

Current Research and Future Trends in Solar Energy Technology Integration with Smart Grids

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Abstract: The growing challenges of solar intermittency and grid instability threaten the reliability and scalability of renewable energy integration worldwide. This study addresses these critical issues by evaluating recent advances in photovoltaic (PV) systems, concentrated solar power (CSP), energy storage, and adaptive grid controls. Through analysis of global case studies, such as Vietnam's solar farms and South Africa's AI-enabled microgrids, it demonstrates how smart inverters, AI algorithms, and hybrid systems effectively reduce variability and enhance overall efficiency. Reviewed literature highlights AI solar forecasting technologies achieving up to 95% accuracy, while hybrid PV-CSP-storage systems deliver 25% higher efficiency. Building on these insights, the study proposes a scalable roadmap for renewable energy adoption that prioritises technological synergy and policy innovation, thereby accelerating the global transition toward sustainable, resilient energy systems.

Keywords: Solar energy, smart grids, photovoltaic systems, energy storage, AI in energy management.

1. INTRODUCTION

Amid soaring global energy demand and climate change urgency, renewables like solar and wind are critical. Solar energy's abundance and plummeting costs position it as a leading renewable source. The International Energy Agency (IEA) forecasts solar PV will drive 60% of global renewable capacity growth by 2024. With increasing affordability and competitiveness, nations are accelerating solar adoption to meet decarbonisation targets [1]. However, integrating solar into conventional grids remains challenging despite its rapid expansion. Solar's weather-dependent nature, which relies on daylight and variable conditions, creates risks of grid instability. Intermittent generation strains grid reliability, complicating seamless energy transitions [2].

Traditional grids, designed for centralised, predictable power flows, struggle with renewable variability like Solar. Smart grids counter this by deploying automation and real-time analytics to balance fluctuating inputs, optimising

operations, and boosting grid reliability and efficiency [3]. This integration of solar energy with smart grids, among other technologies, is promising in lowering greenhouse gas emissions, lowering costs, and balancing demand and supply to pave the way for real-time data use with minimum outages [4].

Smart grids integrate solar to enhance reliability, using advanced metering, Distributed Energy Resource Management System (DERMS), and automated demand response to mitigate solar intermittency. They stabilise supply during solar peaks, reduce outages, and integrate microgrids. Battery Energy Storage System (BESS) stores surplus solar energy for low-generation periods. AI, smart inverters, and Supervisory Control and Data Acquisition (SCADA) enable real-time adjustments to solar variability, paving the way for a resilient, sustainable energy future [5].

This review employs a systematic approach to look at the latest research and future trends in integrating solar energy with smart grids. A comprehensive literature search was conducted using databases such as IEEE Xplore, ScienceDirect, and ResearchGate, focusing on peer-reviewed articles, case studies, and technical reports published between 2018 and 2024. The key search terms included solar energy integration, smart grids, energy storage, AI in energy management, etc. Studies were selected based on their relevance to technological advancements, challenges, and case studies of successful implementations. The review summarises findings from global projects and emerging technologies, identifies gaps in current technology, provides actionable recommendations for policymakers, and suggests future directions to improve grid efficiency. The main contributions of this systematic review are:

1) Employment of A structured search process of Technological Advancements:

This article synthesizes recent research (2018–2024) on solar energy integration with smart grids, providing a comprehensive overview of emerging technologies such as smart inverters, AI-driven forecasting, hybrid PV-CSP-storage systems, and blockchain-enabled trading.

2) Validation through Global Case Studies:

By analyzing real-world implementations (e.g., Vietnam's solar farms and South Africa's AI microgrids), it validates the practical effectiveness of these technologies in improving reliability and reducing emissions.

3) Identification of Challenges and Future Directions:

It outlines key obstacles, including cyber risks, regulatory gaps, and high storage costs, and proposes future strategies centered on AI, IoT, adaptive policies, and decentralized management to support the scalable transition to sustainable, low-carbon energy infrastructures

These contributions were spread across the different sections of the article. Section 2 discusses various solar energy technologies and their emerging advancement, the concept of the smart grid, the importance of integrating solar into the smart grid, and case Studies of Successful Integration of Solar Energy in Smart Grids. Section 3 is made up of reviews on technologies needed for the integration of solar energy. Energy storage solutions for solar-integrated smart grids are discussed in Section 4. The various opportunities and challenges facing the integration of Solar into the smart grid are discussed in Section 5 of the article, while the concluding remarks come in Section 6.

2. OVERVIEW OF SOLAR ENERGY AND SMART GRID SYSTEMS

Solar energy technologies and smart grid systems enhance power supply reliability and efficiency. With the potential for decentralised, clean electricity production, photoelectric systems, solar thermal systems, and concentrated solar power plants are employed.

2.1 Solar Energy Technologies

1) **Photovoltaic (PV) Systems:** Photovoltaic (PV) technology converts sunlight into electricity via semiconductors, with systems advancing in efficiency and cost-effectiveness. Innovations like bifacial panels harness sunlight on both sides, while third-gen PV, organic, quantum dot, and perovskite cells target higher efficiency and affordability over silicon. Concentrated PV optimises sunlight capture onto smaller, high-efficiency cells. However, cooling solutions for these technologies require further development to address heat management challenges [6], [7], [8].

2) **Solar Thermal Technologies:** Solar thermal technologies harness sunlight for heating and electricity. Collectors convert sunlight into thermal energy via heated fluids, ranging from residential

flat-plate systems to large-scale solar concentrators. Hybrid PV/Thermal systems merge photovoltaic and thermal technologies, generating electricity and heat, ideal for industrial use. Innovations like nanofluids and phase-change materials enhance heat absorption and storage, boosting efficiency in smart grid integration [9].

3) **Concentrated Solar Power (CSP):** CSP deploys mirrors/lenses to focus sunlight onto a fluid heat exchanger, driving electricity turbines. Unlike PV, CSP stores thermal energy, enabling 24/7 power and reducing solar intermittency. Key designs include parabolic troughs, solar towers, linear Fresnel, and dish engines. Storage-integrated CSP now rivals PV in cost but offers superior grid stability through dispatchable power. Recent advances include molten salt storage upgrades and hybrid systems combining CSP with wind or biomass [10], [11].

2.2 Emerging Advancements in Solar Energy

Emerging solar innovations like quantum dot coatings and floating solar farms (maximising space and curbing evaporation) are advancing efficiency. AI and ML optimise plant performance and grid integration, enabling predictive maintenance and real-time energy management. Solar with smart grids enhances stability via demand response and higher renewable penetration. Paired with AI-driven tools, advances in PV, CSP, and thermal systems will solidify Solar's role in reliable, future-ready energy systems [12]. Hybrid systems combine PV and CSP technologies with storage solutions to maximise solar energy use, ensuring reliable energy supply and improving grid integration [13]. Figure 1 shows the growth trend in global solar energy installations.

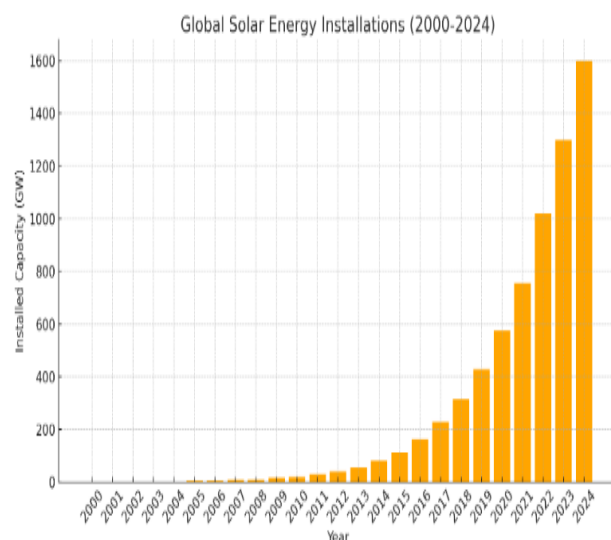


Figure 2: Graph showing the growth trend in global solar energy installations

2.3 Smart Grid Concepts: Components and Their Role in Enhancing Grid Operations

A smart grid is a digitalised two-way energy network that integrates conventional infrastructure with modern technologies to optimise power generation, distribution, and consumption. Integrating sensors, communication networks, and control systems transforms grid operations, focusing on reliability, efficiency, and real-time control. An important component of this evolution is the Smart Grid Asset Management (SGAM), which ensures the effective management of physical and digital assets within the advanced networks of the smart grid. SGAM improves efficiency, reliability, and sustainability by leveraging real-time monitoring, predictive maintenance, and data-driven decision-making. Unlike traditional reactive approaches, it supports cost optimisation, renewable energy integration, and improved customer service [14].

- i. **Sensors:** Monitoring of grid health and faults, as well as real-time data on energy flow, are all facilitated by sensors (temperature, voltage, and current sensors) [15]. This real-time grid information is transmitted as a signal to the control stations. For example, with smart temperature sensors, instantaneous temperature fluctuations in transmission lines would be easily monitored. To conclude, smart sensor node integration with advanced routing algorithms shall give smart grids the ability to achieve optimal communication among nodes through enhanced overall grid performance [16]. Presenting smart sensors in smart grids improves reliability and efficiency through real-time surveillance, data collection, and automation, with Wireless Sensor Networks (WSNs) playing an important role [17]. Smart meters with sensors will be able to measure electricity consumption and other grid parameters for demand-side management and reduction of energy losses [18].
- ii. **Communication Technologies:** Communication networks in the smart grid facilitate an easy data transfer across sensors, smart meters, and control systems to develop a conceptualised real-time interaction between utilities and consumers with wireless and wired infrastructures [19]. Advanced technologies like Worldwide Interoperability for Microwave Access (WiMAX), Power Line Communication (PLC), and 5G are being used to support efficient, high-speed data transfer and grid control [20]. PLC is a preferred communication mode in smart metering systems due to its reliability and enhanced interaction between front-end sensors and grid monitoring systems [21]. Technologies enable timely communication of energy supply, demand, and faults for proper decision-making to manage energy supply. IoT in smart grids enhances monitoring and controlling, improving energy management, fault detection,

and operational efficiencies when working with smart meters and sensors [22].

- iii. **Control Technologies:** These systems use advanced algorithms to automate smart grid management, dynamically balancing supply and demand to optimise power flow. They enable self-healing capabilities, autonomously detecting and isolating faults to enhance reliability. Combining Advanced Metering Infrastructure (AMI), Intelligent Electronic Devices (IEDs), and control algorithms, they manage voltage, frequency, and power distribution in real-time [23]. Edge computing reduces latency and increases the performance of the distributed control systems in the grid by shifting the processing data closer to the generation point [24], [25]. Researchers explore blockchain technologies to provide enhanced security and privacy to smart grids, enabling grid operators to securely transmit data with minimum cyber-attack risk [26].

Using Dynamic Line Rating (DLR) [27], [28] and Electric Vehicles (EVs)[29], [30] as an example, EVs serve as sensors, controllers, and communication hubs in smart grids. They monitor battery charge levels and grid load at charging stations as sensors. EVs enable real-time load balancing and energy storage management through smart charging, demand response, and Vehicle-to-Grid (V2G) integration. Their communication capabilities link charging infrastructure, grid operators, and cloud platforms to optimise schedules, facilitate billing, and enhance grid stability, positioning EVs as vital enablers of modernised energy systems.

DLR also plays an important role in smart grid technologies, primarily contributing to sensors and control, with a reliance on communication [31], [32]. DLR uses sensors to monitor real-time environmental and line conditions (temperature, wind speed, and conductor sag), providing accurate assessments of transmission line capacity. It enables control by dynamically adjusting power line operating limits to optimise grid performance and ensure safety. Communication infrastructure is essential for transmitting data obtained from the sensors and updating operators with real-time ratings.

2.4 Importance of Solar-Grid Integration

Integrating solar energy into smart grids presents immense potential but also complex challenges. While solar enhances grid sustainability, its inherent intermittency requires precise coordination and advanced management strategies to ensure stable power delivery. Effective integration demands balancing technical hurdles, such as Solar variability disrupting grid stability, with opportunities to maximise renewable utilisation [33]. In addition, grid stability and voltage fluctuations become critical issues due to the potential for voltage instability and harmonic distortions. Integrating Solar PVs can lead to power quality problems, particularly in weaker AC grids, including

infrastructure overload [34]. Distributed Flexible AC Transmission System (FACTS) devices and adaptive control strategies are recommended to address these concerns. Energy storage is another crucial aspect. Because solar energy is intermittent, energy storage systems are essential to smooth out power fluctuations; however, technologies like batteries are costly and demand substantial investments. Grid operators must conduct economic assessments and pursue optimised solutions for cost-effective integration [35]. Solar forecasting is another key element of efficient integration, as accurate solar energy predictions help balance supply and demand, reducing grid inefficiencies [36].

Despite these challenges, several opportunities have emerged to enhance solar-grid integration. For instance, smart grids can accommodate innovative technologies, such as smart inverters and Distributed Energy Resources (DERs), which can enhance grid efficiency. The Photovoltaic Integration Index (PV II) has been proposed as a novel tool to optimise photovoltaic plant placement and improve voltage stability and operational efficiency in smart grids [35]. Solar energy sources reduce fossil fuel use and consequently reduce the associated greenhouse gas emissions, increasing grid reliability. Energy distribution efficiency is bound to increase further using IoT-based smart solutions [37]. Various technological advancements, such as the development of perovskite solar panels, smart inverters, grid-forming technologies, and power electronics, create an avenue for better grid control and allow for dynamic operations with higher solar penetration [38]. These developments enable better energy management that is more reliable and reduces energy transmission loss when integrated within smart grids [39].

The next best viable opportunity for use is embedding smart control and automation. Advanced control strategies, such as AI and decentralised systems, can allow for better solar energy integration into smart grids by managing power variability and facilitating peak shaving [40]. Battery Energy Storage Systems (BESS) offers an efficient approach capable of handling the intermittency of solar power. These systems smoothen fluctuations, improve grid reliability, store excess energy generated at peak solar generation, and release it during periods of low generation [41]. Demand response strategies and smart metering technologies are important in balancing solar generation and grid load, enabling real-time monitoring and adjustments to energy consumption [42]. Hybrid energy systems are a reliable means of handling the variability in solar energy by combining solar energy with other renewable energies such as wind energy or energy storage systems. This hybrid approach will improve the power supply's stability and reduce dependence on conventional energy sources [43].

2.4 Case Studies of Successful Integration of Solar Energy in Smart Grids

Integrating solar into smart grids enhances reliability through advanced technologies like predictive algorithms,

smart controllers, and energy storage. Solar-powered grids address conventional grid limitations by mitigating intermittency challenges, enabling sustainable energy delivery.

A prominent approach combines solar photovoltaic systems with Battery Energy Storage Systems (BESS). In a case study by Baseer and Alsaduni, SPV-BESS integration improved grid reliability by minimising power losses and stabilising voltage during demand fluctuations. This model leverages optimisation algorithms like Horse Herd Optimization (HHO) to maximise efficiency, showcasing Solar's role in resilient, adaptive energy networks [44]. Reinforcement learning (RL) enables self-learning systems to optimise solar-grid integration. These algorithms forecast solar generation in real-time, allowing grids to dynamically adapt to changes in sunlight. This results in reliable energy availability even during low sunlight, ensuring consistent power delivery [45].

Vietnam's Hau Giang province demonstrates renewable energy's grid-strengthening potential. Its solar farms reduced system losses and stabilised voltage, improving reliability indices post-integration [40]. In South Africa's KwaZulu-Natal, a microgrid combining renewables and battery storage uses Adaptive Model Predictive Control (AMPC) to pre-empt disruptions and adjust loads in real time. This approach cuts emissions, lowers costs, and bolsters reliability during peak demand [41].

A pilot project at the University of Technology in Paraná, Brazil (UTFPR), demonstrated a 10-kW grid-tied PV system combined with BESS to reduce peak load dependency. Through intelligent scheduling, the project-maintained grid reliability and efficiency even with variable solar output, which lowered operational costs and reliance on the grid. This case illustrates the potential of solar and storage for large institutional applications [46]. In Dubai, an advanced approach was implemented, integrating IoT sensors with distributed solar generation to improve demand-side management and fault identification. Real-time monitoring allowed for increased system visibility and reduced faults, which enhanced overall grid reliability. This case highlights the critical role of the IoT in supporting solar-integrated smart grids through precise monitoring and demand management [47].

3. TECHNOLOGIES FOR INTEGRATION OF SOLAR ENERGY

3.1 Power Electronics and Inverters

Recent advancements in inverter technology enhance solar energy management and grid stability. Power electronics and inverters enable solar-grid integration by regulating voltage, minimising losses, and balancing supply-demand fluctuations. These innovations serve as the backbone for optimising solar efficiency and grid reliability. Table 1 summarises key advancements, their benefits, and challenges.

Table 1: Power electronics and inverter assessments

Key Development	Description	Merits of Findings	Limitations / Recommendations
Switched-Capacitor Multilevel Inverter (SCMLI) [48]	Enhances voltage levels with selective harmonic elimination	Reduces high-order harmonics and increases voltage support for HFAC applications	Costly due to additional components; suggests integration with more economical solutions
Cascaded Multilevel Inverters [49]	New topology with reduced power switches for different voltage levels	Lowers installation cost and area; improves voltage modulation and reduces harmonic distortion	Limited voltage range in asymmetric mode; recommends adaptive configurations for larger setups
High-Frequency Resonant Inverters [50]	Enhances current sharing with phase and magnitude control	Reduces circulating currents, improves load-sharing, and enhances system stability	Complex modulation strategies; recommends simplified control methods for scalability
Grid-Forming Inverters [51]	Grid-forming inverters operate independently of the grid, providing synthetic inertia to stabilise the grid during power fluctuations.	Enhances grid stability, particularly in low-inertia grids with high renewable penetration.	Grid-forming inverters are more costly and complex; further research is needed to lower costs and simplify integration.
Exponential Droop Control [52]	A novel droop control method, Droop-e, for grid-forming inverters that improves frequency stability in highly renewable scenarios.	Effective in maintaining frequency and voltage stability under low-inertia conditions.	It is not yet widely implemented and needs further validation in large-scale grid settings.
Reactive Power Optimisation [53]	Uses optimisation algorithms to maximise the reactive power output of PV inverters for voltage stability.	Reduces power loss and increases load stability in solar-integrated grids.	Limited applicability in low-voltage networks; further research is recommended for broader applicability.
Hybrid GoA-FPA Control [54]	A multi-objective optimisation technique for inverters to reduce Total Harmonic Distortion (THD).	Reduces THD to below 1.5%, enhancing power quality even under variable irradiance.	Computationally intensive, further optimisation is needed for real-time applications.

3.2 Energy Storage Systems

Energy storage systems are critical for grid stability, balancing supply and demand. Established technologies like lithium-ion, flow, and solid-state batteries offer short- to medium-term storage. Emerging solutions such as compressed air, thermal storage, hydrogen, and gravity-

based systems provide long-duration capabilities, enhancing renewable integration and grid resilience. These innovations ensure consistent power availability during periods of low renewable generation. Table 2 summarises key advancements, merits, and limitations in Energy Storage systems.

Table 2: Energy storage systems assessments

Key Development	Description	Merits of Findings	Limitations
Closed-Loop Pumped Hydro [55]	Closed-loop systems that recycle water between two reservoirs minimise environmental impacts on rivers.	Enhances grid reliability and provides large-scale, long-duration storage.	Limited to specific geographic areas and sizeable upfront investment, more research into minimising construction costs is needed.
Battery Energy Storage Systems (BESS) [56]	Lithium-ion batteries store energy for short-term fluctuations, ideal for rapid discharge needs.	Highly responsive, ideal for short-term storage, and supports grid reliability in fluctuating conditions.	Higher cost per kWh and limited to short-duration storage; lifecycle and disposal impact pose environmental challenges.
Emerging Storage	Evaluated novel options like thermal	Provides storage diversity, potentially low	Emerging technologies require further scaling and cost reduction for grid integration.

Key Development	Description	Merits of Findings	Limitations
(Thermal, Flywheels) [57]	and flywheel storage for solar integration.	cost, and reduces dependency on chemical batteries.	
Compressed Air Storage (CAES) [58]	It stores energy via air compression in deep ocean reservoirs and is suitable for coastal applications.	Provides seasonal storage potential with high storage volume, complementing short-term battery storage. Compressed gas tanks are costly due to carbon fibre requirements, while liquid hydrogen systems suffer a 0.05% daily boil-off loss.	It requires a high initial investment and specific coastal locations; economic feasibility and efficiency improvement are needed.
Hydrogen Storage System [59]	It's critical for enabling its use as a clean energy carrier, particularly in renewable energy integration	Economically, high capital costs for liquefaction plants, pose significant barriers. Additionally, underground storage raises environmental concerns due to risks of geochemical contamination.	Material innovation should focus on nanostructured composites to advance hydrogen storage for higher storage density and faster kinetics. Thermal management solutions, such as advanced insulation, are needed to reduce LH ₂ boil-off losses. Policy support should prioritise standardising safety protocols, incentivising green hydrogen infrastructure, and fostering global collaboration to scale up international projects like the Australia-Japan LH ₂ supply chain.

3.3 Grid Management and Control Systems

Table 3 highlights advancements in grid control systems, SCADA, DERMS, and real-time analytics, that optimise operations. These tools enhance resiliency, anomaly

detection, and DER integration while addressing challenges like cyber-attacks and latency. Further development is needed to maximise grid stability and efficiency.

Table 3: Grid management and control systems

Key Development	Description	Merits of Findings	Limitations
Anomaly Detection [60]	Anomaly detection using CNN-LSTM for protection against false data injection (FDI) attacks.	Achieves 95.43% accuracy in detecting FDIs, significantly reducing the false positive rate.	Further research is needed to generalise model effectiveness across diverse grid configurations.
SCADA and DERM Integration [61]	Implements DC-side and AC-side control for PV systems	Ensures power quality and stability; enables control of large-scale solar PVs	Complexity in managing large datasets suggests optimised data handling for scalability
Hybrid Solar-Wind Control for Grid [62]	Controls active/reactive power in solar-wind systems with SPWM control	Achieves unity power factor and optimises energy flow	Limited to hybrid configurations; suggests adaptive control strategies for varying solar-only loads
Real-Time Data Analytics in Battery-Integrated PV Systems [63]	Combines PV systems with Battery Energy Storage for real-time grid analysis	It enhances voltage regulation stability and provides backup power	High cost for battery setups; recommends cost analysis for economic feasibility in broader applications
Advanced Control with FAGI Algorithm [64]	Applies FAGI for compensating reactive power in solar PVs	Maintains grid quality and supports load stability in non-ideal conditions	Needs adaptation for various grid codes; suggests expanded testing under diverse load scenarios
Hierarchical Utility-Scale PV Control [65]	Employs a hierarchical structure to manage variability in utility-scale PV	Provides ancillary services and adapts to cloud cover changes for stability	Complexity in implementation; recommends streamlined control for simpler deployment.

Key Development	Description	Merits of Findings	Limitations
Two-Stage Grid-Tied Control [66]	Features active power regulation and Massively Parallel Processing MPP estimation without storage	Enables frequency control and simplifies PV integration	Limited by lack of storage, suggests testing with integrated energy storage for enhanced stability
Grey Wolf Algorithm for Dynamic Control [67]	Uses optimised gains for dynamic grid performance in solar PVs	Improves grid stability and power quality, minimising voltage regulation issues	Complexity in algorithm setup suggests more user-friendly software for wide adoption

3.4 Forecasting and Predictive Models

This section reviews some of the latest forecasting models, as shown in Table 4, underlining methods such as hybrid deep learning [68], and ensemble models [69] that improve the accuracy of short-term and day-ahead solar

prediction with broad applicability for efficient solar integration into the grid. Recommendations emphasise increased model simplicity and computational efficiency for broader, real-time grid applications.

Table 4: Forecasting and predictive model assessments

Key Development	Description	Merits of Findings	Limitations
Ensemble Machine Learning [70]	Employs ensemble learning (RF, XGBoost) for solar radiation prediction from meteorological data.	Increases forecast accuracy by reducing variation and bias through model combination.	Computationally intensive, real-time implementation requires optimised computational resources.
Hybrid CAN-ANFIS Model [71]	Utilises cascaded neural network and ANFIS for short-term solar irradiance and demand forecasting.	Offers <5% forecast error, supporting optimal demand management.	Model complexity requires substantial computational power; simplification is recommended for real-time use.
Temporal Fusion Transformer (TFT) [72]	Attention-based model for day-ahead PV power forecasting across multiple sites.	Outperforms traditional models in accuracy and is adaptable for varied forecast durations.	High resource demand; scaling for large-scale deployment recommended.
Hybrid Model with Satellite and Sky Images [73]	Integrates satellite and sky images for intra-hour solar prediction	Improves accuracy under varying weather conditions, setting groundwork for nowcasting	Limited to high-resource settings; recommends scaling for broader applicability
Atmospheric-Driven Forecasting [74]	Integrates atmospheric data for accurate irradiance forecasting	Supports carbon-neutral goals by enhancing solar-grid integration	Dependent on atmospheric data quality; calls for stronger data integration practices
Physics-Augmented ML Models [75]	Incorporates physical parameters with ML to enhance forecast accuracy	Outperforms traditional models with better cloud interaction capture	Limited by parameter complexity; recommends simpler interpretability techniques

By providing real-time monitoring and analysis of solar PV systems to ensure grid stability, Jia et al. survey shows the transformative impact of IoT in solar energy integration. IoT enables enhanced load management and demand response techniques, such as IoT-based home energy management systems, to optimise peak-hour consumption. IoT improves the solutions for energy storage by observing and regulating the storage systems to address intermittency issues in solar energy. IoT applications include smart metering systems, distribution systems, and demand response systems with the implementation of Model Predictive Control (MPC) and event-triggered schemes (ETS) for frequency stability and cybersecurity. Despite the various advancements, data security, privacy, and the <https://doi.org/10.53982/ajeas.2025.0301.10-j>

necessity for the standardisation of communication protocols are critical for the widespread implementation of IoT for PV-powered systems [76].

Folgado et al. present an experimental implementation of Industrial IoT (IIoT) architecture for a pilot microgrid with the integration of photovoltaic energy and hydrogen in their study. The architecture is structured into four layers: the sensing Layer, the Network Layer, the Middleware Layer, and the Application Layer. The system was tested on a microgrid with four subsystems: PV generator, battery, hydrogen generator, and fuel cell, which are equipped with sensors (temperature, current, voltage, and irradiance). This implementation showcases IoT's role in enabling extensive

monitoring, efficient energy management, and system resilience in a PV-powered microgrid [77].

4. ENERGY STORAGE SOLUTIONS FOR RELIABILITY IN SOLAR-INTEGRATED SMART GRIDS

4.1 Battery Storage Technologies

- a. **Lithium-ion Batteries:** Dominant in energy storage systems, Li-ion batteries boast high energy density, long cycle life, and efficiency. Thus, Li-ion batteries are used widely in grid-level storage systems, making them very effective in managing power fluctuations in smart solar grids. For example, their fast response and modularity enable grid frequency regulation, peak shifting, and integration with renewable sources [78] [79].
- b. **Solid-State Batteries:** At the same time, solid-state batteries are in an even more experimental phase compared to Li-ion, but they show promising improvements concerning energy density and safety. These batteries replace the liquid with a solid electrolyte, eliminating all risks of leakage or fire. Still under development, it is expected that this would minimise life cycle cost over time and turn into a probable grid solution as

time passes by, concerning reliability and capacity [80], [81].

- c. **Flow Batteries:** Flow batteries, such as vanadium redox, provide scalable storage with separated power/energy components, enabling longer lifespans and easier scaling for grid needs. Their flexibility in modulating energy and power independently aids solar integration. However, higher costs and lower energy density than lithium-ion batteries limit their feasibility to niche, large-scale applications [82], [83].

4.2 Role of Storage in Addressing Solar Intermittency

Energy storage systems are crucial in damping solar power fluctuations and strengthening the grid's reliability, realising a real-time balance between supply and demand. Among them, BESS is particularly effective at responding immediately to frequency and voltage shifts, which helps to support grid stability during periods of low sunlight or sudden changes in solar output. BESS will also be able to participate in energy markets for peak shaving and demand management applications, which will improve economic efficiency and reliability [84], [85], [86].

Table 5: Comparative analysis of different storage solutions

Technology	Cost	Efficiency	Lifespan	Scalability
Lithium-ion	Moderate to High	85-95%	10-15 years	High
Solid-State	High	95%+	Expected high	Moderate
Flow Batteries	High	75-85%	20+ years	Very high

5. SWOT ANALYSIS

5.1 Strengths

One of the strongest assets of integrating solar energy with smart grids is the synergy of blockchain and IoT technologies. Blockchain enables secure, transparent, and decentralised energy trading, especially in peer-to-peer (P2P) markets, minimising dependence on centralised authorities. This enhances operational transparency, builds user trust, and lowers transactional overhead. IoT, combined with edge computing, supports real-time monitoring, predictive maintenance, and dynamic load control. This level of responsiveness reduces energy waste, improves uptime, and facilitates data-driven decision-making. Such advancements also strengthen the resilience of the grid in real-time operational scenarios. AI and ML further enhance grid intelligence. These technologies enable accurate solar forecasting, efficient load balancing, and fault detection. Hybrid AI models like Bi-LSTM and AE-LSTM have shown remarkable accuracy compared to traditional statistical methods, while reinforcement learning allows the system to adapt dynamically to changing demand-supply conditions.

Lastly, the integration of real-world case studies from countries like South Africa, Vietnam, and Brazil demonstrates the practicality of solar-smart grid solutions. These cases offer insights into policy models, community-

driven microgrids, and the operational benefits of digitalised solar energy systems.

5.2 Weaknesses

Despite the promising technologies, technical complexity of these technologies is a weakness. Integrating PV with smart grids involves diverse disciplines, ranging from AI to power electronics, making implementation challenging for regions lacking skilled manpower or robust infrastructure. High capital and operational costs remain a hurdle. While solar module prices have declined, the cost of upgrading grids, deploying advanced storage, and maintaining IoT-AI infrastructure can be prohibitive, particularly in developing economies.

5.3 Opportunities

The future presents vast opportunities through AI and ML-driven solutions. Sophisticated algorithms not only improve generation forecasts but also support automated control, enabling responsive demand-side management and optimal energy dispatch. Energy storage technologies, including lithium-ion, flow batteries, and emerging solid-state designs, offer solutions to solar intermittency. Hybrid systems combining solar with wind or CSP plus storage can deliver dispatchable, reliable power across varying timeframes. The integration of blockchain creates potential for fully decentralised energy systems where households

and communities actively participate in local energy markets. Smart contracts and transparent pricing mechanisms can drive efficient resource allocation and empower consumers.

From a regulatory standpoint, there is room for adaptive policy innovation. Updating grid codes and enabling sandbox environments for testing decentralised energy applications can accelerate the adoption of solar-smart grid models, especially in emerging markets. Furthermore, the development of community microgrids offers scalable, inclusive energy access in remote or underserved regions. Such systems reduce transmission losses and empower local economies while supporting national electrification goals.

5.4 Threats

The integration of solar with smart grids also faces significant technical risks. For instance, solar variability can destabilize grids without adequate flexibility mechanisms. The lack of robust control systems may lead to over-voltage, under-frequency, or blackouts during peak mismatch periods. Energy storage trade-offs, while essential, introduce cost, degradation, and environmental issues. Battery recycling and disposal remain largely unaddressed in many countries, raising concerns about long-term sustainability and ecological impacts.

On the regulatory front, outdated frameworks often lag behind technological advancement. In countries like Spain, for example, rigid grid codes and tariffs have limited the full potential of distributed PV systems, discouraging private and community investment. Economic threats include market volatility in solar components, geopolitical disruptions in battery supply chains, and inconsistent financial incentives. Without long-term policy certainty, investors may hesitate to fund grid modernization and solar deployment. Cybersecurity vulnerabilities tend to increase as smart grids become more digitalised. IoT devices, cloud platforms, and peer-to-peer trading networks must be protected against hacking, data breaches, and privacy violations, all of which pose threats to consumer trust and grid reliability.

6. CONCLUSION

The integration of solar energy technologies with smart grids presents a transformative pathway toward a cleaner, smarter, and more resilient power system. Strengthened by AI, IoT, and blockchain, the ecosystem promises improved forecasting, decentralised energy trading, and real-time optimisation. However, challenges such as high implementation costs, technical complexity, regulatory inertia, and cybersecurity threats cannot be ignored. By leveraging innovation, advancing policy reforms, and promoting community-based energy solutions, these barriers can be gradually overcome. As research and field applications continue to evolve, the convergence of digital intelligence and solar energy holds immense promise for the global energy transition.

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