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State-of-Art Techniques for Photovoltaic (PV) Power Systems and their Impacts

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Abstract: *Solar energy, a ubiquitous and free resource, has vast potential for addressing global energy needs through direct conversion into heat or electricity using photovoltaic (PV) and solar thermal technologies. The evolution of photovoltaic (PV) technology has transformed solar energy from a niche application to a major component of the global energy landscape. This article summarises the latest developments in photovoltaic power systems, with an emphasis on crystalline silicon and thin-film technology. It highlights key developments in efficiency, cost reduction, and emerging technologies such as organic photovoltaics and nanostructure oxide films. Despite significant progress, challenges remain, including cost, efficiency, and integration with energy systems. The paper concludes with recommendations for future research, emphasising the need for improved efficiency, durability, and integration of AI and energy storage solutions to improve a viability and sustainability of solar power*

Keywords: photovoltaic, solar cell, efficiency, lifetime, thin film, Organic photovoltaics, crystalline silicon.

I. INTRODUCTION

Although it is used in the most archaic ways, solar energy has been the most accessible and affordable source of energy since the beginning of time. Numerous commercial and industrial applications may be directly powered by solar energy, such as heating, lighting, producing electricity, cooking, heating water, chilling, and drying items[1]. As much as 4 times an Earth's total energy consumption could be converted into heat or electricity using PV and other direct conversion technologies. The quantity of solar energy that reaches Earth's surface is far higher—by several thousand times—and there is a huge amount of potential for this conversion, exceeding 440,000 TW each year[2].

Solar thermal and solar photovoltaic pathways exist for the utilisation of solar energy. Solar thermal devices are collectors and receivers that turn solar energy into thermal energy. PV-generated DC power, which can be either immediately used or stored for use at a later time, is transformed into AC power[3]. Compared to conventional sources, this kind of solar energy is more costly. The pricing difference has, however, narrowed during the last 20 years. SPV technology has evolved as a practical power source for applications like lighting and supplying electricity to towns, hospitals, telecommunications centres, and homes.

The present status of photovoltaic technology has a major impact on global energy production because of the disadvantageous cost structure of solar devices, which has prevented their broad adoption. The use of expensive semiconductor processing technology is the primary economic factor in the production of traditional solar cells. Cost-effectively, R2R printing, coating,and lamination are attractive methods for creating photovoltaic components on thin plastic sheets. Next generation photovoltaic systems, which use materials other than silicon, will have a faster commercial acceptance if large-area coating methods applied to a class of inexpensive materials are widely used[4].

Numerous factors influence local solar radiation intensity, including latitude, season, air quality, pollution index (smog), and atmospheric conditions (such as precipitation, snowfall, fog, humidity, etc.). Hybrid renewable energy systems, which include solar electricity with existing power networks, provide a substantial and persistent technological and stability issue [5]. The problems arise from the fact that solar irradiation, temperature, PV production, expensive energy storage technologies, grid stability, and seasonal influences are always changing. Additionally, this design affects grid stability; integrating PV power network as a backup electric source to satisfy increasing demand is not physically practicable. To sum up, fluctuations in weather conditions cause PV output uncertainty, which in turn causes penetrations, surges, reverse power flows, harmonic distortion, fluctuations in frequency, and other issues with current and voltage waveforms. Power system operating dependability, stability, and scheduling, as well as economic dispatch, are all significantly affected by such erratic output. A trustworthy estimate for PV output will significantly reduce uncertainty, boost stability, and increase economic viability. As a result, accurate PV power forecasting (PVPF) is currently an important area of research.[6]

1.1 Structure of this paper

Here is the structure of the paper: The development of PV power systems and their key features are covered in Section II. Information on the most recent advances in PV power system technology is provided in Section III. Section IV reviews impacts of state-of-art techniques for photovoltaic (PV). Section V presents a literature review. and VI offers recommendations for conclusions and future work.

II. OVERVIEW OF PHOTOVOLTAIC (PV) POWER SYSTEMS

Solar cells are primarily made up of semiconducting materials with electrical connections and a protective layer on top of them. The manufacturing cost, thickness, and photo-conversion efficiency of the resulting devices range greatly because to the large diversity of semiconducting materials used.

2.1 Basic principles of PV technology

The most popular type of conventional solar cell is polycrystalline Si, which uses inorganic semiconductor materials and has p-n junctions that keep the electric field balanced. Solar cells generate a photocurrent when light strikes them and causes an internal field to form and dissociate charge carriers. In contrast, photovoltaic systems made of organic materials use a heterojunction design rather than an internal electric field[7].

2.2 Historical development and evolution

Despite silicon's early domination in labs, it has already entered the commercial module industry. Even though non-crystalline silicon modules made up about 15% to 18% of the industry, crystalline silicon designs have consistently made up more than 80% of a market for commercial modules. The PV industry, defined as an energy delivery system of 1kW or more, is based on amorphous silicon and is almost exclusively used in consumer devices [8]. The majority of silicon modules (94% at present) are either single-crystal or polycrystalline. There is a vast array of PV cell technologies available now, made from various materials, and an even greater variety will be available in the future. Based on the primary component and degree of commercialisation, photovoltaic cell technologies are typically categorised into 3 distinct generations.

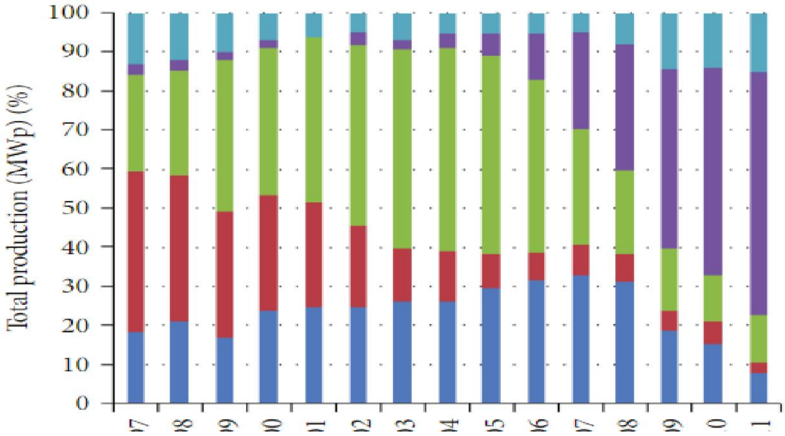

Figure 1: PV cells/modules production by region 1997–2011.

The Japanese firm Sharp, which had just started making commercial PV modules, finished installing the biggest commercial PV installation in the world—a 242-watt (W) module erected on top of a lighthouse—in 1963. This marked the beginning of commercial manufacture of c-Si modules (M.A. Green 2001). Using data from the Navigant consulting graph PSE AG 2012, Figure 1 shows the total output of PV cells and modules by region from 2007 to 2011. It has come to light that Japan's production capacity for PV cells and modules increased from 1997 to 2004 before experiencing a significant decline following 2004. The manufacturing of PV cells and modules followed a similar pattern in Europe as well, but only until 2008. After that, production capacity was reduced. However, the US's production capacity for PV cells and modules peaked in 1997, and it then steadily decreased annually. However, China's production situations for PV cells and modules were exactly the opposite of those in the US. Figure 2 presents another noteworthy image pertaining to the worldwide cumulative PV installation up until 2011. Up until 2011, when the world's PV installations reached 70% of their total, Germany and other European countries continued to play a significant role in this sector. Therefore, the European PV installation industry is exceptionally promising at the moment when compared to other nations[1].

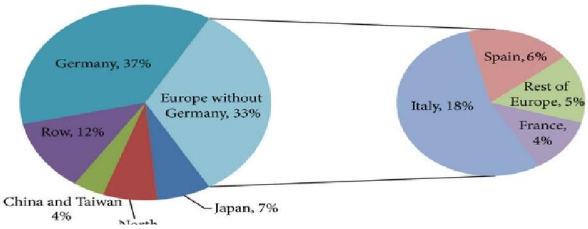

Figure 2: Installation Global cumulative PV installation until 2011 (data: EPA Graph: PSE AG 2012). All percentages are related to the total global.

2.3 Important characteristics of PV technology

Given below are some important characteristics of PV technology:

Efficiency

The principal metric for evaluating a photovoltaic device's effectiveness is its power conversion efficiency, which measures the percentage of solar energy that is transformed into electricity. When choosing a design for a product, efficiency is key.

Lifetime

A key component in the commercialisation potential of PV technology is the lifetime of the device. Based on the usual useful life of PV-powered electronics, the three- to five-year lifespan (*3000 - 5000 operational hours) is considered the entry point for inexpensive devices like mobile information and communication technology products (laptop and mobile phone chargers).

Cost

The production cost, which includes materials, manufacturing, and equipment expenses, is the second critical parameter of a solar device.

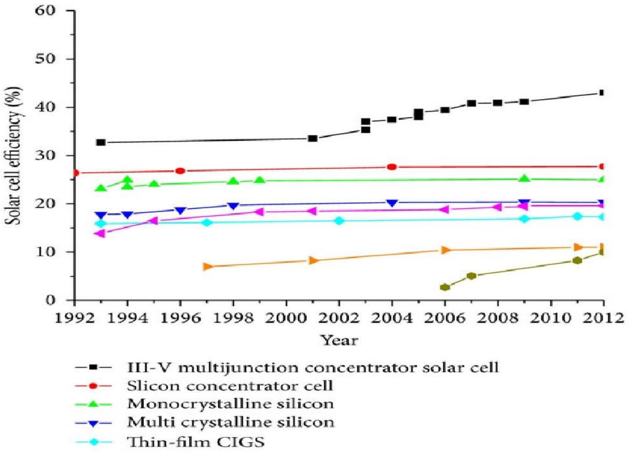

Figure 3: Development of laboratory solar cell efficiency (Data: Solar Cell Efficiency tables (version 1-40), Progress in PV: Research and Applications, 1992–2012, Graph: Simon Philipps, Fraunhofer ISE).

Figure 3 also shows the best laboratory cell compared to the best laboratory module made using various PV technologies. It was noted that the efficiency of monocrystalline solar cells was 25%, and that of modules was 22.9%, while the efficiency of multi-crystalline solar cells was 20.4% and that of modules was 18.2%. It is crucial to keep in mind that a thin-film CI(G)S solar cell's efficiency (area 0.42 cm2) was 19.6%. As a result, there is great potential for improvement in the area of CI(G)S solar cell technology[1].

III. STATE-OF-THE-ART TECHNIQUES IN PV POWER SYSTEMS

Advancements in photovoltaic (PV) power systems are revolutionising the solar energy industry, enhancing efficiency, reliability, and affordability. Innovations such as high-efficiency PV cells, advanced energy storage solutions, and smart grid integration are at the forefront. These state-of-the-art techniques collectively contribute to the rapid growth and widespread adoption of PV power systems worldwide.

The two primary commercially accessible solar technologies—crystalline silicon and thin-film-based photovoltaics—will be discussed in the ensuing subsections.

3.1 Crystalline Silicon

Crystalline silicon (Si) semiconductors allow for the most efficient construction of solar cells [9]. Until a cheaper material and more efficient PV technologies are found, silicon will likely continue to be the most used material for solar cells. Production efficiencies of first-generation crystalline silicon photovoltaic cells range from 14% to 18%, whereas a laboratory-scale cell demonstrates an efficiency of 25%. Theoretically, these cells have a maximum efficiency of 26-28% [2].

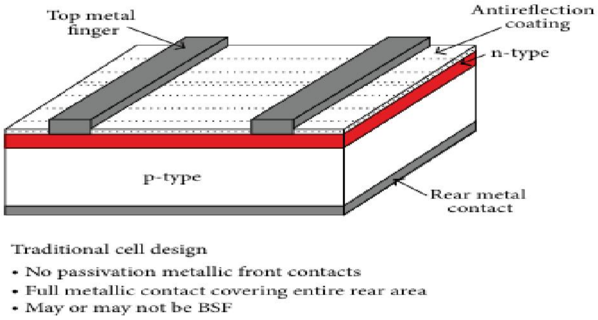

Figure 4: Traditional c-Si cell design

Until the year 2000, Figure 4 primarily covered the traditional c-Si cell design and its evolution. To make crystalline silicon solar cells more efficient, researchers have tried a variety of c-Si cell structures. A number of esteemed educational institutions make use of specific types of solar cells, like metal-insulator NP solar cells, passivated emitter solar cells, interdigitated back contact cells, passivated emitter and rear cells, and passivated emitter and rear locally diffused cells[1].

Market for crystalline silicon photovoltaics

A photovoltaic industry is currently dependent on solar cells made of crystalline silicon. Over the last five years, the photovoltaics market has expanded at a pace of over 50% annually, with crystalline silicon accounting for around 90% of the total volume11. Despite reaching the greatest efficiency on a commercial scale, this sort of solar device is notoriously costly owing to its high production and material costs [2]. Table I displays a rundown of second-generation devices together with their respective laboratory and commercial efficiencies.

Table 1: List of second-generation devices and their efficiencies both on the laboratory and commercial scales

Device material	Laboratory scale efficiency	Commercial scale efficiency
Amorphous/microcrystalline silicon (thin film Si or TFSi)	~13%	6–10%
Polycrystalline semiconductor CdTe	~17%	7–11%
Cu(In,Ga)(S,Se) or CIGS	~20%	9–15%

3.2 Thin-film-based photovoltaics (PV)

A new generation of photovoltaic cells called "2G" solar cells was developed based on thin-film technology in an attempt to lower production costs linked with first-generation devices [10][11]. Primarily designed as single-junction devices, second-generation cells strive to reduce material consumption while preserving the efficiencies of first-generation solar technology. Considering the less materials-intensive production method, thin-film photovoltaic devices offer a promising path towards low-cost, fully integrated technologies with high throughput. To that end, experts predict that thin-film PV technology will see a dramatic uptick in its market share within the next ten years. High-volume production (10 MWp to more than 50 MWp) is now underway for all three of the main inorganic thin-film technologies, which were all hitherto made at pilot size (1–2 MWp). The schematic schematics for second-generation photovoltaic devices, including CdTe, CIGS, and a-Si, are displayed in Figure 5.

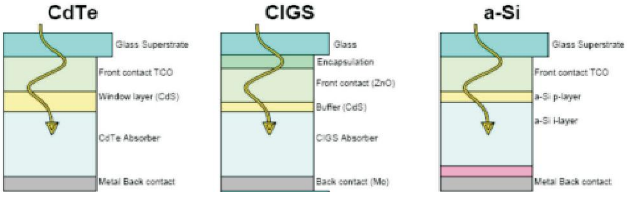

Figure 5: Schematic diagrams for CdTe, CIGS and a-Si second-generation photovoltaic devices.

Its main disadvantage is the poor efficiency that amorphous silicon thin-film cells have achieved up to this point. Although the optimal module efficiency is 10.2% (for a 1,000-cm2 area), reliable, small-area cells may achieve efficiencies of around 13%. Modern thin-film power modules made on amorphous silicon have an efficiency that stays between 6 and 9 percent[2].

Market potential for thin film photovoltaics

The present market share of 2G PV is below 15% of the overall photovoltaic market. However, experts predict that this percentage will expand to 20% by 2010 and more than 30% within the long run. In terms of market share, thin film CdTe currently has a position of 13%. The fundamental obstacle that thin-film PV technologies must overcome is the capacity to scale up their production. Japan, the US, and Europe are projected to account for the bulk of the world's thin film installations, with a combined output capacity of 2 GW per annum by 2012. Europe is home to several thin-film plants and a top-notch research and development infrastructure for thin-film[2].

3.3 Emerging Technologies of Photovoltaic (PV) Power Systems

Organic photovoltaics (OPVs)

Twenty years ago, organic material-based solid-state PV cells were initially found. An early investigation into organic PV demonstrated the concept utilising molecular-based devices; nevertheless, the efficiency of energy conversion was poor. Much interest in this area was aroused in the mid-1990s by a publication that described 2.9% effective cells constructed of conducting organic polymers mixed with C60 derivatives (fullerene). Given their potential for extremely thin solar cell fabrication and exceptionally high optical absorption coefficients, organic photovoltaic cells provide a more cost-effective substitute for inorganic semiconductors like Si-based photovoltaics[12].

Nanostructure oxide films

The material with the highest number of studies and applications is TiO2, a high bandgap semiconductor. The present TiO2 layers used in liquid electrolyte cells are optimal in terms of film thickness, surface area, porosity, and optical characteristics. The film thickness is a crucial consideration since it impacts the cell efficiency due to the fact that the injected electrons must traverse several colloidal particles and grain boundaries. The likelihood of recombination should rise with increasing thickness. Consequently, there is a sweet spot for film thickness that maximises both PV output and fill factor [13].

IV. IMPACTS OF STATE-OF-ART TECHNIQUES FOR PHOTOVOLTAIC (PV)

Here are some Important Impacts of State-Of-Art Techniques for Photovoltaic (PV) Power Systems:

- **Increased Efficiency and Energy Output:**Techniques like Maximum Power Point Tracking (MPPT) and bifacial solar panels significantly improve the efficiency of PV systems, resulting in higherenergy production bythe same surface area.
- **Cost Reduction:** Advances in materials and manufacturing processes, such as perovskite solar cells, reduce production costs, making solar power more affordable and accelerating its adoption.
- **Enhanced Grid Stability and Integration:** Advanced inverters and energy storage integration improve grid stability by managing power fluctuations and ensuring a consistent energy supply, facilitating an integration of renewable energy into a grid.
- **Optimized Land Use:** Innovations like floating solar farms and Building-Integrated Photovoltaics (BIPV) maximise the use of available space, reducing the need for dedicated land for solar installations and integrating energy generation into existing structures.
- **Environmental Benefits:** Increased efficiency and the use of advanced materials reduce the carbon footprint of PV systems. Techniques like floating solar farms also minimise environmental impacts on land.
- **Higher Return on Investment (ROI):** The combined effects of higher efficiency, lower costs, and improved durability lead to better financial returns for investors and quicker payback periods for PV installations.
- **Maintenance and Operational Optimization:** Artificial intelligence and machine learning optimise system performance and predictive maintenance, reducing downtime and maintenance costs, and extending the lifespan of PV systems.
- **Increased Energy Security:** Hybrid PV systems and energy storage solutions decrease reliance on fossil fuels and the grid, providing a more reliable and resilient energy supply, especially in remote or off-grid areas.

V. LITERATURE REVIEW

This section highlights that most research in this area has focused on providing an overview of a current state-of-the-art photovoltaic (PV) system, particularly in context of emerging trends and technologies.

In, Zhao et al., (2019) photovoltaic (PV) power generation has grown swiftly in China and elsewhere in the past few years, as demonstrated in this article. There has been a shift in the role of photovoltaic power generation from supplementary to primary or even leading power supply. The most important component of studying the impact on other areas of a power system is modelling grid-connected PV power-producing plants. A modelling of photovoltaic cells has also been a topic of intense interest and ongoing research for a long time. Many prestigious institutions, like GE, WECC, CIGRE, CEPRI, and many more, have published extensive research on this topic. This study provides an overview of the current research both in China and internationally, analyses the current challenges, and suggests areas for future research[14].

In, Liu et al., (2023) provides positive damping torque for a PV plant operating in conjunction with a synchronous machine through the process of supplementary control, and formulates a plan to regulate grid-connected inverters' damping using FPD, which reduces power oscillations by reasoning and adjusting controller parameters with the damping torque coefficient method. Improve the grid-connected system's resilience to disturbances by including control that considers the characteristics of power double-loop decoupling control for grid-connected PV inverters. Such features are linked to non-linear coupling and, independently, to the dynamic interaction of the grid. The grid's stability and safety are jeopardised by the addition of these elements, which provide additional disturbance factors[15].

A goal of this review article, Hassan and Dhimish, (2022) is to give a synopsis of what is currently known about solar road deployment, including what coating materials are available for PV technology that prevent reflection and soiling. Our aim is to bridge knowledge gaps and provide suggestions for improving the stability, reliability, and resilience of PV panels in solar road applications by examining the latest research on solar roads and PV materials, including anti-reflection and anti-soiling coatings. As a result, solar roadways may be built, which is a great step towards reducing our environmental impact[16].

In, Nivedha, Narmatha Banu and Om Prakash, (2016) PV solar farm inverters may become static synchronous compensators, or STATCOMs, to enhance the power transfer restrictions of the network. A suggested PV solar plant modelling architecture, in conjunction with voltage and damping controllers, can be employed to enhance the interconnected transmission system's grid power transmission restrictions. Harmonic analysis is performed on a grid-connected system with a PV-based STATCOM situated in the middle of the transmission line using the MATLAB/SIMULINK package. In order to increase system stability under fault conditions, this study demonstrates how PV-STATCOM can reduce the value of THD[17].

In, Xiao et al., (2022) is to present a thorough analysis of current developments in PV/T-PCM systems. They take a look back at the research on the PCM's cooling performance in different PV/T collectors, both experimental and numerical. Comprehensive PV/T-PCM performance enhancements by multivariate/multiobjective optimisation techniques, including genetic algorithm, response surface approach, and Taguchi method, are outlined. Lastly, the paper concludes with a discussion of difficulties and potential future research directions for improving the PV/T-PCM technology through the optimisation of systems, performance analysis, and material production and development. One promising strategy for increasing PV's total efficiency is to use phase change material (PCM) in PV/thermal storage modules for both cooling and thermal management[18].

In, Sarvi and Azadian, (2022) plans to summarise the prior articles and offer an appropriate approach to division and performance. For the purpose of making an informed algorithm selection, this details the algorithms' pros and cons as well as their performance and practical applications. The introduction of new algorithms and the improvement of old ones is likely responsible for the explosion of publications covering this subject. An accompanying comparison chart is also available for your perusal. Finally, the 3 algorithms (P&O, IC, and Fuzzy-PI) were applied to a PV system. They examined the outcomes of applying the MPPT's control signals using Boost and SEPIC converters. They have utilised a MATLAB/Simulink program to conduct the simulations. Maximal power point tracking methods have been the subject of numerous articles. Table II summarises the methodologies, key findings, limitations, and future work suggestions for each of the reviewed papers[19]

Table 2: Summary of related work for PV system

Reference	Methodology	Key Findings	Limitations	Future Work
[14]	Review of global research on PV power generation modelling.	PV power generation has evolved from auxiliary to primary power supply. Significant research has been done by GE, WECC, CIGRE, CEPRI, etc.	Existing problems in modelling and integration of PV systems; limited discussion on emerging technologies.	Suggests further research into improving PV system models and integrating new technologies.
[15]	Derivation of additional control mechanisms for PV plants; design of damping control strategy based on Feedforward power decoupling control (FPD).	Improved system stability and reduced power oscillations in grid-connected PV systems using damping torque coefficients.	Non-linear coupling and dynamic interactions present new disturbance factors; limited empirical validation.	Further empirical validation and development of anti-disturbance capabilities for grid-connected systems.
[16]	Review of solar road technologies and anti-reflection/anti-soiling coatings.	Solar roads have potential but are limited by the effectiveness of current PV materials. Identifies gaps in knowledge and suggests improvements.	Current PV materials and coatings are not yet optimised for solar road applications.	Proposes action plans for improving PV panel resiliency, durability, and reliability in solar roads.

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[17]	Modelling PV solar plant as a STATCOM for enhancing power transfer limits; harmonic analysis using MATLAB/SIMULINK.	Reduced Total Harmonic Distortion (THD) is one-way PV-STATCOM that may improve grid stability and power transfer limitations in the event of a failure.	Limited scope of testing and application; focus on simulation rather than real-world implementation.	Suggests further real-world testing and optimisation of PV-STATCOM systems.
[18]	Comprehensive review of PV/T-PCM systems; analysis of experimental and numerical studies.	Phase Change Material (PCM) improves the efficiency of PV/T modules; multivariate optimisation strategies are effective.	Challenges in material fabrication and system optimisation; limited coverage of all application areas.	Calls for further research on material improvements, system optimisation, and performance analysis.
[19]	Review and comparison of PV system control algorithms (P&O, IC, Fuzzy-PI); performance analysis using MATLAB/Simulink.	Various algorithms have been used for maximum power point tracking (MPPT); comparisons of their performance show difference.	Variability in algorithm performance; limitations in comparative analysis of new and optimised algorithms.	Suggests further optimisation of MPPT algorithms and comparison with new methods.

VI. CONCLUSION

The main goals of photovoltaic research have been to find ways to reduce prices while increasing conversion efficiency in a variety of module designs, including crystalline, thin-film, and organic-based systems. The development and deployment of photovoltaic (PV) power systems have undergone significant transformations, with advancements in technology driving improvements in efficiency, cost, and applicability. Crystalline silicon PV cells, while dominant and efficient, are expensive and face competition from emerging technologies such as thin-film and organic photovoltaics. Though they bring their own unique difficulties, these more recent technologies provide the promise of reduced production costs and expanded application possibilities. The management of PV systems' intermittent production and their integration into the grid continue to be major challenges. Innovations like advanced energy storage solutions, smart grid technologies, and enhanced forecasting methods are crucial in addressing these challenges. The future of solar energy depends on continued research and development in these areas, focusing on improving efficiency, reducing costs, and enhancing an integration of PV systems into a broader energy infrastructure. By addressing these challenges and leveraging new technologies, the potential of solar energy to meet global energy needs in a sustainable and economically viable manner can be realised.

Future work should focus on improving the efficiency and durability of emerging PV technologies, such as perovskites and organic photovoltaics. Enhanced integration of AI for system optimisation, along with advancements in energy storage and hybrid systems, will be important to addressing intermittency of solar power and improving grid stability.

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