



Fueling the Solar Evolution: Progress in Photovoltaic Cells and IoT Energy Integration for Agricultural Biotechnology

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ABSTRACT

This comprehensive review examines the transformative impact of solar energy on the renewable resources landscape. Focusing on recent advancements and applications, the article navigates the dynamic evolution of solar power technologies. It explores breakthroughs in photovoltaic cells, energy storage, and smart grid integration, highlighting their collective contribution to harnessing the abundant energy from the sun. The review emphasizes the practical implementations of solar energy across various sectors, from residential and commercial settings to large-scale utility projects. It analyzes the economic feasibility and environmental benefits of solar power, showcasing its potential to mitigate climate change and reduce dependency on traditional fossil fuels. Furthermore, the article discusses emerging trends in solar technology, such as thin-film solar cells, solar tracking systems, and innovations in solar panel design. The integration of artificial intelligence and data analytics to optimize solar energy production is also explored. By providing a concise yet detailed overview, this review aims to serve as a valuable resource for researchers, policymakers, and industry professionals interested in understanding the current state and future prospects of solar energy within the broader context of renewable resources.

KeyWords: Photovoltaic Cells, Renewable Resources, Solar Energy, Sustainability, Technological Advancements

INTRODUCTION

Solar energy, a celestial symphony of photons and technology, charts a course towards sustainable power with unprecedented finesse. The evolution of photovoltaic marvels has transcended mere innovation, unlocking a realm where efficiency converges with affordability. Whether weaving its magic in the intricacies of a residential rooftop array or spanning the vast expanse of utility-scale projects, solar energy manifests as a dynamic force, adaptable to the intricacies of diverse energy needs (Gautam et al., 2021). Yet, its brilliance extends beyond the technical realm. In the delicate ballet of harnessing sunlight, solar power emerges not just as a solution but as a custodian of our planet. With an almost ethereal carbon footprint, solar energy is a cornerstone in the grand narrative of climate change mitigation (Arvizu et al., 2011; Grewal et al., 2016). This dance with renewable resources propels us away from the clutches of finite fossil fuels, and into a future where environmental stewardship and energy needs harmonize. This section immerses in the extraordinary tale of solar energy—its technological ballet and its profound impact on the canvas of our energy landscape. As we delve into the cosmic intricacies of solar energy, we unveil a story of ingenuity and cosmic collaboration. Photovoltaic alchemy transforms sunlight into electricity, forging a pathway from innovation to indispensability. The adaptability of solar solutions, from intimate residential installations to the expansive tapestry of utility-scale ventures, underscores its position as not just an energy source but a transformative force (Govinda R., 2011). In this tale of photons and silicon, solar energy not only powers our present but paints a luminous trajectory for our future energy aspirations.

Beyond its technical prowess, solar energy carries the banner of environmental custodianship (Deshpande, 2021). With a footprint

that treads lightly upon the planet, it emerges as an emissary in our collective efforts against climate change. In a world grappling with finite fossil fuels, solar power emerges as a beacon of sustainability, offering a cosmic handshake between technological advancement and ecological responsibility (Čuček et al., 2015). This narrative unfurls in the subsequent pages, inviting readers into the celestial theater where solar energy, as both protagonist and catalyst, takes center stage in our quest for a sustainable energy paradigm.

Figure 1 shows the connections of Solar energy (Aditya Sharma, 2018). The world faces an energy crisis and environmental challenges, largely driven by traditional fossil fuels. Prioritizing renewable energy, notably solar power, is crucial for clean and efficient electricity production. This involves exploring solar energy's evolution, types, current global energy scenarios, and technological advancements. Solar power brings advantages, and its applications in countries like India contribute to energy solutions, environmental concerns, and economic growth (Dixit, 2020a). The International Solar Alliance's October 2022 Annual World Solar Reports highlight solar technology's pivotal role in the global renewable energy shift. With a nearly 20-fold increase in global solar capacity over the past decade, reaching 920 GW in 2021, solar has become the preferred choice due to technological advancements, cost reductions, and improved grid integration methods. As solar moves into Terawatt-scale deployment, ongoing innovations aim to enhance efficiency, power output, and material efficiency. The expanding manufacturing capacity must align with growing demand to achieve net-zero requirements. Sustained solar investments globally are crucial for scaling installations and supporting the overarching energy transition (Schmela et al., 2023).

The rising demand for self-powered IoT devices has spurred innovation in the electronics

industry, emphasizing reduced battery replacement and extended lifetime. OPVs (Organic photovoltaics) and PSCs (perovskite solar cells) exhibit efficiencies of 18% and 29%, respectively, coupled with notable stability. These technologies offer flexibility, environmental resilience, and efficacy under various lighting conditions, making them ideal for IoT applications. Challenges, including toxic elements in PSCs and health concerns with some organic materials, underscore the need for ongoing research to address environmental impact and manufacturing sustainability. A life cycle assessment is vital for understanding the overall environmental footprint. Despite challenges, OPVs and PSCs show promise for green IoT devices, combining efficiency, flexibility, and sustainability (Panidi et al., 2022).

The growing global commitment to sustainability, propelled by initiatives such as the sESRIA (European Strategic Research and Innovation Agenda) and Agenda of the UN's 2030, highlights the significance of renewable energy, notably solar power. The "Advances in Photovoltaic Materials and Devices" Special Issue in *Crystals* navigates key aspects of PV energy. Research investigates the viability of multi-crystalline silicon as a cost-effective alternative, tackles stability challenges in perovskite solar cells, and advances deposition techniques for scalable production. This succinct overview offers valuable insights into the indispensable role of PV technologies in advancing sustainable energy goals (Lago, 2023). In recent years, significant strides in solar photovoltaic (PV) technology, including materials and systems, have improved efficiency, reduced costs, and expanded energy storage capacities. Despite these advancements, intermittent energy production remains a challenge, necessitating effective energy storage solutions. This study provides a thorough overview of recent research in solar PV materials, emphasizing advancements in efficiency, cost reduction, and durability. Addressing the grow-

ing demand for renewable energy, the development of superior materials is crucial. The review explores progress, considering scalability, stability, and economic feasibility. Novel materials offer transformative potential for enhanced PV devices, contributing to the transition to a sustainable energy system. However, challenges like scalability, stability, environmental impacts, and economic feasibility require further exploration for widespread implementation. Continued research is essential to overcome these hurdles and facilitate large-scale adoption, fostering a sustainable and environmentally friendly energy system (Abouelregal et al., 2021; Dada & Popoola, 2023).

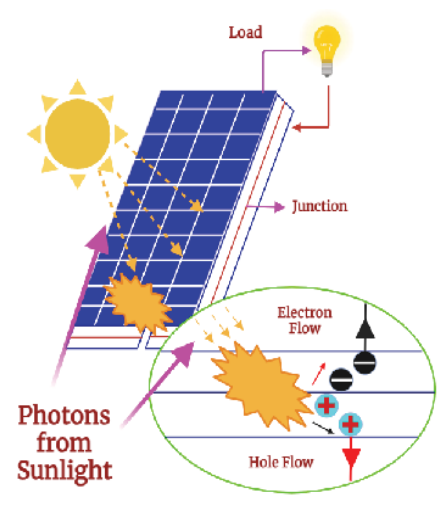


Figure 1 Solar Panel Grid Connection Layout (Aditya Sharma, 2018)

The global energy market, heavily reliant on fossil fuels, contributes significantly to greenhouse gas emissions. Transitioning to renewable energies is crucial for environmental sustainability, with Concentrated Solar Thermal (CST) energy playing a pivotal role. Solar tower (ST) systems, known for high operating temperatures, are in-

creasingly adopted. Developers explore enhancing ST systems by integrating secondary concentrators atop the tower for improved optical and thermal performance. However, commercial high-temperature secondary reflector materials for ST systems face durability challenges. This study introduces an accelerated aging test methodology predicting the lifetime of these materials efficiently. A solar furnace simulates ST operating conditions to validate the aging tests. Applied to a novel secondary material, the results highlight temperature-induced degradation as the main factor. The correlation between accelerated aging and operational tests is validated, with a 0.2% reflectance deviation under representative conditions, showcasing the reliability of the proposed methodology (Bendía-Martínez et al., 2023). Another study examines critical skills essential for STEM/STEAM graduates entering the Solar Energy Technology sector (SETS). Analyzing literature, interviews, and observations, it categorizes specialist skills into academic, industrial, and entrepreneurial elements. Common skills such as engineering, photovoltaic technology, project management, marketing, and consulting are identified. The research recommends a strategically balanced mix of these skills to enhance both employability and entrepreneurial potential. Emphasizing the role of educational institutions, the study suggests urgent development of Solar Energy Technology Training (SETechTra) modules to address the industry's skills gap. Ongoing research is actively creating SETechTra modules aligned with the identified skills. The study underscores the need for targeted education and awareness initiatives to address the skills imbalance in the Solar Energy sector and support SDG-7 and Net Zero goals (Amalu et al., 2023).

RELEVANCE IN RENEWABLE RESOURCES

A comprehensive analysis spanning 1996-2020 across 10 resource-rich Asian countries reveals

that natural resource dependence widens income inequality. However, the study highlights a significant finding: the integration of renewable energy effectively mitigates the adverse impacts of this dependence on income inequality. As a practical solution, establishing captive renewable energy power plants is recommended for specific countries, including India, Pakistan, Malaysia, Mongolia, and Vietnam, offering a targeted approach to address income inequality challenges (Husaini et al., 2024).

The relevance of solar energy within the realm of renewable resources is akin to a guiding star in the sustainability constellation. As a prime mover in the transition toward cleaner energy, solar power emerges as a linchpin in reshaping our energy landscape. Unlike finite resources, solar energy taps into an endless and dependable source—the sun. Its integration into the tapestry of renewable resources is not merely about meeting current energy needs but orchestrating a future where the quest for power aligns seamlessly with environmental stewardship (Sahoo, 2016).

Solar energy's role in the renewable panorama is underscored by its inherent environmental benefits. The extraction and utilization of sunlight generate minimal pollution and contribute little to the carbon footprint, standing in stark contrast to conventional fossil fuel methods (Obaideen et al., 2021). In this regard, solar energy serves as a beacon for sustainable practices, illustrating the transformative power of harnessing nature's boundless energy. Moreover, as technological innovations drive down costs and enhance efficiency, solar power becomes increasingly accessible. This democratization of energy production allows individuals, communities, and nations to participate actively in the renewable revolution. The relevance of solar energy in the realm of renewable resources, therefore, extends beyond immediate environmental considerations; it embodies a paradigm shift towards a future where clean, abundant energy is a collective and achievable goal (Dixit, 2020b).

TECHNOLOGY

The research delves into the potential impact of Industry 4.0 (I4.0) technologies on advancing renewable energy and sustainable materials, emphasizing the importance of real-time data collection, analysis, and decision-making. It specifically discusses the pivotal role played by IoT, AI, and advanced manufacturing techniques. Despite facing challenges such as technical, economic, and regulatory barriers, the study suggests solutions to enhance efficiency and sustainability in these sectors. It serves as a comprehensive resource, outlining research objectives, methodology, interdisciplinary approaches, and case studies. The report underscores the significance of I4.0 technologies in renewable energy and materials development, offering valuable insights for educational purposes, curriculum development, and research initiatives. It contributes depth and credibility by addressing critical concepts and concerns related to implementing I4.0 in renewable energy and materials development (Onu et al., 2023).

With a projected investment of \$170 billion by 2025, solar photovoltaic (PV) systems encounter challenges such as dust accumulation, solar radiation, and temperature-induced efficiency reduction. To tackle these issues, the review examines various cooling techniques, including Absorption & adsorption-based, PV/T hybrid, Microtechnology-based, and Water and air-based systems. Additionally, it provides comprehensive insights into Passive cooling methods, such as Radiative cooling, Evaporative cooling, Liquid immersions, and Material coatings, outlining their performance metrics, advantages, and challenges (Mariam et al., 2024). In the pursuit of optimal efficiency in solar energy farms, a detailed examination of each inverter's metrics—ranging from voltage and current to temperature and power—is essential. This scrutiny not only curtails maintenance costs but also elevates production and fine-tunes invert-

er performance across diverse scenarios. The study hones in on a 140 kWp photovoltaic plant with 300 modules of 255 W and 294 modules of 250 W, augmented by intelligent monitoring devices. Comprising SMA Tripower inverters (25 kW and 10 kW), this research extends to a 590 kWp photovoltaic plant featuring 1312 Trina solar 450 W modules and SMA Sunny Tripower inverters (440 kW). Leveraging supervised learning algorithms, the investigation integrates a networked data infrastructure and a fault classification algorithm, fostering heightened energy efficiency. Beyond accuracy assessments of these algorithms, the study proposes solutions for amplified energy production and robust component reliability, emphasizing advanced monitoring and optimization of inverters (Pereira & Silva, 2024).

Traditional hybrid photovoltaic solar thermal systems face a significant challenge—an ongoing decline in module power efficiency due to elevated temperatures resulting from closed-loop cooling. To address this constraint, the study presents a novel approach by integrating an evacuated tube and adopting an open-loop cooling setup, coupled with a unique flow control strategy. The primary objective is to improve cooling efficiency, resulting in enhanced energy capture and better economic feasibility. Using TRNSYS 18 software, a numerical model is constructed to evaluate the techno-economic aspects of the proposed enhanced hybrid system. The model's accuracy is confirmed through validation and experimental techniques. The comprehensive results reveal a significant 10% increase in annual renewable energy production compared to the standard hybrid photovoltaic solar thermal system. Additionally, substantial cost savings are realized, with operational expenses reduced by 48%. The system's flexibility to accommodate various hot water and electricity demands further enhances its energy capture capabilities, ultimately shortening payback periods and doubling its economic advantages, ren-

dering it more appealing for rapid adoption (Johnson et al., 2024).

ADVANCEMENTS IN PHOTOVOLTAIC CELLS

Recent years have witnessed a transformative wave of innovation in photovoltaic (PV) technology, catapulting solar energy into a new era of efficiency and versatility. Breakthroughs in materials science and engineering have paved the way for novel PV designs, significantly enhancing the conversion of sunlight into electricity. One noteworthy advancement lies in the development of next-generation solar cell materials, such as perovskite and tandem cells. Perovskite solar cells exhibit remarkable efficiency gains and cost-effectiveness, challenging traditional silicon-based cells (Boukourt et al., 2023). Tandem cells, stacking multiple layers with distinct absorption spectra, maximize sunlight utilization, pushing the boundaries of efficiency. In addition, the evolution of thin-film technologies has led to flexible and lightweight solar panels, expanding deployment possibilities to unconventional surfaces. These advancements not only contribute to increased energy capture but also offer greater design flexibility for diverse applications (Schwartz, 1969).

Furthermore, improvements in manufacturing processes, including roll-to-roll printing and advanced deposition techniques, have streamlined production, reducing costs and enhancing scalability. The integration of artificial intelligence in PV systems is optimizing performance by predicting and mitigating efficiency losses, ushering in an era of intelligent solar energy. As we delve into these advancements, it becomes evident that the trajectory of photovoltaic cells is not merely about incremental improvements but rather a paradigm shift towards more efficient, accessible, and intelligent solar technologies (Solak & Irmak, 2023).

Table 1 depicts a comparative analysis of effi-

ciency, cost, and lifespan among different photovoltaic cell technologies, providing a succinct overview of advancements in the Advancements in Photovoltaic Cells section (Fazal & Rubaiee, 2023).

Table 1 Comparison of Photovoltaic Cell Technologies

Technology	Efficiency (%)	Cost (USD per Watt)	Lifespan (years)
Silicon-Based Cells	22	0.30	25
Perovskite Cells	28	0.25	20
Thin-Film Cells	20	0.20	15

The study investigates nanofluid effects on copper and aluminum oxides in photovoltaic systems. Factors examined include incoming radiation, fluid temperature, absorber temperature, and nanofluid types (aluminum oxide, copper oxide). Findings show increased fluid inlet temperature raises outlet temperature, maintaining thermal efficiency. Copper oxide surpasses aluminum oxide in thermal efficiency, but elevated pressure drop reduces overall efficiency, favoring aluminum oxide. Raising incoming air temperature heats the absorbing surface, lowering system efficiency; nanofluids mitigate these changes. The study guides optimizing unused heat energy through nanofluid and water circulation for enhanced thermal and electrical efficiency.

The research used Ansys Fluent, SolidWorks, and Ansys Meshing software for simulation and analysis. The focus on a single component, the riser, managed system complexity and calculation challenges, offering insights into system behavior. (Amirreza Abdollahi et al., 2024). Kazem et al. highlight advancements in solar-assisted heat pumps (HPs) with a focus on the integration of Photovoltaic/Thermal collectors (PVT) over the past two decades. The coupling of PVT collectors with HP systems has demonstrated improved performance and oper-

ational reliability, particularly in demanding environmental conditions. The integrated systems serve multiple purposes, providing heat, hot water, and electricity for diverse applications such as industrial and agricultural needs. The emphasis is on research contributing to the technology's evolution, showcasing the mechanism and benefits of the combined PVT-HP systems in enhancing overall efficiency and functionality (Kazem et al., 2024). In the study, Marei et al., the energy-saving efficacy of four transparent wall configurations—basic glass, Façade, basic glass with integrated photovoltaics (GPV), and Façade with integrated photovoltaics (FPV)—was thoroughly examined using ANSYS mechanical and ANSYS Fluent solvers.

The 3D thermo-electric models simulated scenarios in an air-conditioned space exposed to Egypt's summer weather. Key findings include Façade and FPV walls reducing daily heat transfer by approximately 64% to 65.54% compared to conventional glass. GPV and FPV showed similar power generation from CdTe PV cells (about 2,369 Wh/day), with FPV exhibiting superior thermal insulation. Façade excelled in natural illumination, followed by FPV and basic glass, while GPV performed the least. Integration of CdTe PV cells significantly reduced natural light, with FPV maintaining higher illumination levels for longer. Incorporating GPV, Façade, and FPV transparent walls in air-conditioned office areas led to substantial daily energy consumption reductions of around 32.2%, 47.2%, and 80.5%, respectively, compared to basic glass configurations. The study provides detailed insights into energy-saving mechanisms, performance data, and trade-offs associated with diverse transparent wall configurations across varied operating conditions (Marei et al., 2024). Efficiency in photovoltaic cells, a focal point of extensive research, varies across types—crystalline silicon (up to 27.6%), multijunction (up to 47.4%), thin film (up to 23.6%), and emerging cells (up to 33.7%). Industrial-scale challenges

persist due to recombination rates, defects, and temperature sensitivity. Mitigation approaches involve nanoparticle integration, ion beam studies, magnetite materials, and magnetic field applications. Magnetic fields enhance charge transfer states, extending separation time, albeit introducing spin effects probed by synchrotron radiation techniques like XMCD. Innovations, including TiO-BiFeO dye-sensitized cells and Fe-doped SnO in heterojunction organic solar cells, show significant efficiency gains under magnetic influence (Verma & Gautam, 2023).

An exceptionally efficient hybrid power generation setup, comprising both traditional solar panels and state-of-the-art solar window systems, showcases the potential to slash grid dependency by as much as 75%, thereby substituting fossil fuels. This configuration stands capable of fulfilling the city's power requirements during peak periods, with an excess of less than 2%, thereby contributing back to the primary grid. The research underscores the efficacy of an all-PV amalgamation (comprising Rooftop installations, PV windows, and Semitransparent PV modules) in cities abundant with sunlight, thereby enriching urban landscapes and bolstering contemporary infrastructure development, which includes multi-level parking structures equipped for electric vehicle recharging. Further research is needed to address power loss management, cost-effectiveness, and the integration of machine learning for building energy efficiency (Nur-E-Alam et al., 2024).

ENERGY STORAGE AND SMART GRIDS

The evolution of solar energy extends beyond photovoltaic breakthroughs, encompassing advancements in energy storage and smart grid technologies. These developments play a pivotal role in overcoming the intermittency challenges inherent in solar power, ensuring a reliable and resilient renewable energy ecosystem. Energy storage systems have undergone significant

enhancements, with a focus on improving both capacity and efficiency (de Freitas Viscondi & Alves-Souza, 2019). Lithium-ion batteries, propelled by ongoing research and development, dominate the energy storage landscape, offering higher energy density and longer cycle life (Nitta et al., 2015). Emerging technologies, such as solid-state batteries and flow batteries, show promise in addressing scalability and environmental concerns. Simultaneously, the integration of smart grids has revolutionized the way energy is managed and distributed. Smart grids leverage digital communication and control technologies to optimize the flow of electricity, enhance grid reliability, and accommodate the variable nature of solar power. Advanced sensors and real-time data analytics enable grid operators to respond dynamically to fluctuations in energy generation and consumption. The synergy between energy storage and smart grids is pivotal in creating a more adaptive and efficient energy infrastructure.

As solar energy generation becomes more decentralized, these technologies ensure a seamless integration into existing power systems, fostering a future where renewable energy plays a central role in meeting global energy demands (Abir et al., 2021). Leveraging Rayleigh's probability density function and Monte Carlo experiments, this study models the integration of renewable energy sources, with a focus on the indispensable role of Vehicle-to-Grid (V2G) operations in Electric Vehicles (EVs). The escalating EV numbers pose challenges to the power grid, addressed by V2G operations and smart charging for robust network support. Effectively managing intermittent sources like solar and wind necessitates combining energy storage and power regulation, where V2G operations and battery storage prove pivotal for increased renewable penetration. EV batteries, optimal for power regulation, uphold grid stability. The synergistic integration of solar energy, wind power, battery storage, and V2G operations emerges as a promising solution for resilient energy pro-

duction. The study underscores the advantages of integrating intermittent sources with battery storage and V2G operations, including peak demand support, load optimization, and smoothing power fluctuations from renewables. As global interest in renewable energy grows, these innovations enhance power grid reliability, paving the way for a substantial share of intermittent renewables. The research provides insights into the strategic role and multifaceted benefits of integrating battery storage and V2G operations, creating a resilient and sustainable renewable power supply (Johnson et al., 2024).

APPLICATIONS:

Residential and Commercial Use

The integration of solar energy into residential and commercial sectors has transcended mere adoption; it has become a transformative force reshaping the dynamics of energy consumption and sustainability. In residential settings, solar photovoltaic systems have evolved beyond traditional rooftop installations. Innovative solar shingles and building-integrated photovoltaics (BIPV) seamlessly blend solar functionality with architectural design, making solar energy an integral part of the home rather than an appendage (Alipour et al., 2021). This not only enhances energy production but also elevates the aesthetic appeal of solar solutions. Commercial applications, on the other hand, span a wide spectrum of industries. Large-scale solar arrays, coupled with energy storage solutions, are powering factories and warehouses, offering a reliable and sustainable source of electricity. Furthermore, businesses are increasingly incorporating solar technologies into their infrastructure, not only as a cost-effective means of energy production but also as a commitment to corporate social responsibility and environmental stewardship (Islam et al., 2022). The economic feasibility of solar energy, coupled with government incentives, has catalyzed a surge in residential and commercial solar installations

globally. As solar solutions continue to evolve, the residential and commercial sectors stand as beacons of successful integration, demonstrating the tangible benefits of transitioning towards cleaner and more sustainable energy sources (Mohanty et al., 2017a). Efficient and eco-friendly hydrogen generation in the foreseeable future hinges on the adoption of well-established or nearly mature technologies. This research centers on evaluating a high-temperature electrolytic hydrogen production system by integrating nuclear and solar methods. The investigation delves into the combined performance of nuclear and solar technologies, measuring the effects of hybridization on the size of photovoltaic fields and the costs associated with hydrogen production. Results indicate reduced field size and production costs with hybridization, emphasizing its potential advantages for efficient and cost-effective hydrogen production (Boudries & Khellaf, 2024).

In the burgeoning era of the Internet of Things (IoT), Indoor Photovoltaics (IPVs) are gaining momentum, particularly CsPbI_xBr_{3-x} Perovskite Indoor Photovoltaics (PIPVs), which exhibit great promise due to their optimal band-gap and high Voc, making them well-suited for sustainable IoT systems. Despite the current Power Conversion Efficiency (PCE) of around 34%, focusing on thickness optimization for indoor applications could potentially elevate PCE to nearly 50%. Notably, the transition from outdoor to indoor settings necessitates a shift in research methodologies, considering factors such as device architecture, perovskite film thickness, and charge transport properties. Standardized measurement procedures with a fixed indoor light source and a reference IPV, such as a-Si, are crucial for reliable performance assessment and fair comparisons. Flexible PIPVs are also vital for versatile integration into various devices. The IoT, projected to encompass around 75 billion devices by 2025, underscores the need for off-the-grid power solutions, with IPVs emerg-

ing as a key player for seamless, low-cost integration of sensors through harvesting indoor light. Various PV cell technologies, including a-Si, GaAs, GaInP, OPVs, DSSCs, and PSCs, have demonstrated suitability for IPVs, with the potential to supply ample power for indoor gadgets (Guo et al., 2023).

Utility-Scale Projects. The canvas of solar energy applications expands exponentially with the emergence and proliferation of utility-scale projects. These monumental installations mark a shift towards large-scale renewable energy deployment, playing a crucial role in meeting the power demands of entire communities and regions. Utility-scale solar projects harness expansive solar arrays, often covering vast landscapes (Rachid et al., 2023). These projects leverage economies of scale, optimizing energy production and cost-efficiency. Photovoltaic systems in utility-scale deployments are characterized by high-capacity solar panels, sophisticated tracking systems, and advanced inverters to maximize energy yield. The impact of utility-scale solar is profound, contributing significantly to reducing reliance on conventional energy sources. These projects not only bolster the capacity of national grids but also serve as milestones in the global transition towards sustainable energy (Talwar et al., 2021). Moreover, advancements in energy storage technologies are complementing utility-scale solar installations, addressing the intermittency challenge. Large-scale batteries are employed to store excess energy during peak sunlight hours, ensuring a stable and consistent power supply, even during periods of low solar input. As utility-scale projects continue to evolve, they stand as testament to the scalability and viability of solar energy on a grand scale, ushering in an era where clean, renewable power plays a central role in meeting the world's growing energy demands (Baldinelli et al., 2020).

Global electricity demand is sharply rising, with 60% relying on fossil fuels, leading to greenhouse gas emissions, irreversible deple-

tion, and severe climate impacts. Rapid adoption of reliable, eco-friendly renewable energy is crucial. Integrating these technologies into the grid poses challenges, addressed by power electronics, ensuring high reliability, cost-effectiveness, and efficiency with semiconductor switches and converters for streamlined connection to the grid (Shenbagalakshmi et al., 2024).

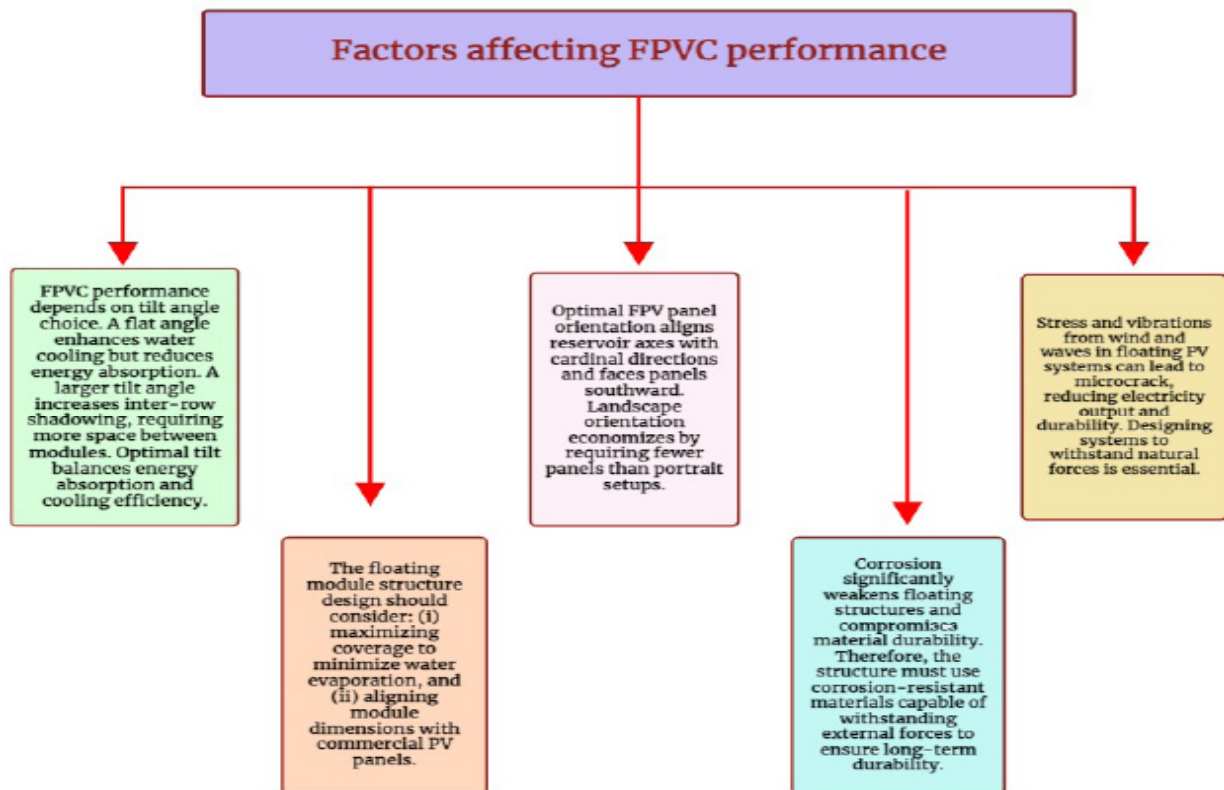
In the pursuit of carbon neutrality, perovskite solar cells (PSCs) have rapidly advanced, especially with the emergence of perovskite-based tandem solar cells. These developments offer a significant opportunity to surpass theoretical efficiency limits. Improved encapsulation technology has addressed stability issues and lead leakage concerns. The ongoing progress in lead-free PSCs contributes to a more environmentally friendly ecosystem. The versatility of PSCs has expanded their application scenarios,

making them pivotal in various fields. While challenges remain for industrialization, the current development pace suggests the imminent commercialization of PSCs, holding promise for utility-scale projects (Hu et al., 2023).

ECONOMIC AND ENVIRONMENTAL IMPACT

The economic feasibility of solar energy has undergone a remarkable transformation, making it a compelling choice for a broad spectrum of consumers. The declining cost of solar panels, coupled with government incentives and innovative financing models, has democratized access to solar energy. Residential, commercial, and industrial entities are increasingly recognizing the long-term economic advantages of investing in solar power systems. This shift towards affordability has positioned solar en-

Figure:2 illustrates the main factors affecting the performance of FPVSS. (El Hammoumi et al., 2022)



ergy as not just an environmentally conscious choice but a financially savvy one, fostering a sustainable energy landscape. The environmental benefits of solar energy are fundamental to its role in the renewable energy portfolio. Solar power stands as a linchpin in the global pursuit of mitigating climate change (Mohanty et al., 2017b). Unlike traditional fossil fuels, solar energy generation produces minimal greenhouse gas emissions, significantly reducing the carbon footprint associated with electricity production. The transition to solar energy also curtails air and water pollution, contributing to cleaner and healthier environments. As solar technologies continue to advance, the environmental benefits amplify, solidifying solar energy's pivotal role in fostering a more sustainable and ecologically responsible energy paradigm (Maka & Alabid, 2022). In Saudi Arabia, there is a notable recognition of the crucial role that green hydrogen plays in its energy transition.

It acknowledges a current global demand for green hydrogen at 8 GW, which is projected to escalate to 80-100 TW-hours by 2030. Despite the implementation of aggressive solar initiatives, meeting this demand necessitates the development of a robust hydrogen infrastructure. While existing pipelines facilitate the transport of gaseous hydrogen, the economic feasibility of tank ships for long-distance distribution remains essential. By proactively establishing hydrogen alliances, Saudi Arabia aims to generate 5 GW by 2025, highlighting the importance of cost-effective storage methods. These methods are not anticipated to compete with batteries until approximately 2035 (Hassan et al., 2024).

Emerging Trends

THIN-FILM CELLS AND SOLAR TRACKING INNOVATIVE PANEL DESIGNS

The frontier of solar energy is continuously expanding with the rise of emerging technologies, two of which stand out as catalysts for efficien-

cy and versatility: thin-film solar cells and solar tracking systems. Thin-film solar cells represent a departure from traditional silicon-based counterparts (Agarwal et al., 2022). Innovation in solar panel design is reshaping the aesthetics and functionality of solar installations. Beyond the traditional rooftop arrays, architects and engineers are exploring creative solutions such as solar shingles, transparent solar windows, and even solar-integrated textiles.

These innovative designs not only enhance energy production but also seamlessly integrate solar technology into everyday structures, transforming the built environment into a dynamic and sustainable energy landscape. As these trends gain traction, they signify a paradigm shift in how solar energy is harnessed and integrated into diverse settings. The convergence of thin-film technology, solar tracking systems, and innovative panel designs heralds a future where solar energy is not only a source of power but an integral and harmonious component of our surroundings (Luo, 2011). In recent years, inverted perovskite solar cells (IPSCs) have garnered significant attention for their operational stability, minimal hysteresis, and low-temperature manufacturing processes, aiming to meet global energy demands sustainably.

The efficiency of perovskite solar cells has surpassed 25% through advancements in nanocrystalline film synthesis at low temperatures and effective management of interfaces and electrode materials. This review delves into the processes refining stability and power conversion efficiencies in IPSCs, covering structural configurations, tandem solar cell prospects, mixed cations and halides, film fabrication methods, alterations in charge transport materials, effects of contact electrode materials, and the use of additives and interface engineering materials.

Achieving efficiencies above 23%, many IPSCs use organic hole transport materials (HTMs) such as self-assembled monolayers (SAMs) and PTAA, with PTAA-based devices

exhibiting excellent commercialization potential under damp heat conditions. However, the cost of organic HTMs remains a constraint for broader PSC utilization. Despite the promising features of NiOx as an inorganic HTM, its low efficiency poses challenges for commercialization. Continuing research endeavors aim to enhance the quality of NiOx films through surface modification or doping, targeting a competitive efficiency of 25% coupled with high photoelectric characteristics, similar to conventional organic hole-transporting materials (Khadka et al., 2021; Ma et al., 2021; Nyiekaa et al., 2024). In the quest for sustainable energy solutions, thin-film solar cell technologies have emerged as promising alternatives, with both established (a-Si, CIGS, CIS, CdTe, GaAs, GaAs tandem) and emerging (PSC, PSC tandem, DSSC, OPV, CZTS, QD) types under examination. This extensive life cycle assessment (LCA) investigates twelve distinct technologies, juxtaposing them against traditional crystalline silicon solar cells (mono-Si and multi-Si). Factors influencing LCA outcomes include solar cell type, manufacturing processes, material configuration, deposition method, location, weather conditions, and estimation methods.

Notably, emerging technologies outperform their commercial counterparts, boasting superior life cycle energy requirements (103–3546 MJ/m²), energy payback times (0.43–7.12 years), and global warming potential (5–286 KgCO₂eq/m²). Commercial technologies exhibit wider ranges (1054–7939 MJ/m², 2.11–6.35 years, 61–437 KgCO₂eq/m²).

Perovskite solar cells show the highest environmental impact, while CZTS stands out with the lowest. GaAs tandem leads in primary energy consumption among commercial types. Despite lower efficiencies, thin-film solar cells present a compelling case by minimizing raw material and energy use, leading to improved environmental performance in cumulative energy demand and global warming potential

compared to crystalline silicon cells. The study underscores the environmental advantages of thin-film solar cells, particularly a-Si, CIGS, and OPV technologies, emphasizing the need for further research on advanced CZTS systems for holistic sustainability assessments (Si et al., 2024). Exploring the history of solar array structures in US-led robotic planetary science missions reveals a fascinating journey since the dawn of space exploration. Initially relying on body-mounted solar cells, the designs swiftly advanced to incorporate extended panels for enhanced power generation. Early “paddle” configurations gave way to the prevalent use of deployable twin rectangular “wings,” a feature ubiquitous in commercial telecommunications satellites and pivotal in scientific missions. The narrative reflects a continuous drive for innovation spurred by the escalating intricacies of missions venturing into harsh and distant reaches of the solar system. This progression, marked by larger solar arrays to power sophisticated spacecraft in challenging environments, has been a consistent theme since the 1960s, striking a balance between mission complexity and cost-effectiveness (Mercer, 2023). Examining key strategies for optimizing PV energy, this research focuses on solar trackers and floating PV systems. Highlighting dual-axis closed-loop trackers as widely adopted for their simplicity, the study notes the prevalent use of the “on-off” control algorithm and explores the integration of intelligent controllers for enhanced tracking accuracy. Solar tracking systems prove efficient in increasing energy production by 10%–50%, contingent on factors like location and climate. Shifting to floating PV systems, the research positions them as a promising alternative, emphasizing reduced land use, enhanced module performance, and eco-friendly attributes. Proposing innovation, the integration of solar trackers with floating PV systems is introduced, creating the concept of tracking-type floating PV systems (TFPVS) (Dada & Popoola, 2023b).

The TFPVS explores unique actuation mechanisms for adjusting PV panel angles, potentially leveraging natural wave energy or water pumping. The study also underscores the strategic advantage of installing floating PV systems in hydroelectric dams, reducing water evaporation and boosting hydroelectricity production in a cost-effective manner (El Hammoumi et al., 2022)

Biotechnological Applications

The integration of photovoltaic cells and IoT energy systems holds immense promise for revolutionizing biotechnological applications in agriculture. Photovoltaic cells, through their efficient conversion of sunlight into electricity, provide a renewable energy source crucial for powering various biotechnological processes. In agriculture, this energy is utilized to drive precision irrigation systems, automated crop monitoring devices, and sensor networks for environmental data collection. Moreover, the incorporation of IoT technology enables real-time monitoring and control of agricultural parameters, such as soil moisture levels, nutrient content, and plant growth patterns. By harnessing solar energy and IoT integration, biotechnologists can optimize resource utilization, enhance crop yields, and mitigate environmental impacts associated with traditional farming practices. The accelerated adoption of solar-powered solutions underscores a paradigm shift towards sustainable and data-driven approaches in agricultural biotechnology.

Delving into Compound Parabolic Concentrators (CPC)-based solar PV systems

This comprehensive study scrutinizes diverse design configurations. Groundbreaking insights reveal the suitability of 2D CPC troughs for ground/rooftop applications, while ACPCs and 3D CCPCs excel in building façade integration. Weight considerations drive the preference for lens-walled CPCs, proving adept at solar radiation collection. A crucial detail emerges: a geometric concentration ratio (CR) below 5 negates the need for sun-tracking. Despite outperforming non-concentrating modules, experimental results often face setbacks due to intricate system losses, including optical losses, series resistance, elevated cell temperatures, and non-uniform illumination. The exploration extends to active cooling techniques and the promise of bifacial absorbers, signaling avenues for future research to create technically feasible and economically viable CPC-based PV systems that meet burgeoning renewable energy needs (Masood et al., 2022).

Navigating the challenges posed by weather conditions and contaminants, this paper delves into automated solar panel cleaning systems, essential for sustaining optimal efficiency. Divided into active and passive methods, the study evaluates systems like Brush Cleaning System (BCS), Electrostatic Cleaning System (ECS), Heliotex Cleaning System (HCS), Robotic Cleaning System (RCS), and Coating Cleaning System (CCS). Among these, the automated BCS stands out as a cost-effective strategy, reducing reliance on fossil fuels and delivering a monthly efficiency boost of up to 9.2%. Each system's suitability is scrutinized, with insights into their effectiveness, environmental impact, and adaptability to diverse climates (Farrokhi Derakhshandeh et al., 2021).

IoT Energy Integration: Accelerating the Solar Revolution

Indoor photovoltaics have garnered research

focus for IoT applications, powering wireless and battery-less devices in modern technology (Mishra et al., 2022). Residential IoT systems, characterized by fungibility, convertibility, and dispersal, leverage blockchain technology for transparent, secure, and decentralized energy management. Challenges in blockchain-powered power trade involve security, resource extraction, and green IoT considerations, necessitating user identity verification through smart contracts. Diverse energy resources, including thermal, light, electromagnetic, chemical, and mechanical, contribute to IoT systems.

Fuel cells, surpassing batteries (e.g., methanol with energy density: 17.6 kJ/cm), address issues like constant voltage and the need for backup power. Miniature heat engines overcome challenges associated with fossil fuels. Durable photovoltaic systems and LEDs, with lifespans of 25 and 15 years, respectively, align with a 15-year IoT target. Hybrid energy storage enhances overall performance, with power and hydrogen storage integration activating fuel cells during low battery charge.

The peak power outputs of various IoT resources demonstrate a range of variability (Li coin cell - 110 mWcm⁻³, Li-ion 18650 - 2170 mWcm⁻³, Fuel cell - 145 mWcm⁻³, Supercapacitor - 128 mWcm⁻³, Dedicated RF - 0.440 mWcm⁻³, Solar (outdoors) - 26.7 mWcm⁻³, Solar (indoors) - 0.0926 mWcm⁻³, Mechanical (piezoelectric) - 0.375 mWcm⁻³, Mechanical (active human motion) - 8.5 mWcm⁻³). Achieving a balance between benefits and hurdles is crucial, with blockchain IoT playing a significant role in aiding residential energy management, enabling market participation for consumers and renewable energy producers. Optimal energy comprehension requires high-density, efficient usage. Predictions indicate 20 billion IoT devices by 2020, a global IoT market value of \$151.40 billion in 2024 (12.020% CAGR), an IoT energy market worth \$26.5 billion in 2023 (15.5% CAGR), and the global IoT

industry reaching \$457.0 billion in 2020 (28.5% CAGR).

According to forecasts, Industrial IoT, smart cities, and connected health are anticipated to capture significant portions of the market, comprising 24%, 26%, and 20% shares, respectively. Following closely behind are connected cars (7%), smart homes (14%), wearables (3%), and smart utilities (4%) (Aldin et al., 2024; Aman et al., 2024). Stakeholder acceptance is vital for new energy technologies like SUN2CHEM, focusing on solar energy chemical storage. The study explores factors at socio-political, market, and community levels. Socio-political acceptance relies on capacity, politics, and regulation, where coherent strategies and support yield positive outcomes. Market acceptance is influenced by installation, production, information, and financing, with favorable conditions and infrastructure enhancing it. Community acceptance considers participation, siting, and public perceptions, benefiting from ownership recognition and positive media discourse. The study identifies stakeholders, emphasizing balanced management for success and the importance of early consideration. It suggests applying its approach to diverse technologies, offering indicative trends and recommending early strategies without predicting post-implementation behavior (Kadenic et al., 2024).

The evolution of power networks necessitates a shift from traditional energy management systems (EMS) to integrated energy management systems (IEMS). IEMS, utilizing technology and communication advancements, balances grid load and power supply efficiently. Solar energy forecasting (SEF), demand side management (DSM), and supply side management (SSM) collaboratively enhance system reliability by up to 18% (Archana et al., 2022). IEMS is crucial for decentralized solar-based mini-grids, ensuring effective alignment of load and supply. Predicting integrated renewable energy sources (RES) minimizes power system

uncertainty.

Interaction with both supply and demand sides is vital for smart grids. Integrating SEF and EMS with DSM optimizes energy utilization. Renewable smart hybrid mini-grids (RSHMG) serve as advanced options for solar integration. The IEMS structure varies based on SEF approaches, SSM, and DSM responses, tailored to specific constraints and objectives. Emphasizing the importance of Battery Energy Management Systems (BESS), IEMS minimizes issues related to capacity size, optimizing charging and discharging processes while ensuring safety and environmental impact. In unforeseen imbalances, IEMS prevents energy mismatches, providing real-time adjustments between supply and consumption (Falope et al., 2024; Karunanithi et al., 2017). Standalone solar PV systems in off-grid settings have long been a focus for delivering clean, affordable electricity to rural communities, especially in developing countries.

Nevertheless, the constrained capabilities lead to considerable daily energy loss because of insufficient battery storage. Enabling peer-to-peer (P2P) connection among current solar PV systems offers a chance to accommodate extra loads and encourage self-reliance in rural regions. This research investigates the viability of P2P solar energy distribution, introducing an IoT-enabled, economical automated system comprising three operational segments. The analysis reveals a significant 13.66% increase in community self-sufficiency and an 11.16% improvement in self-consumption. Beyond addressing current mini/microgrid obstacles, this innovative approach substantially enhances the life cycle of rural communities, underlining the considerable benefits of the proposed energy-sharing system (Sayed et al., 2024). Innovating the utilization of renewable energy for fixed-wing UAVs, this research delves into a meticulous analysis of various components, culminating in the design of a solar photovoltaic

system tailored to meet the demands of actual flight mission test conditions.

Validating the aerodynamic and energetic design through sophisticated software tools, the study incorporates a thorough examination of meteorological factors such as irradiation, temperature, wind speed, wind direction, atmospheric pressure, and humidity. Employing tools like FoilSim III and MatLab, the research provides intricate insights into the UAV's aerodynamic behavior and energy consumption under different flight conditions, optimizing construction efficiency. Crucially, battery analysis emerges as a pivotal aspect, offering a profound understanding of UAV energy management. The integration of C60 photovoltaic cells enhances the UAV's design, particularly for stealthy video surveillance applications, fostering improved autonomy (Ye et al., 2022).

The analysis of simulation results has led to the formulation of an objective function focused on enhancing the capacity for charging batteries, with the potential to quadruple the autonomy of UAVs, even in the absence of photovoltaic backup. It's important to highlight that these findings are assessed under optimal conditions, characterized by a clear sky and wind speeds below 3 m/s. Future initiatives target the improvement of programming in the control propellers system and its seamless integration with embedded systems to establish resilient IoT communications (Salazar et al., 2024).

FUTURE OUTLOOK:

The future of solar energy is entwined with the capabilities of artificial intelligence (AI) as a key driver for optimization. AI technologies are increasingly being integrated into solar power systems to enhance efficiency, reliability, and overall performance. Machine learning algorithms analyze vast datasets in real-time, allowing for dynamic adjustments in energy production and consumption. Predictive analytics optimize energy storage, grid interactions, and maintenance

schedules, ensuring that solar installations operate at peak efficiency. As AI continues to advance, its integration into solar energy systems promises a future where solar power is not only intelligent but adaptive, contributing to a more resilient and responsive energy infrastructure (Rajasundrapandiyaneebanon et al., 2023). The trajectory of solar energy points towards a pivotal role in shaping a sustainable energy future. The ongoing advancements in technology, coupled with increasing affordability and widespread adoption, position solar power as a cornerstone in the global transition to cleaner energy sources. Beyond individual installations, solar energy is becoming an integral part of comprehensive energy strategies at regional and national levels. Governments and industries worldwide are recognizing the imperative to reduce dependence on fossil fuels, and solar energy, with its minimal environmental impact and abundant availability, is poised to play a central role in meeting the rising energy demands sustainably (Mohanty et al., 2017b). As we look to the future, the collective commitment to shaping a sustainable energy landscape hinges on the continued innovation and integration of solar power into the fabric of our global energy infrastructure.

Examining the utilization of renewable energy during the Fifth Technology Revolution in ASEAN nations, this inquiry employs the autoregressive distributed lag (ARDL) approach alongside unrestricted fixed and random panel data methodologies. Over a span of two decades (2000-2022), the investigation utilizes econometric modeling and machine learning to scrutinize factors influencing renewable energy adoption. These factors encompass technological advancements, governmental regulations, public consciousness, electricity usage, population size, foreign direct investment, import and export dynamics, and economic expansion. Initial observations highlight the significant influence of technological advancements, governmental policies, and public awareness on

renewable energy utilization within the ASEAN region. These insights provide valuable guidance for fostering sustainable energy practices amidst the Fifth Technology Revolution (Hoa et al., 2024).

CONCLUSION:

In the symphony of innovation and sustainability, solar energy emerges as a transformative force, reshaping the contours of our energy landscape. The dynamic evolution of photovoltaic technology, coupled with the emergence of intelligent solutions like AI integration and innovative designs, underscores the remarkable journey of solar power. From residential rooftops to expansive utility-scale projects, solar energy transcends mere adoption; it embodies a commitment to a future where clean, renewable power is the cornerstone of our energy paradigm. The economic feasibility and environmental benefits of solar energy amplify its significance, propelling us towards a more sustainable and resilient future. As we witness the rise of thin-film cells, solar tracking, and groundbreaking panel designs, it becomes evident that the narrative of solar energy is not static; it is a story of constant innovation, adaptation, and integration. Looking ahead, the integration of AI promises an era where solar power is not just a source of energy but an intelligent, responsive ally in our quest for sustainability. The future of solar energy is intricately linked to the broader narrative of shaping a sustainable energy future. As we navigate this path, solar energy stands poised as a beacon, guiding us towards a cleaner, greener, and more sustainable tomorrow.

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