tracking systems and concentrator technologies are reviewed for their benefits in optimizing solar energy capture. Environmental considerations encompassing manufacturing, operation, and disposal of PV systems are explored, along with efforts to mitigate their impacts through recycling initiatives and eco-friendly materials. The article also examines economic and policy factors driving solar PV adoption, including cost trends, government incentives, and policy frameworks. It concludes by discussing the challenges ahead, such as improving stability, reducing costs, and enhancing grid integration, while presenting ongoing research and future prospects for further advancements in PV technology. This comprehensive overview illuminates the progress made and the potential of PV technology to shape the future of solar energy generation.

Index Terms: Efficiency Improvement, Energy Storage Integration, Manufacturing Innovations, Photovoltaic Technology.

1 Introduction

1.1 Overview

The worldwide demand for energy, especially electrical energy, is continually expanding in tandem with time [1]. Energy is considered a prime agent in the generation of wealth and a significant factor in any country's economic development and its citizens' living standards [2]. Although petroleum-based energy sources are still abundantly available, global ecological concerns have been vehemently encouraging renewable energy sources. Among other sources of renewable energy, solar power, in particular photovoltaic energy, is the most promising

sustainable source because it does not have both supply constraints and physical byproducts that cause an environmental hazard. Solar PV is anticipated to be the highest power generation supplier among all the foreseeable sustainable power sources by 2040 [1]. The greatest advantage of solar energy as compared with other forms of energy is that it is environmentally friendly, abundantly available, and can be supplied without any environmental pollution [2].

Photovoltaic (PV) technologies, more commonly known as solar panels, generate power using devices that absorb energy from sunlight and convert it into electrical energy through semiconducting materials [3]. In 1954, researchers at the Bell Telephone Laboratories demonstrated the first practical conversion of solar radiation into electric energy by using a p-n junction-type solar cell with 6% efficiency [2]. A PV panel contains photovoltaic cells, also called solar cells, which convert light photons (light) into voltage (electricity). This phenomenon is known as the photovoltaic effect [4]. A single PV device is known as a cell. A basic solar cell be seen in Fig 1 . An individual PV cell is usually small, typically producing about 1 or 2 watts of power. These cells are made of different semiconductor materials and are often thinner than the thickness of four human hairs. To withstand the outdoors for many years, cells are sandwiched between protective materials in a combination of glass and/or plastic [5].

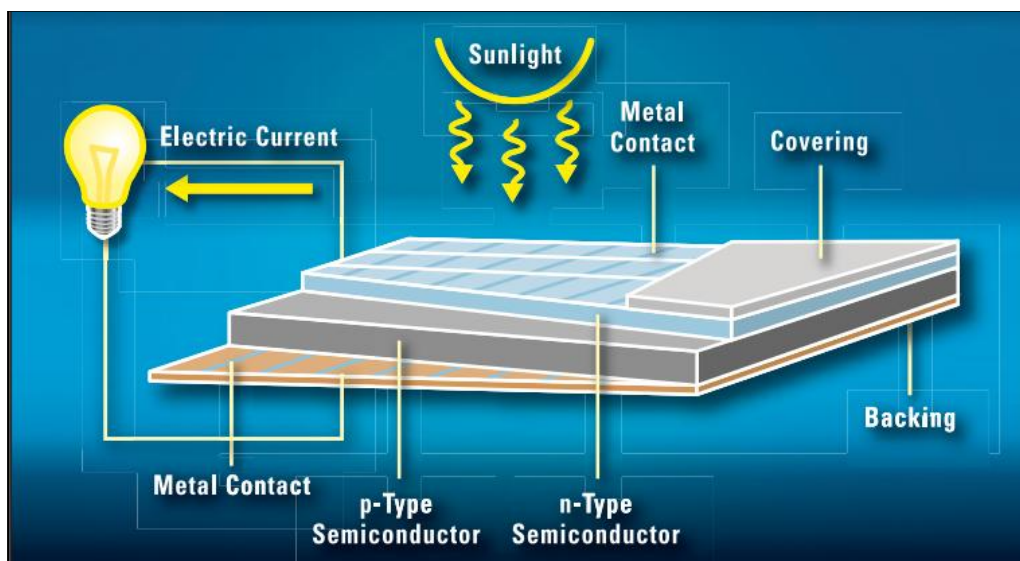


Fig. 1. A basic solar cell [6]

1.2 How Does Solar Photovoltaic Work?

The photovoltaic (PV) cell works in three steps:

1. Photons in sunlight hit the solar panel and are absorbed by semiconducting materials, such as silicon.
2. Electrons (negatively charged) are knocked loose from their atoms, allowing them to flow through the material to produce electricity. Due to the special composition of solar cells, the electrons are only allowed to move in a single direction.

3. An array of solar cells converts solar energy into a usable amount of direct current (DC) electricity [7].

The photovoltaic effect is the basic physical process through which a PV cell converts sunlight into electricity. Sunlight is composed of photons (like energy accumulations), or particles of solar energy. These photons contain various amounts of energy corresponding to the different wavelengths of the solar spectrum. When photons hit a PV cell, they may be reflected or absorbed [8]. Photovoltaic panels consist of semiconductor materials (usually silicon). When sunlight strikes the surface of a PV panel, the semiconductor absorbs energy from the photons. That reaction releases electrons from their atomic bonds. It creates a flow of electrons, resulting in an electric current [4]. The generated electric current is in the form of a direct current (DC). An inverter converts the DC power into alternating current (AC) to make this electricity usable for most household appliances and the electrical grid [4]. Fig. 2 shows a Solar panel diagram.

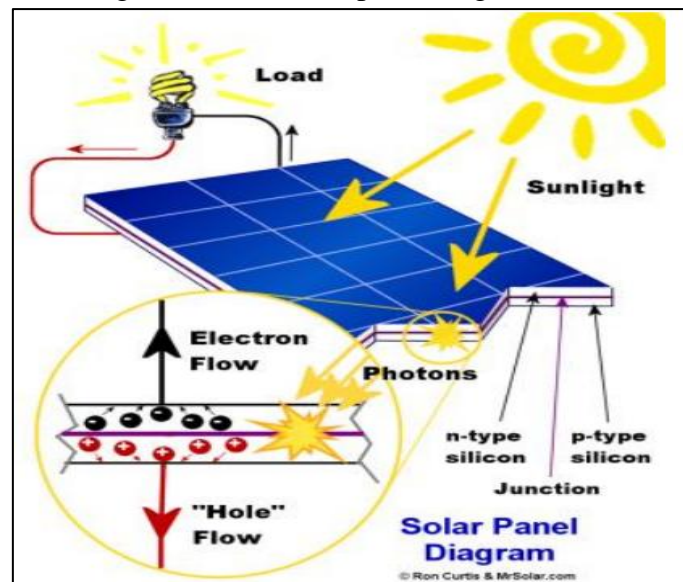


Fig.2. Solar panel diagram [7]

2 EFFICIENCY IMPROVEMENTS.

Advancements in increasing the efficiency of solar cells have played a significant role in improving the overall performance and cost-effectiveness of solar panels. Through the development of new materials, novel cell architectures, and manufacturing techniques, researchers and engineers have made substantial progress in enhancing efficiency and reducing the cost of solar energy generation.

2.1 New Materials:

- a. **Perovskite Solar Cells** - Perovskite solar cells have garnered significant attention due to their potential for high efficiency and low fabrication costs. Researchers have made strides in improving the stability and efficiency of perovskite materials through

composition engineering, interface engineering, and encapsulation techniques. These advancements have contributed to achieving higher power conversion efficiencies [9].

- b. **Tandem Solar Cells** - Tandem solar cells employ multiple materials with complementary absorption properties to capture a wider range of the solar spectrum, resulting in increased efficiency. By integrating materials like silicon with perovskites or III-V semiconductors, researchers have achieved record-breaking efficiencies in tandem solar cells. The combination of different materials enables better utilization of solar energy and improved performance [10].

2.2 Novel Cell Architectures:

- a. **Passivated Emitter Rear Contact (PERC) Cells** - Passivated Emitter Rear Contact (PERC) technology has become widely adopted in the solar industry. By adding a passivation layer to the rear surface of the solar cell, PERC cells reduce recombination losses and enhance light absorption. This approach improves the efficiency of silicon-based solar cells and is compatible with existing manufacturing processes, contributing to their commercial success [11].
- b. **Heterojunction Solar Cells** - Heterojunction solar cells combine different semiconductor materials to minimize energy losses at interfaces. By utilizing a combination of amorphous and crystalline silicon layers, heterojunction cells achieve efficient charge separation and improve overall cell efficiencies. Researchers have focused on optimizing this cell architecture to enhance performance [12].

2.3 Manufacturing Techniques:

- c. **Silicon Wafer Technologies** - Advancements in silicon wafer technologies have contributed to increased solar cell efficiency. Techniques such as diamond wire sawing and kerfless wafering allow for the production of thinner wafers, reducing material consumption and improving cell performance. These manufacturing techniques have played a crucial role in reducing costs and enhancing the competitiveness of silicon-based solar cells [13].
- d. **Thin-Film Solar Cells** - Thin-film solar cells, including CdTe and CIGS, have seen advancements in manufacturing techniques such as roll-to-roll deposition and co-evaporation. These techniques enable large-scale production, cost-effective manufacturing, and improved cell performance. Thin-film solar cells have the potential to offer competitive alternatives to traditional silicon-based cells [14].

3 EMERGING PV TECHNOLOGY

What is the idea behind the “Emerging PV Technology”?

Emerging PV technology is a continuous process that involves collaboration, innovation, and a multi-faceted approach. By focusing on efficiency, materials, storage, system design, manufacturing, durability, cost, integration, and policy support, you can contribute to the advancement of photovoltaic technology. Emerging PV technology represents the latest

advancements that have the potential to revolutionize the solar industry and drive the widespread adoption of solar energy as a clean and sustainable power source. So, let's see how we can emerge PV technology by going through some main points.

3.1 Efficiency Enhancement

- a. **Advanced Solar cell materials** – Explore and develop new materials with enhanced properties for solar cells. Research into materials such as perovskites, organic semiconductors, and quantum dots has shown promise in achieving higher conversion efficiencies. These materials can offer better light absorption and charge carrier transport properties, leading to improved efficiency[15].
- b. **Multiple-Junction Solar Cells** – Utilize multiple layers of different semiconductor materials to create tandem or multi-junction solar cells. Each layer absorbs a specific portion of the solar spectrum, allowing for more efficient utilization of sunlight. This approach has been successful in achieving high efficiencies in specialized applications, such as space and concentrated solar power[15].
- c. **Passivation Techniques** – Implement passivation techniques to minimize recombination losses within the solar cell. Surface passivation and defect engineering methods can reduce the loss of charge carriers, thereby improving the overall efficiency of the solar cell[15].
- d. **Anti-Reflective Coatings** – Apply anti-reflective coatings to the surface of solar cells to minimize reflection losses. These coatings reduce the amount of incoming light that bounces off the cell's surface, increasing the amount of light absorbed and converted into electricity[15].
- e. **Light-Trapping Structures** – Incorporate light-trapping structures within the solar cell design to enhance light absorption. These structures, such as textured surfaces, nanostructures, or photonic crystals, can help capture more light by extending the light path within the solar cell, increasing the probability of absorption[15].
- f. **Improved Contacts and Interfaces** – Optimize the design of contacts and interfaces within the solar cell to minimize resistance losses and improve charge carrier collection. Efficient charge extraction from the solar cell is crucial for achieving high conversion efficiencies[15].
- g. **Quantum Efficiency Enhancement** – Work on improving the quantum efficiency of solar cells, which relates to the ability to convert different wavelengths of light into electricity. By optimizing the spectral response of the solar cell and minimizing losses at specific wavelengths, overall efficiency can be improved[15].
- h. **Concentrated Photovoltaics (CPV)** – Implement concentrated photovoltaic systems that use optical elements to concentrate sunlight onto smaller, high-efficiency solar cells. This approach allows for higher sunlight concentration, which can lead to increased efficiency in specific applications where high solar concentration is feasible[15].

3.2 Advanced Materials

Advanced photovoltaic (PV) materials refer to novel materials that show promise for

improving the efficiency, cost-effectiveness, and performance of solar cells. These materials are being actively researched and developed to overcome the limitations of traditional PV materials, such as silicon, and to enable the next generation of solar cell technologies. Here are some examples of advanced PV materials.

- a. **Perovskites** – Perovskite solar cells have gained significant attention in recent years due to their rapidly increasing efficiency and low-cost potential. Perovskite materials have a unique crystal structure that can be easily synthesized and processed into thin films. They offer advantages such as high light absorption, tuneable bandgaps, and the ability to be used in various PV device architectures. Perovskite solar cells have achieved efficiencies comparable to traditional silicon solar cells, making them a promising candidate for future PV applications[17].
- b. **Organic Semiconductors** – Organic solar cells utilize organic (carbon-based) materials as the active semiconductor layer. These materials can be solution-processed, allowing for low-cost and large-area fabrication. Organic semiconductors have the potential for flexible and lightweight solar panels. While their efficiencies are currently lower than silicon-based solar cells, ongoing research aims to improve their performance through material engineering and device optimization[17].
- c. **Quantum Dots** – Quantum dot solar cells utilize tiny semiconductor nanocrystals that exhibit unique electronic and optical properties due to quantum confinement effects. Quantum dots can be tuned to absorb different portions of the solar spectrum by controlling their size and composition. They can be incorporated into solution-processed solar cells and have the potential for low-cost production and high-efficiency photovoltaics[17].
- d. **Multi-Junction Solar Cells** – Multi-junction solar cells incorporate multiple semiconductor materials with different bandgaps to absorb a broader range of the solar spectrum. By stacking layers of different materials, each capable of absorbing a specific portion of the sunlight, multi-junction solar cells can achieve higher efficiencies compared to single-junction solar cells. These cells are commonly used in specialized applications like space exploration and concentrated solar power [17].
- e. **Tandem Solar Cells** – Tandem solar cells combine different solar cell technologies, such as silicon and perovskite, in a stacked configuration to maximize light absorption and improve efficiency. By integrating complementary materials with different bandgaps, tandem solar cells can capture a broader spectrum of light and achieve higher conversion efficiencies compared to single-junction cells [17].
- f. **Transparent Solar Panels** – Transparent solar panels, also known as transparent photovoltaics (TPV), aim to integrate solar cells into windows, screens, and other transparent surfaces. This technology enables the conversion of sunlight into electricity without compromising the functionality or aesthetics of the underlying surface [17].
- g. **Bifacial Solar Modules** – Bifacial solar modules can capture sunlight from both sides of the panel, allowing them to generate electricity from direct sunlight as well as reflected and scattered light. This technology can enhance the overall energy output of PV systems by utilizing available sunlight more efficiently [17].

- h. Nanostructured Materials** – Nanostructured materials, such as nanowires, nanotubes, and nanopillars, are being explored for their potential to enhance light absorption and charge carrier transport within solar cells. These materials can provide a larger surface area and shorter carrier diffusion lengths, leading to improved efficiency. They are typically fabricated using advanced nanofabrication techniques[17].
- i. 2D Materials** – Two-dimensional (2D) materials, such as graphene and transition metal dichalcogenides (TMDs), have unique electronic properties and can be used in thin-film solar cells. These materials offer advantages such as flexibility, transparency, and tuneable bandgaps, making them suitable for various PV applications [17].

3.3 Energy Storage Integration

By improving the integration of energy storage in PV technology, solar energy becomes more reliable, flexible, and accessible. It allows for greater self-consumption of generated solar energy, increased energy independence, and enhanced grid support capabilities, contributing to a more efficient and sustainable energy ecosystem.

- a. Battery Technologies** – Explore and develop advanced battery technologies that are suitable for PV energy storage. Lithium-ion batteries are currently the most used technology due to their high energy density, efficiency, and declining costs. However, ongoing research aims to improve their performance and longevity while exploring alternative technologies, such as flow batteries, solid-state batteries, and advanced chemistries[18].
- b. Sizing and Capacity** – Properly size the energy storage system to meet the specific needs of the PV installation. This involves considering factors such as peak power demand, energy consumption patterns, and the desired level of autonomy (the ability to operate independently from the grid). By matching the storage capacity to the PV system, you can ensure optimal utilization of the generated solar energy[18].
- c. Charge Controller and Power Electronics** – Implement intelligent charge controllers and power electronics to optimize the charging and discharging processes of the energy storage system. These devices monitor the state of charge, manage the flow of energy, and ensure efficient utilization of stored energy. They also facilitate bidirectional energy flow between the PV system, energy storage, and the electrical grid[18].
- d. Energy Management Systems** – Utilize advanced energy management systems to optimize the operation and interaction between the PV system and the energy storage. These systems employ algorithms and predictive analytics to optimize energy flow, manage charging and discharging cycles, and make decisions based on real-time data. By intelligently managing the energy flow, these systems can maximize the utilization of solar energy and minimize reliance on the grid[18].
- e. Time-of-Use Optimization** – Incorporate time-of-use optimization strategies to leverage energy storage in scenarios where electricity rates vary throughout the day.

By charging the energy storage system during periods of low-cost electricity and discharging during high-cost periods, you can optimize cost savings and maximize the financial benefits of PV energy storage [18].

- f. **Hybrid PV Systems** – Consider hybrid PV systems that combine multiple renewable energy sources, such as PV, wind, or hydro, with energy storage. These systems allow for a diversified and more reliable energy supply by harnessing the complementary characteristics of different renewable sources. The energy storage component helps balance the intermittent nature of renewable energy generation and ensures a stable power supply [18].
- g. **Remote Monitoring and Control** – Implement remote monitoring and control systems to enable real-time monitoring of PV energy generation, energy storage performance, and system health. These systems facilitate remote diagnostics, maintenance, and optimization, reducing the need for on-site interventions and improving overall system reliability[18].
- h. **Lifecycle Analysis and Optimization** – Conduct lifecycle analysis and optimization to ensure the long-term viability and sustainability of PV energy storage systems. This involves considering factors such as the lifespan of the batteries, their environmental impact, and the potential for recycling or repurposing at the end of their life cycle. It is essential to optimize the system design, operation, and maintenance to maximize the economic and environmental benefits[18].

3.4 Durability and Reliability

Increasing the durability and reliability of photovoltaic (PV) technology is crucial for ensuring long-term performance and maximizing the return on investment. Here are several key approaches to enhance the durability and reliability of PV systems,

- a. **Robust Component Selection** – Choose high-quality components that are specifically designed for PV applications. This includes selecting reliable solar panels, inverters, wiring, connectors, mounting structures, and balance system components. Consider factors such as product warranties, certifications, industry reputation, and track records of manufacturers to ensure reliability[16].
- b. **Stringent Quality Control** – Implement rigorous quality control measures throughout the manufacturing, installation, and maintenance processes. This involves inspecting and testing components for defects or damage, verifying adherence to specifications, and ensuring proper installation practices. Quality control protocols should cover all aspects of the PV system, including modules, wiring, connections, and overall system integration.
- c. **Proper System Design** – Design the PV system with robustness and reliability in mind. This includes proper sizing of components, appropriate wire gauge selection, correct system grounding, and adherence to local electrical codes and standards. Avoid design choices that can lead to excessive stresses, hotspots, or reliability issues, such as mismatched components or inadequate ventilation[16].

- d. Adequate Weatherproofing** – Ensure effective weatherproofing measures are in place to protect the PV system from environmental elements. This includes using appropriate sealants, gaskets, and junction boxes to prevent water ingress, moisture damage, and corrosion. Proper insulation and protection against extreme temperature fluctuations are also essential[15].
- e. Regular Maintenance and Inspections** – Implement a routine maintenance schedule to detect and address potential issues before they become significant problems. Inspections should include visual inspections of components, electrical connections, and mounting structures. Clean the solar panels to remove dirt, debris, or shading that may reduce their efficiency. Regularly monitor the system performance and analyze data to identify any deviations or anomalies.[15].
- f. Monitoring and Diagnostics** – Install a monitoring system that provides real-time data on the performance of the PV system. This includes monitoring parameters such as energy production, voltage, current, and temperature. Advanced monitoring systems can detect and alert you to potential issues, such as module failures, shading, or electrical faults. Use the collected data to analyse trends, identify inefficiencies, and optimize system performance[16].
- g. Overvoltage and Surge Protection** – Implement surge protection devices and overvoltage protection mechanisms to safeguard the PV system from transient voltage spikes, lightning strikes, and power surges. These protective devices help prevent damage to sensitive components and ensure the system remains operational during unforeseen events.
- h. Proper Installation and Mounting** – Ensure proper installation practices are followed during PV system installation. This includes using appropriate mounting structures, securely fastening panels, and employing correct electrical connections. Properly trained and certified installers should carry out the installation to ensure compliance with industry best practices.
- i. Lifespan and End-of-Life Considerations** – Consider the expected lifespan of the PV system and plan for end-of-life scenarios. This includes selecting components with long-term reliability and recyclability, as well as implementing proper decommissioning and recycling processes for retired modules. Properly managing the end-of-life phase minimizes waste and environmental impact.

3.5 Cost Reduction

Reducing the cost of photovoltaic (PV) technology is crucial for its widespread adoption and competitiveness with conventional energy sources. Here are several strategies to help decrease the cost of PV technology,

- a. Economies of Scale** – Increase production volumes to achieve economies of scale. As the demand for PV technology grows, manufacturers can take advantage of higher production volumes, leading to reduce per-unit costs. This can be achieved through government incentives, supportive policies, and market expansion initiatives that promote the widespread adoption of solar energy[21].

- b. Manufacturing Efficiency** – Continuously optimize manufacturing processes to improve efficiency and reduce costs. This involves streamlining workflows, implementing lean manufacturing principles, adopting advanced automation technologies, and optimizing supply chain management. By reducing material waste, improving yield rates, and minimizing production cycle times, manufacturing costs can be significantly reduced[21].
- c. Advanced Materials** – Develop and utilize advanced materials that offer improved performance at lower costs. This includes the development of next-generation solar cell materials with higher efficiency and lower production costs. For example, thin-film solar cells and perovskite solar cells have the potential to be produced at lower costs compared to traditional silicon-based solar cells[21].
- d. Reduction in Balance of System (BOS) Costs** – Focus on reducing the costs associated with a balance of system components, including mounting structures, wiring, inverters, and installation labor. Innovations in BOS design and integration can lead to cost savings, improved installation efficiency, and lower overall system costs[21].
- e. Standardization and Certification** – Promote standardization and certification processes to ensure the quality, interoperability, and safety of PV products. Standardization helps streamline manufacturing processes, facilitates mass production, and reduces costs associated with product customization and testing[21].
- f. Improved Installation and Maintenance Practices** – Enhance installation and maintenance practices to reduce labor costs and ensure optimal system performance. Developing standardized installation guidelines, providing training programs for installers, and implementing effective maintenance strategies can help lower overall system costs and improve long-term reliability[21].
- g. Supply Chain Optimization** - Optimize the PV supply chain to reduce costs and increase efficiency. This involves identifying opportunities for local sourcing of materials, establishing strategic partnerships with suppliers, and implementing effective inventory management practices. By reducing transportation costs and streamlining supply chain operations, overall system costs can be reduced[21].

Emerging or Improving PV technology is a continuous process that involves collaboration, innovation, and a multi-faceted approach. By focusing on efficiency, materials, storage, system design, manufacturing, durability, cost, integration, and policy support, you can contribute to the advancement of photovoltaic technology.

4 MANUFACTURING INNOVATIONS

In recent years, there has been an ever-increasing global demand for clean and sustainable energy sources to combat the challenges posed by climate change and dwindling fossil fuel reserves. Solar energy has emerged as a frontrunner in the renewable energy sector, and photovoltaic (PV) technology lies at the heart of solar power generation. Manufacturing innovations have played a vital role in advancing photovoltaic (PV) technology for solar

energy generation. The growing demand for renewable energy sources, coupled with the need for more efficient and cost-effective solar panels, has spurred significant advancements in PV manufacturing processes. These innovations have resulted in improved efficiency, reduced costs, and expanded applications of solar energy. In this context, we will explore the key manufacturing innovations that have contributed to the advancements in PV technology.

4.1 Anti-Reflective Coatings and self-cleaning coatings

Two main factors contribute to the decline in the efficiency of the solar panel: soil and reflection. Solar panels use cover glass, which is typically made with low-iron content. The thickness of the cover glass can vary, with options including 2.0 mm, 3.2mm, and 4.0mm. Thicker glass offers greater strength but reduces the amount of light transmitted. Presently, the preferred choice is low-iron glass with a thickness of 3.2mm. Thinner glass helps to minimize light absorption losses. Thicker glass provides better resistance to outdoor elements, while thinner glass allows higher light transmittance [22]. When sunlight reaches the surface of the solar panel at a specific angle, it passes through the protective glass and reaches the cell. However, not all of the light that reaches the glass surface is transmitted to the cell; approximately 8-10% of the light is reflected from a clean glass surface. A silicon cell itself reflects around 35-36% of the incident light. This reflection of sunlight leads to the loss of electrical power. Therefore, reducing these optical losses is a crucial factor in increasing the panel's efficiency. To address this issue, an antireflective coating (ARC) is applied to the cover glass, which helps minimize optical losses [22]. Another factor contributing to the decrease in PV panel efficiency is soiling. Various materials, such as dust, organic waste, water droplets, and snow, can accumulate on the surface of the PV system depending on its installation location. To counter this problem, self-cleaning applications are employed to remove soil from the cover glass of PV panels[22].

a. Anti-Reflection coating

Numerous studies have been conducted to minimize cell reflections by using antireflective coatings (ARCs). ARCs play a crucial role in solar cell cover glass, and their significance has been recognized since the development of the first ARC in 1964. Presently, over 70% of the PV panels available in the market are equipped with ARCs either on the cover glass or the solar cell itself. Considering the environmental conditions, ARCS needs to possess favorable optical properties and durability. Panels located in dusty or rainy areas require high-strength and long-lasting ARCs[22]. The primary objective of ARC research has been to enhance the efficiency of PV panels by targeting optical properties. Specifically, the aim is to reduce the reflection index (n). The reflection index of air is 1.00, indicating that sunlight consistently transitions from a lower index (e.g., air) to a higher index (e.g., cover glass). In the case of cover glass, the reflection index is 1.52. The goal of coatings is to bring the reflection index as close to 1.00 as possible without compromising light transmittance. Coatings applied to the air-facing side of the glass effectively diminish reflection losses[22].

b. Self-cleaning coatings

Anti-reflection and self-cleaning applications are commonly used in various applications such as solar cells, building windows, glasses, car windows, fabrics, and clothes. In the case of large-scale solar power plants, which consist of numerous photovoltaic panels, they are susceptible to dust storms and organic soiling depending on their location. The accumulation of dirt directly diminishes the power output of both the solar panels and the entire power plant. In areas with significant soil contamination, annual power losses due to soiling can reach up to 50%. Such losses are undesirable for efficient electricity production, thus necessitating the development of mechanisms to clean the cover glass of solar panels. Self-cleaning is achieved through two approaches: hydrophobic (water-repelling) and hydrophilic (water-dispersing) properties[22].

Hydrophobic surfaces exhibit a water contact angle (WCA) of more than 90° , while superhydrophobic surfaces have a water contact angle exceeding 150° , with a hysteresis contact angle (CAH) below 10° . An example of hydrophobicity is the lotus leaf's superhydrophobic property, which allows water to easily flow off the surface. Consequently, if dirt adheres to the surface, it can be washed away when water is introduced, effectively cleaning the surface. The high contact angle of water droplets with a hydrophobic surface facilitates quick water flow and the removal of dirt. On the other hand, hydrophilic surfaces enable active cleaning by collecting soil on water droplets and spreading water across the surface. Water droplets exhibiting a water contact angle of 90° are considered hydrophilic, while super hydrophilic surfaces have a water contact angle below 10° . However, the superhydrophobic self-cleaning property has not received significant attention in the literature [22].

c. Methods

Various methods are employed for anti-reflection coatings,

- I. Sol-gel method
- II. Dip-coating
- III. Spin-coating
- IV. CVD (Chemical Vapor Deposition)
- V. Thermal evaporation
- VI. Electron beam (E-beam)
- VII. RF and DC magnetron
- VIII. Spray pyrolysis
- IX. Electrospinning [22]

4.2 Textured Surfaces and Light-Trapping Structures

a. surface texturing

Surface texturing, whether used in combination with anti-reflection coating or independently, serves to minimize reflection and enhance the performance and efficiency of solar cells. By

introducing roughness to the surface, the chances of reflected light bouncing back to the surface increase, reducing reflection toward the surrounding air. Solar cells rely on this technique to diminish light reflection and improve light trapping. An essential parameter for surface texturing is surface finish or surface topography, representing the shape and characteristics of the surface, including surface roughness, lay, and waviness. These factors describe the small, localized irregularities of a surface in comparison to an ideal flat surface.

b. Different types of techniques used for Surface Texturing

Surface texturing can be achieved through various methods. One approach involves etching along the crystal planes of a single crystalline substrate. The crystalline structure of silicon naturally forms a surface with pyramids when properly aligned with the internal atoms. This technique, known as "random pyramid" texturing, is commonly employed in the single crystalline wafer industry. Chemical processes can also be used to etch the surface of solar cells. An example is an anisotropic wet chemical etching, which creates pyramids on the silicon wafer surface by selectively etching back to the crystal planes. Another type of surface texturing is known as "inverted pyramid" texturing, where pyramids are etched downward into the silicon surface rather than pointing upwards. For multi-crystalline wafers, only a small portion of the surface exhibits the necessary orientation, making these texturing techniques less effective. However, alternative methods can be employed. Multi-crystalline wafers can be textured using photolithographic techniques or mechanical sculpting, such as laser ablation or cutting with dicing saws, to shape the surface as desired [23].

c. light trapping structures

Light trapping increases the effective "optical thickness" of a solar cell, surpassing its physical thickness. This is accomplished through two mechanisms: (1) Guiding light rays to traverse the cell at oblique angles, and (2) Creating non-zero internal reflectance at the front and rear surfaces to prevent ray escape. By augmenting the optical thickness beyond the actual thickness, the light rays are compelled to spend more time within the solar cell. Consequently, there is enhanced absorption of long-wavelength photons, resulting in a higher generation current[24]. Initially, light trapping methods were primarily devised for solar cells featuring thick active layers. In such cases, techniques like incorporating an anti-reflection coating or implementing surface texturing on a large scale in the range of super-microns and confine light through total internal reflection (TIR), facilitating improved absorption within the semiconductor material. However, for thin film organic solar cells, modifications are necessary for light trapping approaches. This is due to factors such as the low refractive index of the substrate, challenges in implementing extensive textured structures, and the distinct optical characteristics exhibited by light in thin films. Therefore, alternative strategies need to be developed to effectively enhance light trapping in thin-film organic solar cells[25].

4.3. Roll-to-Roll Manufacturing

The production of flexible PV devices cannot be accomplished using conventional PV device processes that rely on high-vacuum film deposition and high temperatures. As a result,

alternative manufacturing methods are necessary. In numerous studies and articles discussing flexible PV devices, roll-to-roll (R2R) processing has been emphasized as the most recent high-throughput, large-scale production technology. Firstly, gravure printing is extensively utilized for printing magazines and high-volume print jobs, such as catalogs. The success of gravure printing relies on achieving uniform ink transfer onto the patterned substrate. A typical gravure printing machine consists of two heavy cylinders, an ink supply, and a doctor's blade. The substrate is passed between the top and bottom cylinders, where it is printed with the desired pattern. Excess ink is then removed by the doctor's blade. Although this technique has been historically used for photographs and newspapers, its potential for solar cell production has been explored in a few scientific journals.

On the other hand, flexographic printing is considered faster and simpler compared to gravure printing. It involves direct printing onto rubber or plastic materials, such as polyvinylidene fluoride (PVDF). Flexographic printing has been employed for printing transparent electrodes and active layers in organic solar cells. However, despite its advantages, the quality of the final product is often compromised due to the low pressure applied during the ink application. Screen printing, which has been in use for over a century in fabric, paper, and ceramic design, is another popular printing technique. It entails stretching a mesh over a modified frame and manually transferring ink onto the substrate using a squeegee. Screen printing allows for the rapid formation of a layer on the substrate and is a cost-effective process. In rotary screen printing, an automatic roller is employed instead of the manual squeegee used in conventional screen printing. This enables faster printing, as the roller can quickly apply ink to the substrate [26].

4.4 Advanced Encapsulation

The efficiency of a photovoltaic (PV) module primarily relies on PV cell technology, and ensuring the long-term operational stability of PV cells is crucial for the widespread adoption of this technology. PV cells undergo significant morphological and structural changes, decay in optical absorption, and degradation of optoelectronic properties over extended periods of outdoor operation, which negatively impact the performance of PV modules. Encapsulation has proven to be an effective and widely accepted approach to enhance the operational stability of PV cells. It serves to prevent degradation caused by weather-related factors such as moisture, UV light, oxygen, and temperature, while also providing mechanical strength against external impacts.

Various encapsulation methods have been developed, with ethylene vinyl acetate (EVA) copolymer being the dominant encapsulating material in many studies. However, EVA is susceptible to environmental degradation, resulting in a decline in PV module power production efficiency. Therefore, researchers have focused on exploring new techniques to improve the aging resistance of EVA encapsulation films. These techniques involve extending the cross-linking network structure in the polymer matrix and incorporating antioxidants, UV absorbers, and photo stabilizers.

Over time, advancements in polymer technology have greatly influenced the design strategies for polymer encapsulation. Polymer composites reinforced with carbon or inorganic fillers offer excellent barrier properties against moisture and gas permeability. These composites can be utilized as encapsulating components for electronic devices, protecting harsh environmental conditions. Additionally, photo-responsive polymers, which exhibit responsiveness to UV or sunlight, have gained attention. These smart polymers rapidly cure and form a cross-linking network structure when exposed to light, making them suitable for various electronic applications such as adhesion, sealing, potting, gasketing, and encapsulation. Inspired by the remarkable properties of high-performance polymers, researchers have dedicated their efforts to designing new and advanced polymer encapsulates that offer enhanced operational durability. Fig 3 summarizes the studies on polymer encapsulate materials with different polymer matrices and chemistry [27].

Polymer matrix	Class	Filler	Merits
ethylene vinyl acetate (EVA)	Composite	Y ₂ SiO ₅ : Ce ³⁺ , Yb ³⁺	High thermal conductivity and good adhesion to glass substrate.
EVA	Composite	bacterial cellulose (BC) nanofibres	Delay in EVA yellowing, increment in thermal stability and tensile strength with optical transparency of 85%.
EVA	Composite	Boron Nitride (BN) particles	Encapsulate film with improved thermal conductivity enhances the cooling rate of the PV module.
EVA	Composite	graphene nanoplatelets (GN)	Encapsulate film exhibited good resistance for water vapor transmittance.
EVA	Composite	graphene oxide (GO)	Optically transparent encapsulate film exhibited good resistance for weather degradation.
Polyurethane (PU)	Composite	cellulose nanocrystal (CNC)	Lifetime of the DSSC device was extended by around 336 h with the same initial power conversion efficiency.
PU	Photo-responsive	—	Encapsulate film exhibits high tensile strength and good adhesion to ETFE substrate through a cross-link network structure
PU	Composite	ceramic powders (Al ₂ O ₃ and AlN)	Encapsulate film efficiently cools the PV cell and enhances its power generation efficiency.
Epoxy	Composite	glass fibre	Transparent composite encapsulate system protects the PV cell from external impacts and enhanced its operational performance.
Epoxy	Photo-responsive	—	Encapsulate film is self-healable under sunlight irradiation and prevents the Pb leakage from PSC device.
Epoxy	Photo-responsive	—	UV curable epoxy adhesive is utilized as an edge sealant to seal the PSC device. It has facilitated the adhesion between FTO glass and cover glass encapsulate at low temperatures.
Saran F-310	Composite	Boron nitride nanotubes (BN-NT)	Composite film exhibited good barrier efficiency and thermal stability.
polyvinyl alcohol (PVA)	Composite	sodium montmorillonite (MMt–Na ⁺)	Encapsulate film had good optical transparency and excellent barrier performance against gas and moisture.
polyisobutylene (PIB)	Photo-responsive	—	Encapsulate film is self-healable. It has good barrier performance and can extend the device stability
Surlyn	Composite	cellulose microfibers (MFC)	Lifetime of the device has been extended up to one-week by the composite film with high tensile and peel strength and good barrier properties.
polyvinyl butyral (PVB)	Composite	graphene nanoplates (GN)	Superior thermal conductivity of the GN makes encapsulate more efficient to cool the PV module and to extend its lifetime.
acrylate	Photo-responsive	—	UV-curable adhesive with low curing shrinkage and good barrier properties exhibited improved adhesion to the PET barrier film.

Fig. 3. List of studies on different polymer-based encapsulate materials for PV modules.[27]

4.5 Automation and Robotics

The digitalization of solar photovoltaic (PV) refers to the application of digital technologies to manage solar PV assets more efficiently. This involves using monitoring systems and sensors to gather data from solar panels and equipment, allowing for informed decisions to maximize power production. Through digitalization, solar PV systems can integrate energy storage and communicate with the grid, enabling the dispatch of electricity even after sunset.

This, in turn, allows solar PV generators to command higher prices in auctions and power purchase agreements. Automation in solar PV involves the use of robotics and automation technologies to streamline solar plant operations and reduce costs. There are five main categories of automation in solar technology: supervisory control and data acquisition (SCADA)/distributed control system (DCS), operations and maintenance (O&M) automation, automation in plant installation, automation in the balance of systems, and automated communication systems.

Despite the increasing capacity of solar PV installations worldwide, the solar PV industry faces challenges such as the impact of irregular and extreme weather conditions, environmental limitations, inefficient asset management, reliance on labor-intensive work, and high O&M costs. To address these challenges and promote digitalization and automation in solar PV, it is crucial to reduce dependence on manual labor through the use of new technologies and solutions. Recent advancements in sensing, computation, the Industrial Internet of Things (IIoT), 5G, and robotics/AI have made it more feasible to replace labor-intensive work in solar PV O&M with machines. Research and innovation in digitalization and automation can cover all stages of a solar plant's lifecycle, including planning, construction, operation, maintenance, and recycling [28].

5 ENERGY STORAGE INTEGRATION

5.1 The use of a combined battery-SC coordinated system to improve the overall performance of the microgrid system.

The integration of energy storage systems with solar PV systems is important for addressing the challenges posed by fluctuations in PV power caused by cloud changes. This study focuses on analyzing different control methods, namely ramp-rate (RR) and step-rate (SR) control, to mitigate these fluctuations in a DC microgrid environment. Energy storage systems, such as batteries and supercapacitors, are utilized alongside control algorithms to enhance the performance and reliability of the microgrid system. The battery functions as a continuous energy application, while the supercapacitor helps eliminate transients in the battery system, optimizing system performance. To evaluate the effectiveness of the proposed methods, battery cycle analysis, and depth are conducted using the well-established Coulomb counting technique. Simulation results are validated using MATLAB/Simulink, and real-time testing is performed on an OP-5700 hardware-in-the-loop test bench.

Under high solar variability irradiance profile conditions, the storage requirements and performance of the RR and SR methods for smoothing PV power fluctuations are compared. The results demonstrate that the RR controller requires less battery energy and experiences fewer battery cycles compared to the SR method. Additionally, the RR method achieves faster regulation of the DC link voltage and lower voltage drop, resulting in higher system efficiency (98.07%) compared to the SR method (approximately 95.6%). The RR control method proves more effective in minimizing variations in PV power output and maintaining power balance at the DC link compared to the SR method. It also exhibits higher effectiveness in terms of storage time, responding quickly to changes in demand and charging

requirements. While this evaluation focuses on a single radiation day, further research is needed to gain a comprehensive understanding of the battery's lifetime operation. Future studies may explore the development of a lifespan model to delve deeper into these operational aspects [29].

5.2 Integration of solar photovoltaic distributed generation (SPVDG) with battery energy storage systems (BESS) using hybrid algorithm-based optimal planning.

As global electricity consumption continues to rise and concerns over economic and environmental impacts grow, the need for alternative energy sources becomes increasingly evident. Solar photovoltaic distributed generation (SPVDG) has emerged as a promising solution, harnessing the power of renewable energy. To maximize its benefits and overcome the challenges associated with solar energy, a recent study proposes an innovative approach to integrate SPVDG with battery energy storage systems (BESS) within power distribution systems (PDS). The key focus of the study is to optimize the placement and sizing of SPVDG and BESS, aiming to reduce peak demand and improve the voltage profile in the PDS. To achieve this, researchers introduce a novel hybrid algorithm that combines the enhanced elephant herding algorithm with the Jaya algorithm. This hybrid approach effectively balances global exploration and local exploitation, enabling the discovery of near-global optimum solutions. The problem formulation revolves around finding the optimal arrangement of SPVDG and BESS while considering critical factors such as voltage limits, maximum current limits, and BESS charge-discharge constraints. Additionally, the study examines the hourly variations in SPVDG generation and demand profiles, accounting for seasonal impacts on energy production and consumption. To validate the algorithm's performance, the researchers utilize the IEEE 69 bus PDS as a testing platform. The results demonstrate the effectiveness and accuracy of the hybrid algorithm, outperforming other optimization approaches reported in the literature.

In summary, this research highlights the importance of integrating SPVDG with BESS to overcome the limitations of solar energy and reduce peak demand in power distribution systems. By introducing a novel hybrid algorithm, the study offers an advanced optimization solution for determining the optimal placement and sizing of SPVDG and BESS while considering various constraints and system dynamics. The algorithm's performance is rigorously validated using the widely recognized IEEE 69 bus PDS, showcasing its promising potential compared to existing optimization methods. As the world strives for cleaner and more sustainable energy sources, this breakthrough in SPVDG and BESS integration paves the way for more efficient and reliable power distribution systems, contributing to a greener and more resilient future [32].

5.3 Using orbiting solar reflectors (OSRs) as an Alternative to energy storage (ES) systems.

As the demand for renewable energy continues to soar, researchers have discovered a groundbreaking alternative to energy storage (ES) for maximizing the output and profitability of

solar farms. A recent study delves into the realm of orbiting solar reflectors (OSRs), which offer an innovative solution to extend solar energy generation beyond daylight hours. Traditionally, solar farms have been limited by the availability of sunlight. However, OSRs present a revolutionary concept by beaming additional illumination from space during crucial periods, effectively prolonging production hours and significantly increasing energy generation. The study focuses on assessing the short-term profitability and long-term economic viability of integrating OSRs or ES with solar photovoltaic (PV) farms. Various scenarios are examined, including fluctuating market conditions with hourly electricity price variations. The objective is to compare the economic value of integrating OSRs or ES under different circumstances, shedding light on their potential impact on solar farm profitability. The findings unveil a compelling insight. Irrespective of market conditions, integrating OSRs with solar farms proves to offer superior economic value compared to ES integration. This suggests that leveraging OSRs to enhance solar farm output emerges as a financially advantageous choice, outperforming the reliance on energy arbitrage achieved through energy storage systems.

In summary, this research introduces a game-changing proposition in the renewable energy landscape. The integration of orbiting solar reflectors (OSRs) with solar farms showcases exceptional potential for amplifying energy generation and bolstering profitability. Economic analyses conducted across various market conditions strongly support the economic superiority of OSR integration over energy storage systems. These findings mark a significant step forward in harnessing solar energy efficiently and reinforcing its viability as a key component of the energy transition. Looking ahead, future work will delve deeper into the impact of financial mechanisms and incentives, such as support policies and subsidies, on the deployment and utilization of OSRs for solar energy generation. Additionally, the economic feasibility of OSRs will be further examined alongside another fascinating concept: solar power satellites (SPS), which aim to harness renewable energy from space. With the advent of orbiting solar reflectors, the solar energy industry is poised for a transformative leap forward. This innovative technology holds immense potential to unlock new levels of profitability and extend solar energy production, propelling us closer to a sustainable and resilient future [31]. Fig. 4 illustrates a sketch of positioning solar reflectors around Earth.

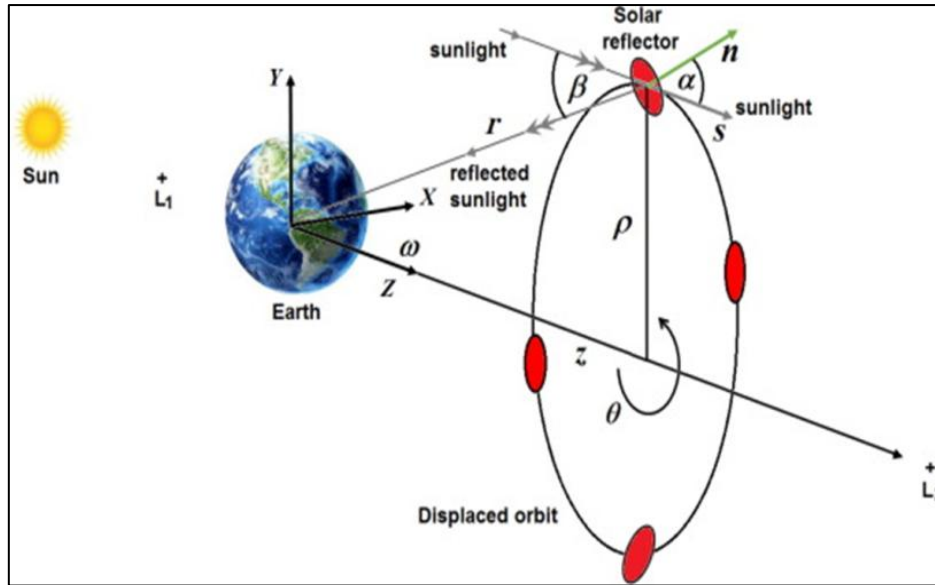


Fig. 4. Sketch of positioning solar reflectors around Earth [31]

5.4 The integration of flexible photovoltaic systems into grid management

In the quest for reliable and sustainable power systems, researchers have discovered a breakthrough approach using flexible solar power plants to provide ancillary services and implicit storage. A recent study examines the viability of leveraging solar energy to enhance grid management and ensure a stable electricity supply. Ancillary services play a critical role in maintaining the security and stability of power systems, encompassing essential functions such as frequency regulation, voltage control, and black start capability. Traditionally, these services have been fulfilled by large, dispatchable generators. However, the rapid increase in variable renewable energy (VRE), specifically solar power, presents unique challenges to the traditional approach. Solar power's intermittent nature makes it challenging to balance demand and supply, potentially resulting in grid instability. To address this issue, researchers propose harnessing the flexibility of solar photovoltaic (PV) systems to adjust their output in response to changes in demand or grid conditions. By smoothing out the variability of VRE generation, flexible solar power plants offer a more reliable and cost-effective means of providing ancillary services compared to conventional generators. Moreover, these innovative solar systems also offer implicit storage capabilities, referring to their ability to store energy by curtailing generation or shifting load. This implicit storage proves invaluable in balancing demand and supply, particularly during periods of peak demand. Fig. 5 illustrates a Flexible VRE systems scheme.

The benefits of utilizing flexible solar power plants for ancillary services are manifold:

- a. Smoothing out the variability of VRE generation, facilitating better demand-supply balance.

- b. Providing ancillary services reliably and cost-effectively compared to traditional generators.
- c. Offering implicit storage capabilities to support demand-supply balancing during peak demand.

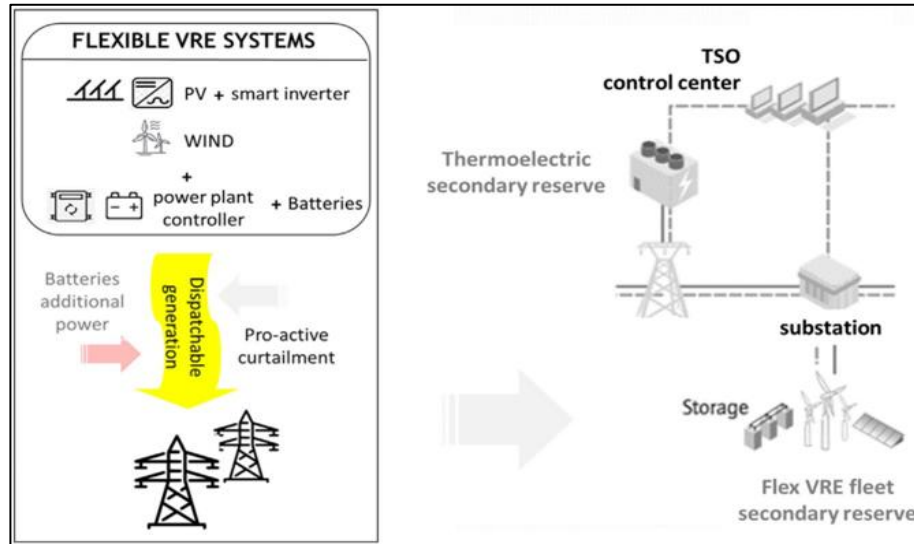


Fig.5. Flexible VRE systems scheme [30]

Nevertheless, the adoption of flexible solar power plants for ancillary services does present certain challenges:

- a. Potential requirements for additional grid infrastructure investment.
- b. Limitations in providing certain ancillary services across all locations.
- c. The need to address the comprehensive range of ancillary services required by the grid.

Overall, this research showcases a promising path for grid management by leveraging the potential of flexible solar power plants. The integration of ancillary services and implicit storage not only enhances the reliability and security of power systems but also contributes to reducing electricity costs. While challenges exist, further exploration and addressing these hurdles will be crucial for widespread adoption. In a paper titled "Ancillary Services via Flexible Photovoltaic Systems and Implicit Storage to Balance Demand and Supply," researchers propose a regulatory and business approach to effectively manage VRE in power systems. The study demonstrates the potential of flexible solar power plants to significantly reduce imbalance volumes and costs in grids with high VRE penetration. The findings indicate that the proposed approach offers a more environmentally friendly solution compared to the traditional reliance on building new thermoelectric reserves for grid balancing. By curbing 5-17% of total VRE generation, the system achieves stability while minimizing environmental impact [30].

6 SOLAR TRACKING AND CONCENTRATION

6.1 Solar tracking

This solar tracking system is an automatic tracking control system. Solar energy is a form of energy produced by capturing the power of sunlight. It is widely regarded as the most environmentally friendly energy source, as it minimizes harm to the climate. However, a significant drawback of solar energy is its inherent weakness. Even in the sunniest areas of the planet, the amount of solar radiation available rarely surpasses 1 kW/m, which falls short of meeting the requirements for effective technological utilization. Therefore, we can use a solar tracker to minimize this problem which ensures the maximum intensity of sun rays hitting the panel surface[33]. A solar tracker is a device designed to align a payload, such as solar panels, towards the sun. By utilizing solar trackers, the production of electricity can be enhanced by approximately one-third, with some sources suggesting increases of up to 40% in certain regions when compared to fixed-angle modules.[35] There are two primary types of solar tracking systems based on the degree of freedom in their movement: the single-axis solar tracking system and the dual-axis solar tracking system[34] as shown in Fig. 6.

- a. **Single-Axis Solar Tracker** - Single-axis solar trackers can be categorized into two types based on their axle orientation: horizontal and vertical. Horizontal axis trackers are suitable for tropical regions characterized by high sun elevation at noon but shorter daylight hours. On the other hand, vertical axis trackers are employed in high latitudes where the sun's elevation remains relatively low, but summer days are considerably longer[35].
- b. **Dual-Axis Solar Tracker** - Dual-axis solar trackers are equipped with both horizontal and vertical axles, enabling them to precisely track the apparent motion of the sun in any location worldwide. This type of solar tracker is extensively used in controlling astronomical telescopes, which means there is a wealth of available software to accurately forecast and follow the sun's trajectory across the sky. Dual-axis trackers provide enhanced power output (approximately a 40% increase) and added convenience as they track the sun both from east to west and north to south[35].

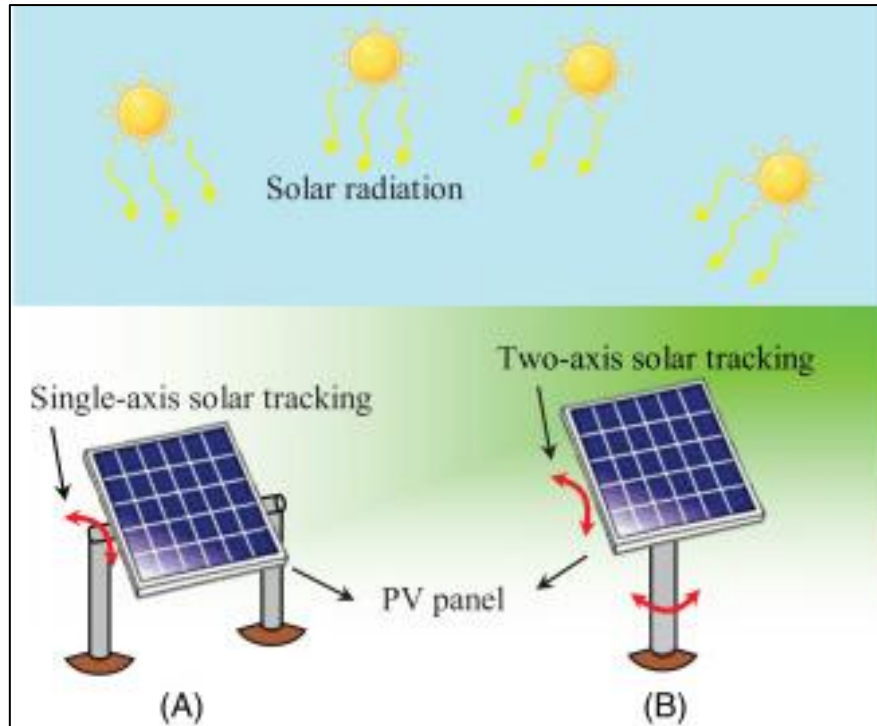


Fig.6. Types of solar tracking systems

Further, solar tracker drives can be categorized into three primary types based on their incorporated drive mechanism and sensing or positioning system as passive trackers, active trackers, and open loop trackers. Passive trackers utilize the sun's radiation to heat gases, propelling the tracker along its path across the sky. Active trackers, on the other hand, employ electric or hydraulic drives along with gearing or actuators to facilitate movement. Open-loop trackers do not rely on sensing mechanisms; instead, they determine the sun's position based on pre-recorded data specific to the site[35]. In various solar energy applications, the utilization of a solar tracking system is crucial. This system offers numerous advantages, including improved power and efficiency when compared to fixed systems. Moreover, it positively impacts the economic evaluation of large-scale solar energy projects [34].

6.2 Solar concentrators

A solar concentrator is a device designed to gather sunlight over a wide area and concentrate it onto a smaller receiver or exit point. It serves as a conceptual representation of a mechanism used to harness solar power for the generation of electricity[36]. Concentrated solar power (CSP) systems operate on a fundamental principle that remains consistent regardless of their specific design. The system involves reflecting the heat from the sun using mirrors, which then concentrate that heat onto a significantly smaller area. For instance, in the case of a parabolic mirror, the small area in focus aligns with the focal point of the parabola. Within this focal point, a receiver (typically a tube) containing a heat-retaining fluid, such as oil or molten salt, is positioned. The heated fluid is then conveyed to a heat exchanger, where heat transfer occurs between two fluids. The receiving fluid is typically water, which generates steam as a result. The steam is directed to a turbine, which drives a

generator to produce electricity [37]. Fig. 7 illustrates the Generation of electricity from the sun, with and without a solar concentrator.

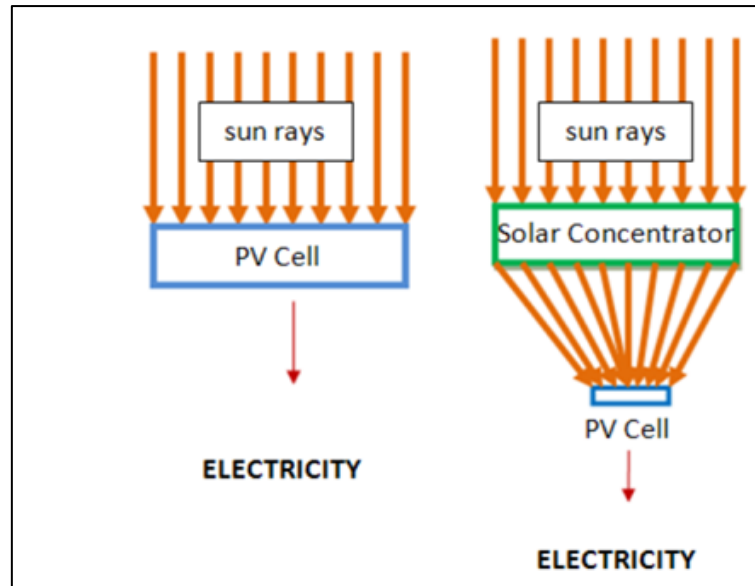


Fig. 7. Generating electricity from the sun, with and without a solar concentrator [36]

Over the last forty years, considerable advancements have taken place in the design of solar concentrators. This paper highlights several notable designs that have made significant contributions to solar technology.

- a. parabolic troughs / Parabolic Concentrator
- b. Hyperboloid Concentrator
- c. Fresnel Lens Concentrator [36]

a. parabolic troughs

A concentrated solar power (CSP) system utilizing a trough design comprises parabolic trough reflectors (mirrors) that concentrate sunlight onto a focal point formed by an absorber tube. The collector fields consist of multiple parallel rows of tubular collectors positioned along the North-South axis (line) as shown in Fig. 8. This setup enables the system to track the sun's movement from east to west throughout the day, ensuring a consistent focus on the sun. The tracking mechanism involves rotating the reflectors around the absorber tube, ensuring that they maintain a constant alignment for reflecting sunlight onto the absorber tube[37]. Currently, there exist two types of parabolic concentrator designs. The first design involves rotating a two-dimensional shape along the x-axis, resulting in a parabolic dish. The second design involves utilizing a parabolic trough. Both designs function as reflectors and are primarily employed in large-scale solar power plants that utilize concentrating solar power systems. While the parabolic concentrator can achieve a significant level of concentration, it necessitates a larger field of view to effectively capture solar energy. To ensure optimal efficiency, a reliable tracking system is essential, which can be quite costly.

Consequently, this type of concentrator is not commonly favored for small residential properties[36].

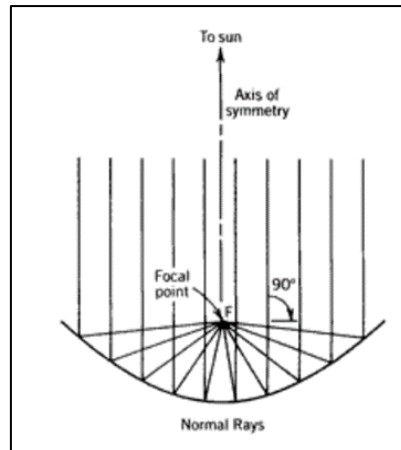


Fig. 8. The sun rays are focused at the focal point of the parabola [36]

b. Hyperboloid Concentrator

Fig. 9 illustrates the typical structure of a hyperboloid concentrator, composed of two hyperbolic sections, AB and A'B'. The hyperboloid concentrator is formed by rotating the two-dimensional design along its symmetrical axis. The diameters of the entrance and exit apertures are denoted as d_1 and d_2 , respectively. When the inner surface of the hyperbolic profile functions as a mirror, sunlight entering the concentrator from AA' is reflected and concentrated towards the exit aperture BB' [36]. The compact nature of this concentrator is its main advantage, as it only requires a truncated version of the full concentrator. Due to this characteristic, it is primarily employed as a secondary concentrator. One notable application of this concentrator is the development by SolFocus, aiming to reduce the cost of solar electricity. Their design, featuring a Cassegrain-like architecture, achieved a peak output of 250W in a single Generation 1 solar panel [36].

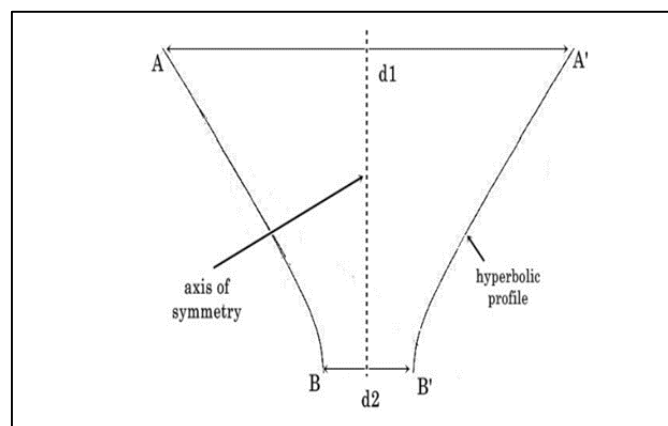


Fig. 9 . Hyperboloid Concentrator [36]

c. Fresnel Lens Concentrator

The Fresnel lens in Fig. 10 operates similarly to a traditional lens by refracting rays of light and converging them at a single focal point. It typically consists of two sections: a flat upper surface and a canted facet-based back surface that approximates the curvature of a lens. A high-quality linear Fresnel lens may feature approximately 100 facets per millimeter. This concentrator can be utilized in two ways: as a point-focus Fresnel lens or a line-focus Fresnel lens. An example of its application is observed in the Sacramento Municipal Utility District, where Fresnel lenses are employed in a 30kW utility grid-connected plant.

A notable advantage of using a Fresnel lens instead of a traditional lens is its thinner profile and reduced material requirement during fabrication. Additionally, it possesses the ability to effectively separate direct and diffuse light, making it well-suited for regulating the illumination and temperature within a building's interior. However, a disadvantage of this concentrator arises from the sharpness of its facets. If there is an error in the manufacturing process, it may result in rounder shapes at the edges of the facets, leading to improper focusing of the rays at the receiver [36].

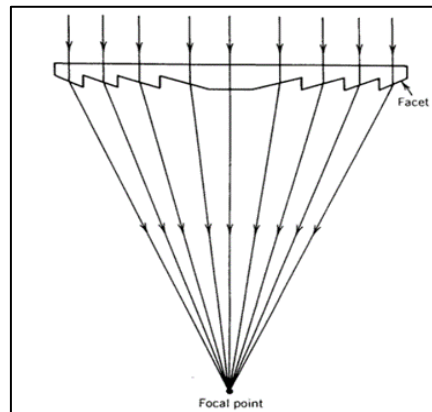


Fig. 10 . Fresnel Lenses [36]

7 ENVIRONMENTAL CONSIDERATIONS

Solar energy is a green energy source that is harnessed by the sun. When it comes to producing electricity using solar power PV (photovoltaic) technologies come to the stage. Emerging PV technologies have the potential to positively impact the environment and have negative impacts too. So, first, let's talk about what is the positive impact of PV technologies.

7.1 Positive Impacts

- a. **Increased Efficiency** – Emerging PV technologies often focus on improving the efficiency of solar panels, allowing them to convert a greater amount of sunlight into electricity. Higher efficiency means that less land or roof space is required to generate the same amount of power, reducing the overall environmental footprint of PV installations. It also enables more widespread adoption of solar energy, contributing to a cleaner energy mix and reducing the need for conventional fossil fuel-based power generation [38].

- b. **Reduced Material Consumption** – Some emerging PV technologies aim to reduce the use of rare or toxic materials traditionally used in solar panels, such as crystalline silicon. For example, thin-film solar cells use thinner layers of active material, reducing the amount of semiconductor material required. By minimizing the use of scarce resources and potentially hazardous substances, these technologies can reduce environmental impact and improve the sustainability of PV production[38].
- c. **Recycling and End-of-Life Management** – As the lifespan of PV systems progresses, there is an increasing focus on recycling and proper end-of-life management of solar panels. Emerging technologies are exploring ways to improve the recyclability of PV materials and optimize the recovery of valuable components. This approach helps prevent the accumulation of electronic waste and promotes the circular economy by reusing materials in the production of new solar panels[38].
- d. **Integration with Building Materials** – Building-integrated PV (BIPV) is an emerging field that seeks to seamlessly integrate solar panels into building materials such as windows, facades, or roofs. By incorporating solar energy generation directly into the built environment, BIPV can reduce the visual impact of PV installations and maximize energy production without requiring additional land or structures. This integration enhances the aesthetics of buildings while contributing to sustainable energy production[38].
- e. **Advanced Manufacturing Techniques** – Emerging PV technologies often explore innovative manufacturing processes that have the potential to reduce energy consumption, waste generation, and emissions during production. For example, some approaches focus on printable solar cells or roll-to-roll manufacturing, which can lead to more efficient use of materials and lower energy requirements. These advancements contribute to a more sustainable and environmentally friendly PV manufacturing industry[38].

While emerging PV technologies offer promising environmental benefits, it's important to consider the potential environmental impacts associated with their production, such as the extraction and refining of raw materials, energy requirements during manufacturing, and waste management. Lifecycle assessments and sustainability considerations are necessary to ensure that the overall environmental impact of these technologies is minimized throughout their entire lifecycle. Overall, emerging PV technologies have the potential to further enhance the positive environmental impact of solar energy by improving efficiency, reducing material consumption, promoting recycling, integrating with buildings, and adopting advanced manufacturing techniques.

7.2 Negative Impacts

- a. **Manufacturing and Raw Material Extraction** – The production of PV panels involves the extraction and processing of raw materials, such as silicon, cadmium, tellurium, and silver. These processes can generate pollution, contribute to habitat destruction, and have energy-intensive requirements. Additionally, mining activities

for rare earth minerals required in some PV technologies can have adverse environmental and social consequences if not managed responsibly[39].

- b. **Energy Intensity** – Although solar panels generate clean electricity during their operational life, the manufacturing process itself requires energy, often derived from fossil fuel sources. The energy intensity of PV production can lead to greenhouse gas emissions and contribute to environmental degradation, especially if the electricity used during manufacturing comes from non-renewable sources[40].
- c. **Waste Management** – PV panels have a long lifespan, typically ranging from 25 to 30 years or more. However, at the end of their life, solar panels can become electronic waste (e-waste). Proper disposal and recycling are crucial to prevent the accumulation of hazardous materials and ensure the recovery of valuable components. Inadequate waste management practices can result in pollution, leaching of toxic substances, and the potential release of heavy metals into the environment[39].
- d. **Water Consumption** – Some PV technologies, such as concentrating solar power (CSP), require water for cooling purposes. Water scarcity or inefficient water usage can pose environmental challenges, particularly in regions where water resources are limited. It is important to adopt water-efficient cooling systems or explore water-free cooling alternatives to minimize the water footprint of PV technologies[39].
- e. **Land Use and Ecosystem Impacts** – Large-scale PV installations require significant land areas, which may involve clearing natural habitats or converting agricultural land. Improperly planned PV projects can lead to habitat fragmentation, loss of biodiversity, and disruption of ecosystems. It is crucial to conduct thorough environmental assessments, prioritize brownfield or degraded land for PV installations, and implement measures to minimize the impact on ecosystems and biodiversity [40].

Addressing these negative environmental impacts requires proactive measures and sustainable practices throughout the lifecycle of PV technology. This includes promoting responsible raw material sourcing, improving manufacturing processes to reduce energy intensity, implementing effective recycling programs, managing e-waste, exploring water-efficient cooling systems, and adopting land use practices that prioritize biodiversity conservation and ecosystem protection. By considering and mitigating these potential environmental impacts, the overall sustainability and positive environmental contribution of PV technology can be maximized.

7.3 How to reduce the environmental impact due to emerging PV technologies.

To mitigate the environmental pollution associated with PV (photovoltaic) technology, several strategies and practices can be implemented throughout its lifecycle,

- a. **Sustainable Manufacturing** – Adopting sustainable manufacturing practices can reduce the environmental impact of PV panel production. This includes improving energy efficiency in manufacturing facilities, utilizing renewable energy sources for power, and implementing stringent pollution control measures. The use of eco-

friendly materials, such as non-toxic coatings or encapsulants, can also minimize pollution risks during manufacturing[42].

- b. **Responsible Raw Material Sourcing** – Promoting responsible sourcing of raw materials is crucial. This involves ensuring that mining activities for the extraction of minerals used in PV panels adhere to environmental regulations and best practices. Encouraging recycling and the use of recycled materials can also reduce the need for extracting new resources, thus minimizing environmental disruption[41].
- c. **Environmental Impact Assessments** – Conducting comprehensive environmental impact assessments before the installation of large-scale PV projects is important. These assessments should consider potential impacts on land use, biodiversity, water resources, and local communities. By identifying and addressing potential environmental risks early in the planning process, appropriate mitigation measures can be implemented to minimize negative effects[41].
- d. **Land Use Planning and Ecosystem Conservation** – Prioritizing the use of already degraded or underutilized land for PV installations can minimize the impact on natural habitats and ecosystems. Incorporating ecological considerations into site selection and design can help preserve biodiversity and promote habitat restoration. Implementing measures to protect and enhance local ecosystems, such as planting native vegetation and creating wildlife corridors, can further mitigate environmental impacts[42].
- e. **Community Engagement and Education** – Engaging with local communities and stakeholders and providing education about the benefits of PV technology can foster acceptance and support for renewable energy projects. Involving communities in the planning and decision-making processes allows for better consideration of environmental concerns and ensures that the benefits of PV technology are shared equitably[41].

By implementing these strategies and practices, the environmental pollution associated with PV technology can be effectively mitigated, allowing for the maximum environmental benefits of solar energy to be realized.

8 POLICIES REGARDING SOLAR PHOTOVOLTAIC TECHNOLOGY

Policies have a significant impact on the development and implementation of solar photovoltaic (PV) technology, which is experiencing rapid growth. The following are several typical policies linked to solar PV technology.

8.1 Feed - in Tariffs (FiTs) Policy

Sijm observes that the term "feed-in tariff" is sometimes used with slight variations in meaning in the literature. Typically, it refers to the minimum price per kilowatt hour that an electric utility is obligated to pay to a private renewable power producer for electricity fed into the grid. However, occasionally it is used to encompass the total amount per kilowatt

hour received by an independent renewable electricity producer, including subsidies and/or tax refunds. In exceptional cases, it may refer only to the extra price paid above the market price of electricity. In this article, the focus is on programs that align with the first and last definitions provided by Sijm. These programs involve guaranteed payments per kilowatt hour to renewable electricity producers, either independently or in addition to the market price of electricity [43].

Currently, 11 out of the 15 countries in the European Union have implemented feed-in tariffs. However, these tariffs can vary significantly across different countries, even if they meet the definition provided earlier. As mentioned before, the payment structure can be either a fixed price or a premium price, which is an additional amount on top of the market price. [43] Germany's system exemplifies the former, while part of Spain's system represents the latter. In Spain, energy developers have the option to choose between a fixed payment or a fixed premium above the market price. Regardless of the choice, these payments are evaluated annually, taking into account market predictions, within a price range of 80% to 90% of the pretax consumer price of electricity [43].

8.2 Net Metering Policy

Net metering is a policy that empowers solar photovoltaic (PV) system owners to export surplus electricity they generate back to the grid and receive compensation in the form of credits. This policy allows PV owners to offset their electricity consumption during periods of low solar production.[44]With net metering, when a solar PV system produces more electricity than is consumed on-site, the excess power is sent to the grid. The utility company then credits the PV owner for the surplus electricity at the same rate they charge for grid-supplied electricity. These credits can be utilized to offset future electricity bills when the PV system isn't generating enough power, such as at night or during cloudy weather [47].

Net metering serves as a financial incentive, reducing the payback period for PV system investments and encouraging their adoption.[44]. It enables individuals, businesses, and institutions to generate their renewable energy, diminishing their reliance on conventional energy sources. Additionally, net metering policies contribute to grid stability and reliability by incorporating distributed generation sources. It's important to recognize that net metering policies may vary across jurisdictions, encompassing specific regulations and criteria. Factors like eligibility requirements, system size limitations, credit rates, and carry-forward periods for surplus credits can differ based on the local regulatory framework [44].

8.3 Renewable portfolio standards (RPS) and renewable energy Targets Policy

Renewable portfolio standards (RPS) have gained significant popularity as a policy tool to support the deployment of renewable energy technologies over the past decade. While the specifics of RPS design can vary, the core concept is fairly straightforward: electricity suppliers, generators, or consumers are mandated to progressively increase their procurement of renewable energy. Many jurisdictions allow for the trading of renewable energy certificates to enhance compliance flexibility and facilitate verification. RPS programs, which may also be referred to as quota systems, renewables obligations, renewable energy

standards, or tradable green certificate programs, are widely implemented at the state level in the United States and have been adopted in countries such as Australia, Belgium, Canada, China, India, Italy, Japan, Poland, Sweden, and the United Kingdom. Despite its widespread adoption, the RPS policy is still relatively new, and there is limited experience and understanding of its effectiveness [45].

8.4 Investment Tax Credits (ITCs) and Grants Policy

The Investment Tax Credits (ITCs) and Grants policy is an important incentive in the realm of solar photovoltaic (PV) technology. This policy provides financial support to individuals, businesses, and organizations that invest in solar PV systems.

- a. **Investment Tax Credits (ITCs)** - ITCs are tax benefits provided by governments to lower the initial expenses associated with solar PV system installations.[44] With ITCs, a portion of the total solar installation cost can be claimed as a tax credit. This credit is subtracted from the tax obligations of the system owner, resulting in a reduced overall tax liability. The exact percentage and eligibility requirements for ITCs can differ depending on the jurisdiction.
- b. **Grants** - Grants are direct monetary support offered by government agencies, organizations, or foundations to promote the adoption of solar PV technology. These grants provide financial assistance to offset a portion of the expenses involved in purchasing and installing solar PV systems. Typically, grants are distributed through a competitive application process and may have specific guidelines and priorities established by the grant provider [46].

8.5 Green Building Codes and Standards

The policy of Green Building Codes and Standards is instrumental in driving the incorporation of solar photovoltaic (PV) technology in building construction and design. It involves the creation of precise regulations, guidelines, and requirements to enforce energy-efficient and sustainable practices, with a particular emphasis on the adoption of solar PV systems.

- a. **Energy Efficiency Standards** - Green Building Codes and Standards include guidelines for energy efficiency in buildings, encompassing criteria related to energy performance, insulation, ventilation, lighting, and other relevant factors aimed at reducing energy usage. These standards frequently feature provisions and incentives to encourage the installation and utilization of solar PV systems, allowing for the generation of clean, on-site renewable energy.
- b. **Solar PV system Integration** - The policy encourages the incorporation of solar PV systems into the design and construction of buildings. It may establish specific guidelines regarding the installation, capacity, orientation, and placement of solar panels to maximize energy generation and minimize potential issues such as shading or obstructions.
- c. **Building Certification Programs** - Green Building Codes and Standards are frequently linked to certification programs like LEED (Leadership in Energy and

Environmental Design) or BREEAM (Building Research Establishment Environmental Assessment Method). These programs evaluate and acknowledge buildings that meet predefined sustainability benchmarks, which may include the incorporation of solar PV technology.

- d. **Compliance and Enforcement** - Compliance and enforcement mechanisms are integral components of Green Building Codes and Standards policies, ensuring that the prescribed requirements are followed. These policies often entail obtaining building permits, undergoing inspections, and obtaining certifications to verify compliance with the energy efficiency and solar PV integration provisions [47].

9 CHALLENGES

The utilization of photovoltaic (PV) cells is on the rise in response to the increasing need for generating environmentally friendly power. However, achieving broader acceptance and implementation of PV technology is expected to hinge upon effectively addressing the following obstacles.

9.1 Performance

Solar panel systems' ability to convert sunlight into electricity, known as performance, determines their efficiency. The performance of photovoltaic (PV) cells is typically evaluated using two standardized conditions: the standard test conditions (STC) and the photovoltaics for utility-scale applications (PVUSA) test conditions, also called the PTC test. STC is an industry-wide standard that assesses PV module performance based on fixed conditions:

- a. Solar cells and ambient temperature are set at 77°F.
- b. Irradiance of 1,000 W/m².
- c. Air mass 1.5 (AM1.5) spectrum.

During manufacturing, solar cell and panel power output may vary (around 5-6 percent). Although STC conditions don't replicate real-world scenarios, they help manufacturers categorize panels by power output to ensure similar panels are used together. For instance, a PV panel with a measured output of 258 W would fall into the "255 to 259.9" watt category. However, to ensure the manufacturer's claimed performance, purchasers/designers of solar modules often engage third-party inspectors for quality control. The PTC test, on the other hand, sets the solar cell temperature to 113°F and the ambient temperature to 68°F. Higher temperatures cause a voltage drop and subsequently decrease power output. The PTC test aids installers in appropriately sizing and selling PV systems while providing a more accurate performance prediction. Designers of PV panels can consider both standards to estimate the optimal inverter size for the system. (Usually, the PTC system's output is approximately 8-10 percent lower than the STC rating) [48].

9.2 Manufacturability

Solar panels typically convert around 15-22 percent of sunlight into usable energy, which can

vary based on factors such as positioning and weather conditions. At 22 percent efficiency, solar panels can provide sufficient power to run a house throughout the night or during a blackout. The three primary types of PV panels are monocrystalline silicon, polycrystalline silicon, and thin film. Among these, monocrystalline silicon panels, constructed with the highest-grade silicon, offer the highest efficiency.

Seeking solar panels with improved efficiency while keeping costs low is challenging for users who prefer affordability. Engineers and scientists are working to enhance cell efficiency and reduce manufacturing expenses to make solar energy more economically competitive. Various factors contribute to the cost of solar panels, with material costs being a significant driver of price fluctuations [48].

9.3 Reliability

In this context, reliability refers to the capacity of an energy source to be self-sufficient and cost-effective. Consequently, designers face a significant challenge in ensuring the use of high-quality materials. PV panels must have a minimum 20-year lifetime warranty to meet the expectations of residential customers who prefer avoiding the expenses, time, and inconvenience associated with frequent reinstallations. The materials used must possess outstanding properties such as efficient reflection and transmission and resilience against moisture and impact, among others [48].

9.4 Location

Solar energy generation achieves higher efficiency in regions with abundant sunny days. Additionally, the positioning of solar panels impacts their efficiency, as direct sunlight exposure enhances their performance. Certain solar panels are equipped with movable tracking systems that enable them to follow the sun's path throughout the day, further increasing their efficiency.

The photovoltaic industry still holds potential for growth and innovation. The demand for alternative energy sources continues to rise, and advancements in solar panel technologies and improved energy storage solutions will aid in overcoming the challenges. This presents an opportunity for further development and progress in the solar energy sector [48].

10 FUTURE OUTLOOK

10.1 Ongoing Research and development efforts

Ongoing research efforts aimed at improving the stability, efficiency, and durability of PV cells and modules.

a. Exciton fission: One photon in, two electrons out

Photovoltaics, which involves converting light into electricity, is a crucial technology for sustainable energy. It has been known since Max Planck and Albert Einstein's

time that light and electricity exist in discrete packets called photons and electrons, respectively. In a solar cell, the energy of a single photon can be transferred to a single electron in the material, but not more than one electron. However, there are a few exceptional molecular materials like pentacene, where one photon can generate two electrons through a process called exciton fission. This phenomenon of exciton fission can significantly enhance photovoltaics' efficiency, particularly in improving the dominant silicon-based technology. In a significant development, researchers have now made progress in understanding the initial step of this process by capturing an ultrafast movie of the conversion of photons to electricity. This breakthrough has resolved a long-standing debate about the mechanism behind this process. The findings hold promise for advancing the field of high-efficiency photovoltaics and could contribute to the improvement of solar energy technologies [49].

b. New findings pave the way for stable organic solar cells that may enable cheap and renewable electricity generation

Organic solar cells offer significant potential for clean energy applications. However, photovoltaic modules utilizing organic semiconductors tend to experience a rapid decline in efficiency when exposed to sunlight, limiting their practical usability. Scientists have recently made a significant discovery that sheds light on the underlying cause of this degradation in organic solar cells during operation. This newfound understanding will fuel the development of more stable materials for organic semiconductor-based photovoltaics, ultimately enabling the generation of affordable and renewable electricity [50].

c. Scientists create high-efficiency sustainable solar cells for IoT devices with AI-powered energy management

The findings, published in the journal Chemical Science, can bring about a revolutionary change in the power source of Internet of Things (IoT) devices. This advancement holds the potential to enhance the sustainability and efficiency of these devices, while also creating new possibilities in sectors like healthcare, manufacturing, and the development of smart cities [51].

d. One-step solution-coating method to advance perovskite solar cell manufacturing and commercialization

Perovskite solar cells (PSCs) have emerged as a highly promising contender for future photovoltaic technology due to their remarkable efficiency and cost-effectiveness, offering the potential to revolutionize the renewable energy sector. However, the current layer-by-layer manufacturing method poses challenges that have impeded the widespread adoption of this technology. In a recent breakthrough, scientists have devised an innovative one-step solution-coating technique that streamlined the manufacturing process and reduced the barriers to commercialization for PSCs [52].

e. The next decade is decisive for PV growth on the path to 2050

Leading solar power experts worldwide emphasize the importance of making a steadfast commitment to the ongoing expansion of photovoltaic (PV) manufacturing and deployment as a primary means of meeting global energy needs. They argue that underestimating the growth potential of PV and relying on uncertain future energy pathways or technological breakthroughs is no longer viable. Taking decisive action toward PV expansion is deemed imperative to power the planet sustainably [53].

10.2 prospects

The prospects of solar energy technology show exciting opportunities for further advancement.

a. Tandem Cell Commercialization

Two significant losses in solar cells are sub-band gap transmission and the thermalization of hot charge carriers. One effective approach to address both issues simultaneously is the development of tandem solar cells. Extensive research by De Vos has focused on the fundamental limit of performance for tandem structures. It has been demonstrated that stacking multiple sub-cells in series can achieve theoretical efficiencies surpassing the Shockley-Quizzer limitation. This improvement is primarily attributed to the enhanced electrochemical potential for extracting charge carriers. While a single solar cell has a maximum efficiency of approximately 30% under non-concentrated sunlight, this value can be increased to 42% for a tandem structure consisting of two sub-cells with band gaps of 1.9 eV and 1.0 eV, respectively. For a tandem with three sub-cells having band gaps of 2.3 eV, 1.4 eV, and 0.8 eV, the efficiency rises to 49%. These efficiencies are further enhanced under concentrated sunlight, reaching 40% (one cell), 55% (two cells), and 63% (three cells).

This model also predicts the ideal efficiency of a stack with an infinite number of solar cells, which could achieve conversion rates of 68% for non-concentrated sunlight and 86% for concentrated sunlight. Recent experimental measurements on a GaInP/GaInAs device under AM1.5G conditions have demonstrated efficiencies as high as 33.8% [54].

b. Building Integrated Photovoltaics (BIPV) System

Building Integrated Photovoltaics (BIPV) refers to the integration of photovoltaic systems into the building envelope, serving as both a power generator and a replacement for conventional building materials. By incorporating PV modules directly into the building structure, the additional costs associated with separate mounting systems are avoided, resulting in improved cost-effectiveness throughout the system's lifecycle.

A complete BIPV system includes:

- I. the PV modules (which might be thin-film or crystalline, transparent, semi-transparent, or opaque).
- II. a charge controller, to regulate the power into and out of the battery storage bank (in stand-alone systems).

- III. a power storage system, generally comprised of the utility grid in utility-interactive systems or, several batteries in stand-alone systems.
- IV. power conversion equipment including an inverter to convert the PV modules' DC output to AC compatible with the utility grid.
- V. backup power supplies such as diesel generators (optional-typically employed in stand-alone systems); and
- VI. appropriate support and mounting hardware, wiring, and safety disconnects.

Fig. 11 shows a BIPV system diagram and, they can be designed to either connect with the utility grid or operate independently as off-grid systems. Producing power at the point of use offers several advantages, including reduced losses associated with transmission and distribution (known as 'grid support') for the utility, and lower electric bills for consumers through peak shaving, which matches peak production with periods of peak demand. Furthermore, buildings that generate power from renewable sources contribute to a decrease in emissions of greenhouse gases, thereby supporting efforts to combat climate change [55].

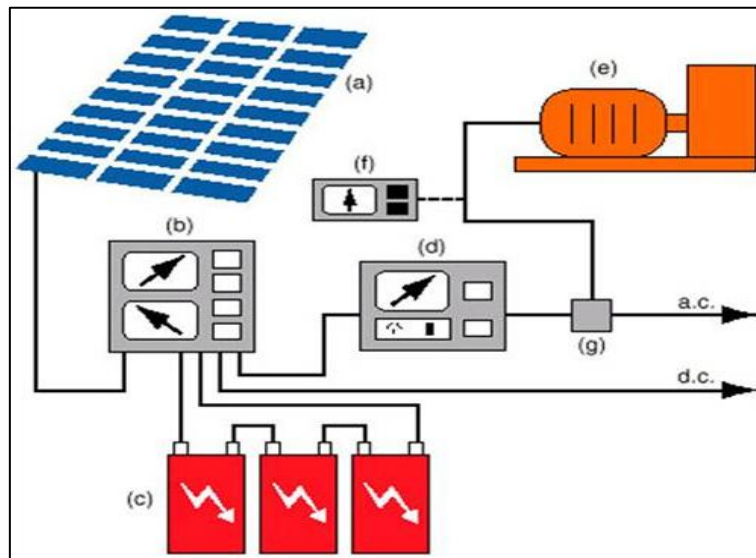


Fig. 11. BIPV system diagram [55]

c. Artificial Intelligence for Optimizing Solar Energy Systems

Artificial intelligence (AI) techniques are increasingly being adopted as alternative approaches or integrated components in various domains. They offer effective solutions to complex practical problems and have recently gained significant popularity. AI systems possess the ability to learn from examples, tolerate faults by handling noisy and incomplete data, address nonlinear problems, and execute high-speed prediction and generalization once trained.

The versatility of AI lies in its symbolic reasoning, adaptability, and explanatory capabilities, which have led to the development and implementation of AI-based systems worldwide across diverse applications. Engineering, economics, medicine, military, and marine industries have embraced AI technology. Its applications encompass modeling, identification,

optimization, prediction, forecasting, and control of intricate systems [56].

d. Perovskite Solar Cells

A perovskite solar cell (PSC) is a type of solar cell that incorporates a perovskite-structured compound, typically a hybrid organic-inorganic lead or tin halide-based material, as its active layer for light absorption. These perovskite materials, such as methylammonium lead halides and caesium lead halides, are cost-effective to produce and easy to manufacture. Over the years, the efficiency of laboratory-scale perovskite solar cells has significantly improved, from 3.8% in 2009 to 25.7% in 2021 for single-junction designs. In tandem cells combining perovskite with silicon, efficiencies have reached 29.8%, surpassing the maximum efficiency achieved by single-junction silicon solar cells. This progress has made perovskite solar cells one of the most rapidly advancing solar technologies since 2016. Their potential for even higher efficiencies and low production costs has made them commercially appealing, although stability issues remain a key area of research.

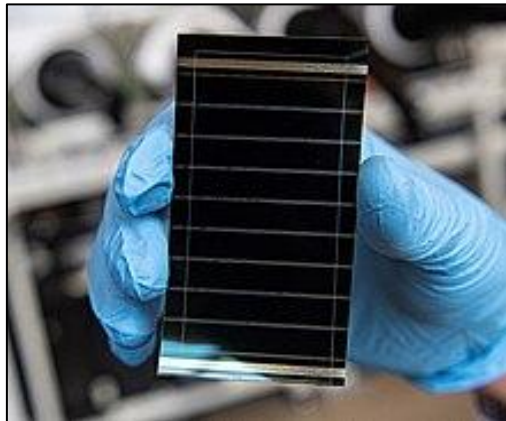


Fig. 12. Perovskite solar cell [57]

Fig. 12 indicates a Perovskite solar cell and, they offer several advantages due to the raw materials used and the fabrication methods employed, such as various printing techniques, which contribute to their affordability. Their high absorption coefficient allows ultrathin films of approximately 500nm thickness to capture the entire visible solar spectrum. These characteristics make it possible to create low-cost, highly efficient, thin, lightweight, and flexible solar modules. Perovskite solar cells have found applications in powering prototypes of low-power wireless electronics for ambient-powered Internet of Things (IoT) devices, and they hold promise for mitigating climate change. Additionally, perovskite cells possess favorable optoelectrical properties for solar cell usage. For instance, they have a small exciton binding energy, facilitating the easy separation of electron-hole pairs upon photon absorption. Furthermore, their long diffusion length and high diffusivity enable charge carriers to travel long distances within the perovskite solar cell, improving their collection and conversion into power. Lastly, perovskite cells exhibit broad absorption ranges and high absorption coefficients, further enhancing their power efficiency by capturing a wider range of photon energies [57].

e. Floating Solar Power Plants

Floating solar, also known as floating photovoltaics (FPV) or floatovoltaics, refers to the installation of solar panels on structures that float on water bodies such as reservoirs, lakes, and canals. Fig. 13 represents a Floating photovoltaic on an irrigation pond. This technology has been implemented in various countries including China, France, India, Japan, South Korea, the United Kingdom, Singapore, and the United States.



Fig. 13. Floating photovoltaic on an irrigation pond [58]

Compared to land-based photovoltaics, floating solar offers several advantages. Water surfaces are often more cost-effective than land, and there are fewer regulations for structures built on non-recreational bodies of water. Life cycle analysis indicates that foam-based FPV systems have a short energy payback time (1.3 years) and low greenhouse gas emissions (11 kg CO₂ eq/MWh) compared to other solar technologies. Additionally, floating arrays can be visually unobtrusive as they are hidden from public view and benefit from the cooling effect of water, resulting in higher panel efficiency. Special coatings can be applied to prevent rust and corrosion. Notable early examples include the floatovoltaic system installed by the Far Niente Winery in California in 2008 and the large-scale 13.4 MW farm developed by Kyocera in Japan. Floating solar farms resistant to saltwater are also being constructed for ocean use. Although the costs of floating systems are slightly higher (10-20%) than ground-mounted systems, the market for this renewable energy technology has experienced rapid growth since 2016. By 2020, the installed power capacity had reached 3 GW, with a projected increase to 10 GW by 2025 [58].

f. grid-Interactive Solar Systems

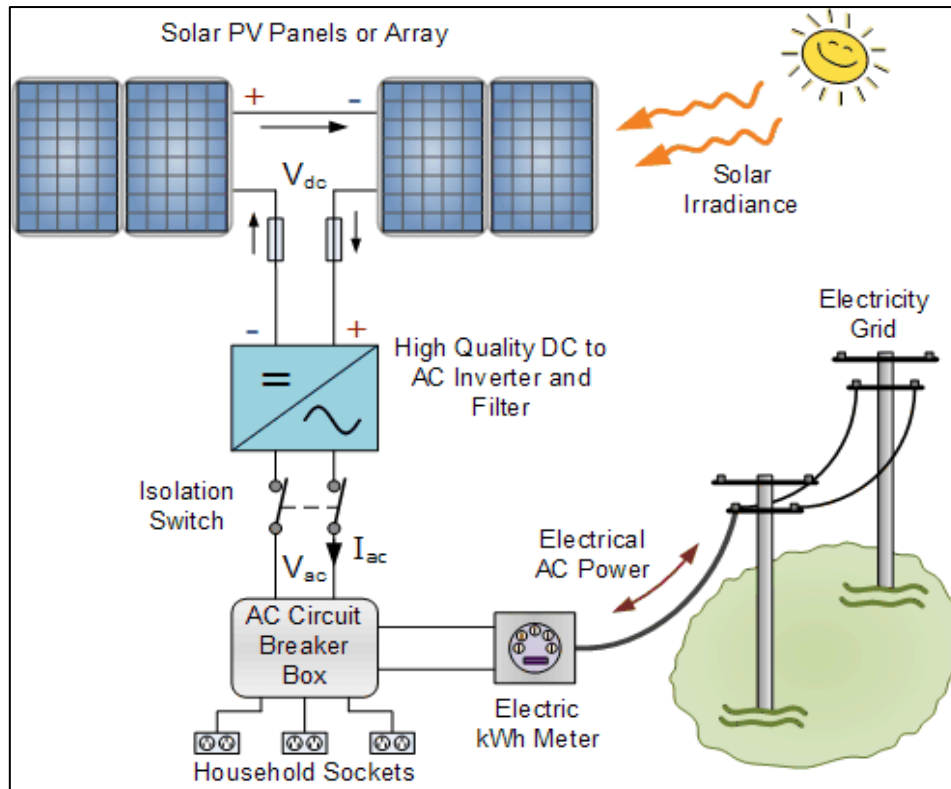


Fig. 14. Simplified Grid-Connected PV System [59]

A grid-interactive solar system harnesses the abundant energy of sunlight to generate clean power. It utilizes grid-interactive inverters that can also utilize other renewable sources like wind or hydropower. During daylight hours, the photovoltaic (PV) system charges its deep-cycle solar batteries and sends any surplus electricity into the grid through the inverter. A simplified Grid-Connected PV System in Fig. 14 and, At night or when solar power is unavailable, the system can draw power from the grid. In the event of a power outage, the inverter can draw clean power from the solar panels and batteries to meet the electricity needs of a home or business, essentially functioning as a stand-alone system. The advantages of a grid-interactive PV system are numerous. It allows the option to feed clean energy into the grid when it is beneficial and disconnect when it is not. It provides independence to use self-generated solar and battery power during grid failures. It also enables access to any available credits and benefits associated with grid-tied systems. Furthermore, it ensures the maximum utilization of the clean energy produced, as opposed to off-grid systems where much of the energy can go to waste. Grid-interactive systems offer two equally available power sources, leading to a more reliable power supply and reduced costs. Additionally, they contribute to a more sustainable energy future. It is important to note that the design and installation of grid-interactive systems can be more complex compared to other solar setups [60].

The prospects for further advancement in the photovoltaic (PV) solar energy sector are highly promising. Researchers and industry professionals are actively working on various fronts to address existing challenges and push the boundaries of PV technology with advancements expected in efficiency, stability, cost reduction, energy storage, grid integration, innovative

designs, and environmental sustainability. Continued research, industry collaboration, and policy support will play crucial roles in realizing these advancements and enabling the widespread adoption of solar PV technology as a clean and sustainable energy solution.

11 CONCLUSIONS

The advancements in photovoltaic (PV) technology have transformed solar energy generation, making it more efficient, affordable, and accessible. Through improvements in materials, cell architectures, and manufacturing techniques, PV efficiency has increased significantly, leading to enhanced overall performance and cost-effectiveness of solar panels. Emerging PV technologies, including perovskite, tandem, and organic solar cells, offer promising advantages, although challenges regarding efficiency, stability, and scalability remain. Innovative manufacturing approaches such as roll-to-roll printing and thin-film deposition have contributed to the scalability and cost reduction of solar panels. The integration of energy storage technologies, such as batteries and advanced energy management systems, has improved reliability and grid integration. Solar tracking systems and concentrator technologies optimize solar energy capture, resulting in increased energy production and improved efficiency. Environmental considerations, including recycling initiatives and the use of eco-friendly materials, aim to mitigate the environmental impacts associated with PV systems. Economic factors and policy frameworks play crucial roles in promoting the widespread adoption of solar PV technology. Despite the progress made, challenges persist in enhancing stability, reducing costs, and improving grid integration. Ongoing research and prospects hold the potential for further advancements in PV technology, paving the way toward a sustainable and renewable energy landscape.

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