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A Review of Megawatt-Scale Photovoltaic Systems for Governmental Buildings: Pathways Toward Zero Grid Consumption and Environmental Sustainability

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ABSTRACT

The rapid evolution of solar photovoltaic (PV) technology has established. This study reviewed recent advancements, persistent challenges, and emerging solutions in solar PV systems, with a focus on their integration into grid and off-grid applications, energy storage systems, and building energy management systems (BEMS). The literature revealed notable improvements in conversion efficiency, market expansion, and sustainability, while also identifying ongoing barriers such as grid instability, high installation costs, and environmental issues like dust accumulation and extreme temperatures. Case studies from various regions, including Iraq, demonstrated the feasibility and benefits of large-scale PV implementation, while underscoring the importance of supportive policies and technological innovation. The proposed methodology employed simulation tools (e.g., PVsyst, MATLAB) alongside real load data to optimize system design. Findings indicated that integrating PV systems with BEMS and battery storage enhances energy efficiency, reduces operational costs, and supports net-zero energy objectives. The study concludes with policy recommendations and future research directions aimed at overcoming implementation barriers and maximizing the potential of solar PV systems.

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1. INTRODUCTION

Solar photovoltaic (PV) systems are currently undergoing rapid global expansion, establishing themselves as a central component in the global transition toward sustainable energy sources. According to the International Renewable Energy Agency (IRENA), the total installed capacity for solar electricity worldwide surpassed 1 terawatt (TWh) in 2022 and is projected to increase steadily throughout the current decade [1]. Since 2010, substantial technological advancements have reduced the cost of solar panel production by up to 82%, making solar energy increasingly competitive with conventional power sources, particularly in developing markets [2].

Iraq possesses one of the highest levels of solar irradiance globally, ranging from 2,000 to 2,500 kWh/m^2 per year [3], indicating strong potential for solar energy development. However, despite this advantage, solar energy contributes only around 1% to the national energy supply, reflecting a very low penetration rate [4]. This underutilization is attributed to a complex mix of technical, environmental, and institutional challenges that require urgent attention.

Key technical barriers to solar PV adoption in Iraq include:

(i) Environmental constraints: Dust accumulation can reduce panel efficiency by up to 45% during summer months, and ambient temperatures exceeding 50°C negatively impact both output and panel lifespan [5];

(ii) Grid integration issues: The national electricity grid is characterized by instability and underdeveloped infrastructure, which hampers the connection of large-scale solar systems [6];

(iii) Political and institutional challenges: These include the absence of a supportive legal framework, insufficient financial incentives, and a shortage of skilled technical personnel, all of which significantly impede solar energy initiatives.

With a particular focus on the Iraqi context, this study provides a comprehensive review of recent developments in solar PV systems. The objectives are fourfold: (i) to analyze recent technological advances in solar energy and storage systems; (ii) to evaluate the technical, environmental, and policy-related challenges of solar deployment in Iraq; (iii) to propose practical solutions for improving system performance under Iraqi climatic conditions; and (iv) to offer policy recommendations that support the adoption of solar energy technologies.

This research adopts an integrated analytical methodology, combining an extensive literature review with field data from case studies in Iraq. It also utilizes simulation tools such as PVsyst and HOMER Pro to model system performance under real-world conditions. Scientifically, the study addresses a critical gap in understanding solar energy applications in hot and dusty environments. Practically, the findings aim to serve as a valuable reference for engineers, policymakers, and stakeholders in Iraq and similar regions. The remainder of this paper is organized into six main sections.

2. METHODS

This study employed a literature survey approach to analyze recent advancements and implementation strategies of megawatt-scale photovoltaic (PV) systems in governmental buildings, with a focus on the Iraqi context. The review integrated findings from peer-reviewed journals, case studies, and technical reports published between 2019 and 2025, which were accessed through databases. Keywords used in the search included “MW-scale PV,” “net-zero buildings,” “solar energy in Iraq,” “BEMS integration,” and “PV system design.”

The selection criteria focused on studies related to PV system efficiency, environmental challenges, energy storage integration, and policy implications. Only articles with empirical data, simulation models, or technical evaluations were considered. The analysis synthesized global developments alongside regional applications using tools such as PVsyst, MATLAB, and HOMER Pro. Iraqi case studies, including 1-10 MW solar projects, were examined to validate design models and compare performance under extreme climatic conditions. This method aimed to derive best practices, identify local challenges, and propose strategies for efficient, cost-effective, and sustainable PV implementation in public infrastructure.

3. RESULTS AND DISCUSSION

3.1. Evolution of Solar PV Technology

The historical development of solar photovoltaic (PV) technologies has been reviewed to assess their impact and anticipate future trends. The analysis focused on key areas such as improvements in conversion efficiency, reductions in production costs, market expansion, and the advancement of sustainable manufacturing processes. Major challenges identified in earlier stages included outdated technologies, financial limitations, and political instability [1].

The large-scale integration of solar PV into national energy systems was also examined, particularly due to its role in enhancing grid stability, supporting energy storage, and meeting growing consumer demand. Collaboration between the industrial sector and academic institutions was emphasized as essential for driving innovation and sustainable development in the solar energy field. Such partnerships are necessary to overcome obstacles related to infrastructure investment, fragmented policy frameworks, and technical complexity [2].

3.2. MW-Scale PV System

The integration of both small- and large-scale PV systems into national electricity grids presents several technical challenges. These include weather fluctuations, underdeveloped infrastructure, mismatches between energy supply and demand, limited storage capacity, and concerns regarding power quality [7]. **Figure 1** illustrates the global growth in installed solar PV capacity over the years, highlighting the rapid increase in deployment, which reflects growing interest in large-scale applications.

To address integration challenges, several solutions have been proposed, such as the implementation of advanced grid control technologies, infrastructure modernization, and enhanced coordination among stakeholders. **Figure 2** presents a schematic diagram of a typical megawatt-scale PV system setup, demonstrating how various components (such as inverters, panels, and monitoring systems) interact to ensure efficient operation within large-scale installations.

A case study evaluating the techno-economic feasibility of a 15 MW solar PV power plant in Pakalia, Bangladesh, further illustrates the potential of large-scale systems. The project offers promising long-term financial returns, environmental advantages, and improved energy accessibility [8]. However, the realization of such benefits remains highly dependent on government support, regulatory policies, and the relative competitiveness of energy prices in the region.

3.3. Zero Grid Consumption and Net-Zero Energy Buildings

Net-zero energy buildings (NZEBs) are increasingly recognized for their ability to balance energy production and consumption through efficient system design and integration with renewable energy sources, particularly solar photovoltaic systems. These buildings contribute significantly to reducing reliance on the electrical grid and lowering carbon emissions [9,10].

However, they also face challenges related to spatial limitations, high upfront costs, infrastructure constraints, and complex planning processes.

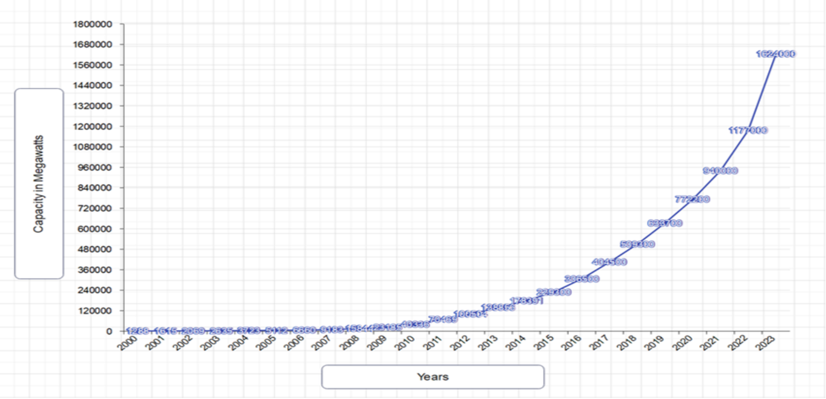

Figure 1. The global growth of installed solar PV capacity throughout the years.

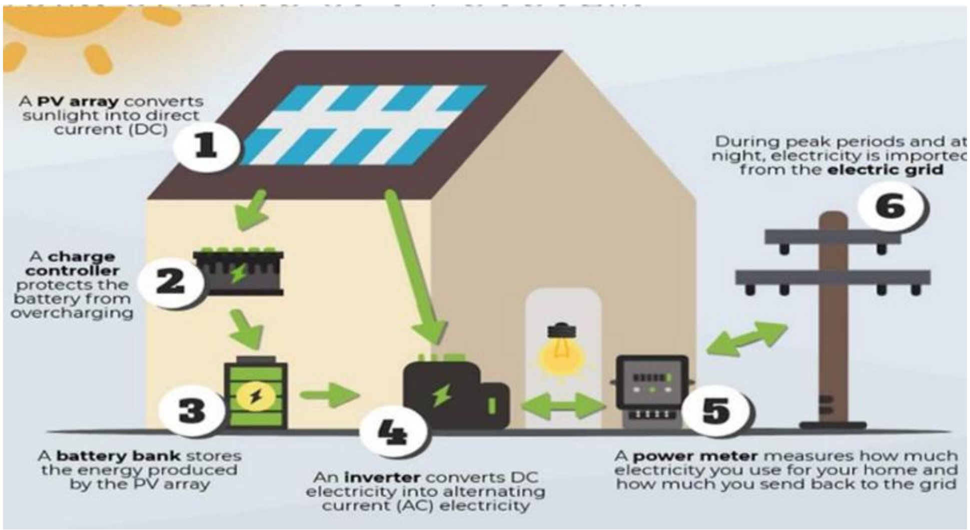

Figure 2. Schematic diagram of a typical MW-scale PV system setup.

Figure 3 illustrates the typical energy flow in an NZEB, showing how renewable energy is generated, stored, and consumed within a closed-loop system to achieve zero grid dependence.

To support NZEB implementation, a method for sizing grid-connected solar PV systems has been proposed. This approach highlights the critical role of site selection, orientation, tilt angles, and building-specific requirements in determining system performance [11]. The importance of integrating these design considerations into new construction has been emphasized, alongside a broader analysis of key drivers that support net-zero energy targets. These drivers include advancements in grid technologies, smart building infrastructure, and renewable energy systems. However, progress is often hindered by factors such as high costs, inadequate infrastructure, and limited storage capabilities.

In the European Union, a review of NZEB definitions revealed significant inconsistencies across member states, complicating implementation and comparability, and posing a risk to the EU's broader energy efficiency objectives [12]. The need for a standardized regulatory framework was emphasized, along with related concepts such as positive energy buildings and building-integrated photovoltaics (BIPV) [13].

In China, six BIPV applications were analyzed using performance assessment tools. These cases demonstrated substantial progress toward achieving net-zero energy targets, though challenges persisted in the form of high initial investment costs, grid integration difficulties, and insufficient financial incentives.

Figure 4 presents comparative case studies of NZEBs utilizing PV systems, highlighting the relationship between energy generation and consumption. These studies reinforce the importance of supportive legislation, coordinated policies, and continued innovation in developing resilient, scalable, and sustainable NZEBs globally.

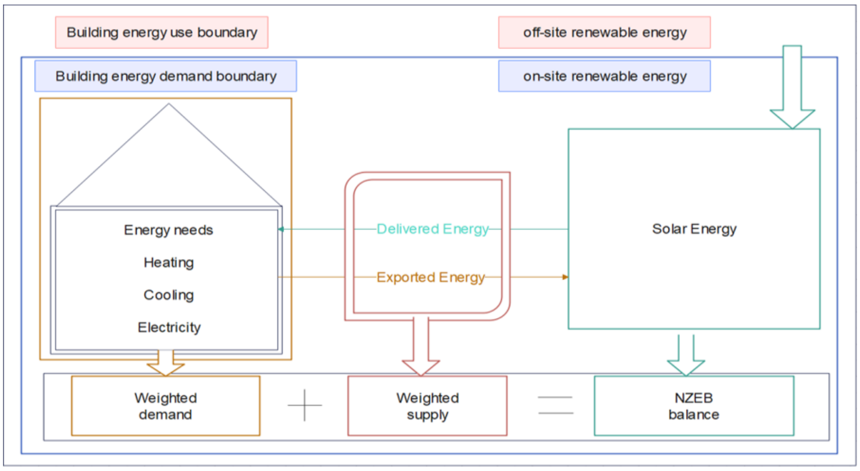

Figure 3. Diagram illustrating energy flows in a net-zero energy building.

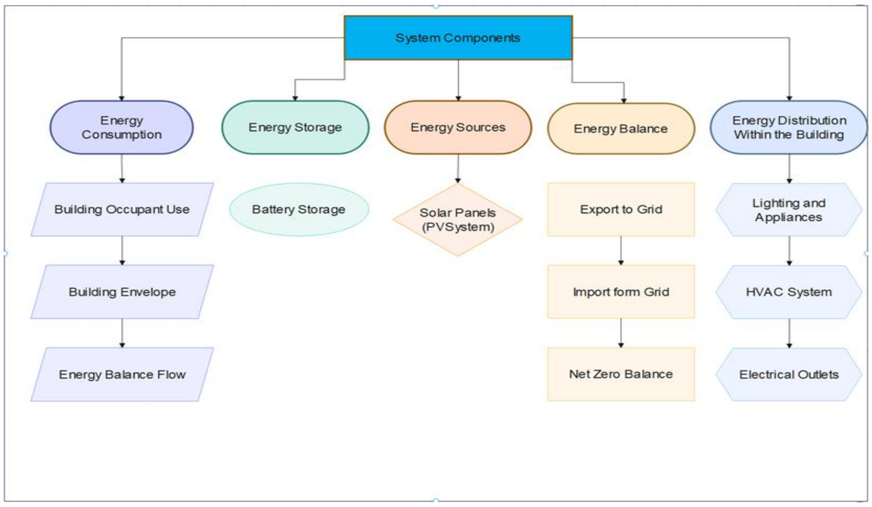

Figure 4. Case studies of NZEBs with PV systems, comparing energy generation and consumption.

3.4. Solar PV System Design and Sizing Methodologies

Designing solar PV systems requires careful consideration of performance factors such as reliability, cost, and environmental impact. Recent studies have highlighted modern sizing approaches, including artificial intelligence (AI)-based techniques and hybrid methods, while also discussing classifications, value indices, and methods for sizing both stand-alone and grid-connected renewable energy systems [14]. **Figure 5** presents a flowchart illustrating a typical process for PV system sizing, emphasizing data input, simulation, optimization, and performance evaluation.

One of the primary challenges in system design lies in integrating multiple energy sources, maintaining a balance between cost and reliability, and minimizing environmental impact [15]. In Finland, for example, the optimal array-to-inverter size ratios for PV systems were found to be 1.6, 1.8, and 2.08 for 10-, 6-, and 3-kW inverters, respectively. These findings demonstrate the potential to reduce fixed electricity costs by adjusting system configurations to local climatic conditions. Southeast–southwest panel orientation was shown to improve performance, especially in low-radiation environments where higher inverter loading ratios could be applied without major energy losses [16].

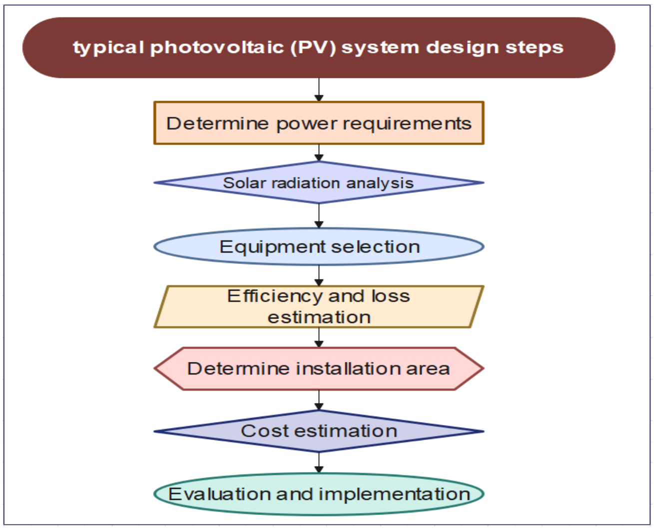

Figure 5. Flowchart of a typical PV system sizing process.

A complementary study in Afghanistan employed PVsyst software to design a 700-kW solar system, providing detailed insights into resource assessment, optimization, system loss estimation, and economic feasibility [17]. Another study using MATLAB-based simulation demonstrated improved efficiency, voltage stability, and compatibility with grid conditions under varying temperatures and irradiance, highlighting its effectiveness for practical system design.

Beyond physical configuration, recent research has also focused on data-driven techniques for load forecasting in integrated energy systems. Emphasis has been placed on data processing, feature extraction, and amplification strategies to improve model accuracy. Advanced machine learning models—such as neural networks, support vector machines, and random forests—have proven highly effective in this domain [18]. Despite challenges related to data quality and computational demands, AI frameworks show promise in improving prediction accuracy and operational control [19].

At the residential scale, system design in hot climates was optimized by analyzing daily and seasonal consumption patterns. The results showed improved efficiency and cost reduction by aligning system capacity with load variability, though challenges remain in achieving a balance between reliability and affordability [20].

In Morocco, a 1 MW grid-connected PV system was analyzed using actual load data, assessing energy production, system efficiency, and the influence of environmental factors [21]. Similarly, advanced experimental methods, including P–V and I–V curve analyses, were used to extract key electrical parameters using explicit, regression-based, and iterative techniques. The slope method yielded high accuracy in estimating peak power, with average errors of just 0.5% for monocrystalline modules and 3% for CIGS modules under uniform irradiation, confirming the technique's reliability for diverse PV technologies [22,23].

In Iraq, two notable case studies further validated real-world design and performance. A 10 MW grid-connected PV plant in Dohuk Governorate was designed using temperature and radiation data to determine optimal tilt angle, system efficiency, and performance ratio [24].

Additionally, a 1 MW distributed PV plant in Baghdad was modeled using real load data, with a comprehensive evaluation of energy output, economic feasibility, and system reliability, reaffirming the viability of such systems in the Iraqi context [25].

3.5. On-Grid vs. Off-Grid PV System

This section evaluates two main types of photovoltaic (PV) systems: conventional photovoltaic systems and photovoltaic/thermal (PV/T) systems, as illustrated in **Figures 6** and **7** [26]. Each component was analyzed individually to assess its potential for development and contribution to overall system performance. Results showed that PV/T systems significantly improve energy efficiency by converting thermal waste into usable heat, thereby enhancing total energy output. These systems also contribute to greater grid stability through the integration of both electrical and thermal renewable energy sources.

Despite these benefits, conventional PV systems still face limitations, particularly in energy loss, with more than half of incoming solar radiation typically unconverted. Furthermore, advanced control strategies are necessary to ensure optimal energy capture, conversion, and distribution. To address these issues, the literature proposes mitigation strategies such as real-time smart control, advanced measurement systems, and the adoption of next-generation PV technologies. These innovations are essential for maximizing the performance of both conventional and PV/T systems, especially in urban environments striving for sustainability goals [27].

A techno-economic feasibility study in Iraq, conducted using the HOMER PRO software, compared two operating scenarios: grid-connected and off-grid. The results revealed that the grid-connected system offered a lower energy cost of approximately \$0.21/kWh, while the off-grid system resulted in a higher cost of \$0.28/kWh. Nonetheless, the off-grid system offered increased energy independence, particularly in areas with unreliable or non-existent grid access. The most effective design combined a 100-kW PV system with battery storage and a diesel generator as a backup. The findings also highlighted the importance of government support to overcome the high capital costs associated with such hybrid systems. These results underscore the viability and sustainability of hybrid PV networks in regions with limited infrastructure and unstable climates.

In remote and economically challenged areas, hybrid PV systems have been proposed as a reliable energy solution. These systems often integrate multiple renewable sources (such as solar and wind power) with storage technologies [28]. Although highly promising, hybrid systems face challenges including high initial investment, frequent maintenance needs, and resource variability. Consequently, policy recommendations have focused on addressing storage limitations and system integration issues in off-grid contexts.

Figure 6 presents schematic diagrams of grid-tied and off-grid PV configurations, highlighting differences in structure and energy flow. **Figure 7** compares the performance of various systems in practical applications.

A study conducted in Brazil's Amazon region demonstrated that small-scale hybrid grids can effectively balance supply and demand, reducing dependence on fossil fuels, lowering emissions, and improving economic outcomes [29]. This setup enhanced the flexibility of both grid-connected and off-grid systems, proving beneficial in low-access regions. Nonetheless, technical integration with storage and load management remains complex and costly, requiring skilled operation and continuous investment. The study contributed practical insights to support utilities, consumers, and policymakers in advancing hybrid PV adoption (particularly for small- and medium-scale users) and expanding market options for clean energy.

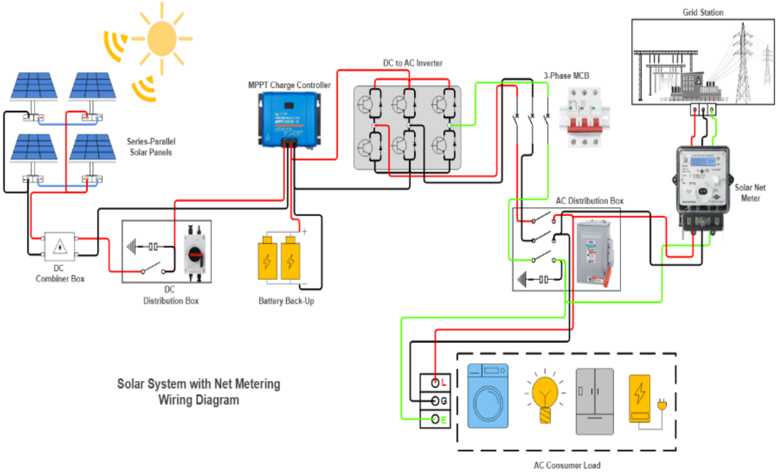

Figure 6. Schematic diagram of grid-tied and off-grid PV system configurations.

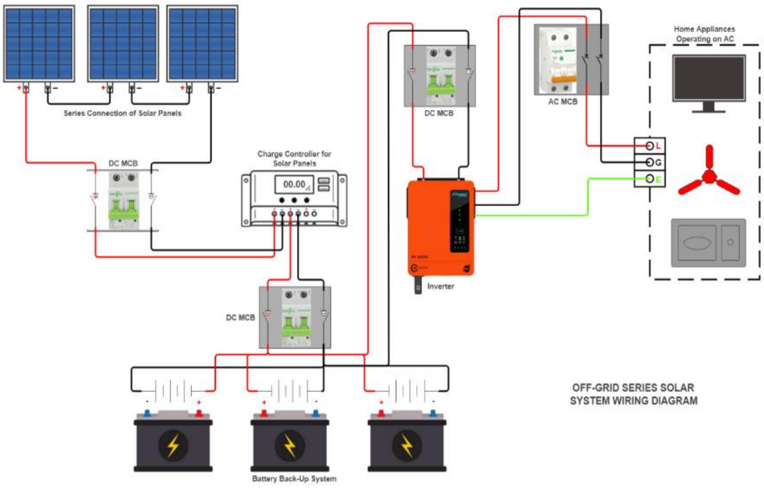

Figure 7. Case studies showing performance comparisons between grid-tied and off-grid systems.

3.6. Energy Storage Solutions in PV Systems

3.6.1. Role of Battery Storage in PV Systems

The historical development, classification, and operational principles of energy storage systems from 1850 to 2022 were comprehensively reviewed [30]. These systems have evolved into five primary categories: mechanical (e.g., pumped hydro and compressed air), thermal (e.g., phase change materials and molten salt), chemical (e.g., hydrogen storage), electrochemical (e.g., lithium-ion and lead-acid batteries), and electrical (e.g., supercapacitors). Among these, lithium-ion batteries have become the most widely adopted in commercial PV applications due to their high energy density and efficiency. However, challenges remain regarding cost, safety, and battery lifespan.

A comparative study across Europe, Africa, and the Middle East emphasized the importance of energy storage in enabling integration of intermittent solar and wind sources. It highlighted the growing role of lithium-ion batteries, which demonstrated round-trip efficiencies between 85% and 90%, and an approximate cost reduction of 80%, making them well-suited for short- to medium-term applications [31]. Nevertheless, safety concerns and limited cycle life continue to pose barriers to large-scale deployment. Coordinated efforts between the public and private sectors are therefore essential to support broader adoption and address these challenges.

3.6.2. Battery Sizing and Integration Accompanying PV Systems

Optimization studies have been conducted on hybrid systems combining solar PV, wind turbines, and battery storage, connected to the grid. As illustrated in **Figure 8**, such systems were capable of meeting up to 80% of energy demand through renewable sources, thereby enhancing overall efficiency and reliability [32]. This configuration also resulted in a reduced annual energy cost of approximately $0.238/kWh.

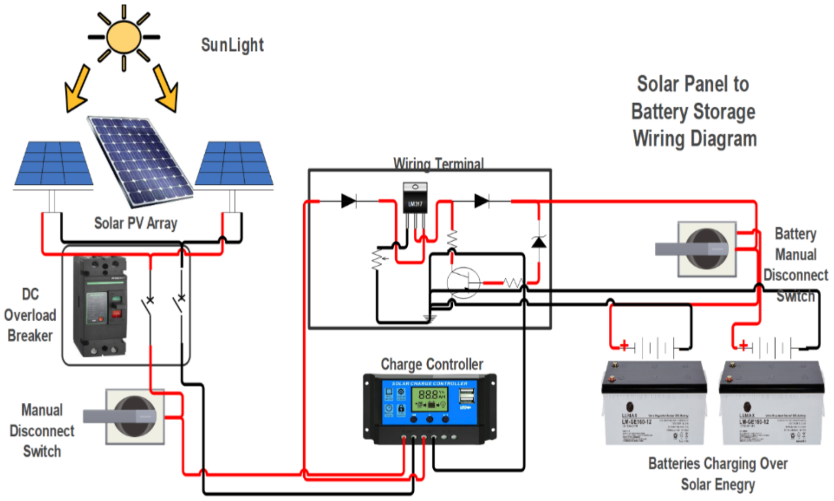

Figure 8. PV system with integrated battery storage.

Advanced sizing methodologies have further refined the determination of battery capacity in PV systems. These approaches account for battery degradation, integrate the use of supercapacitors to prolong battery life, and prioritize cost-effective long-term operation [33,34]. The inclusion of storage is vital for ensuring PV system stability, energy quality, and demand-side management, particularly when integrated with smart control strategies [35].

Despite these benefits, technical and operational challenges remain. These include control and protection issues, accurate monitoring of charge/discharge cycles, safety protocols, system reliability, and high capital costs [36]. Such costs are particularly prohibitive for small and medium-sized enterprises (SMEs), limiting widespread adoption.

Furthermore, integrating batteries into PV systems increases system complexity, requiring advanced energy management solutions. These include accurate load forecasting, real-time scheduling of charging and discharging, and control mechanisms to handle fluctuating demand [37]. Research has contributed to several innovative strategies, such as the use of fuzzy logic controllers to improve power quality [35], machine learning models for more accurate demand prediction under variable load conditions [37], and optimization frameworks that leverage time-of-use pricing and frequency regulation services to improve economic viability [38].

Figure 9 illustrates typical battery charge and discharge cycles within a solar PV system, demonstrating how energy is stored during peak production and released during demand periods, contributing to system reliability and cost efficiency.

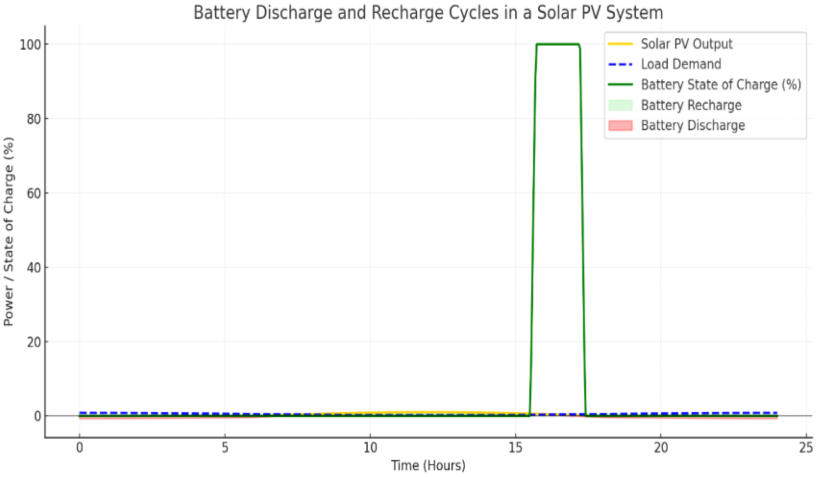

Figure 9. Battery discharge and recharge cycles in a solar PV system.

3.7. Integration of PV System with Building Energy Management Systems (BEMS)

Building Energy Management Systems (BEMS) have emerged as essential tools for optimizing the integration of photovoltaic (PV) systems with building energy consumption. As illustrated in **Figure 10**, BEMS coordinate various components (such as thermal storage, batteries, and predictive control mechanisms) to reduce costs, improve self-consumption of renewable energy, and maintain thermal comfort.

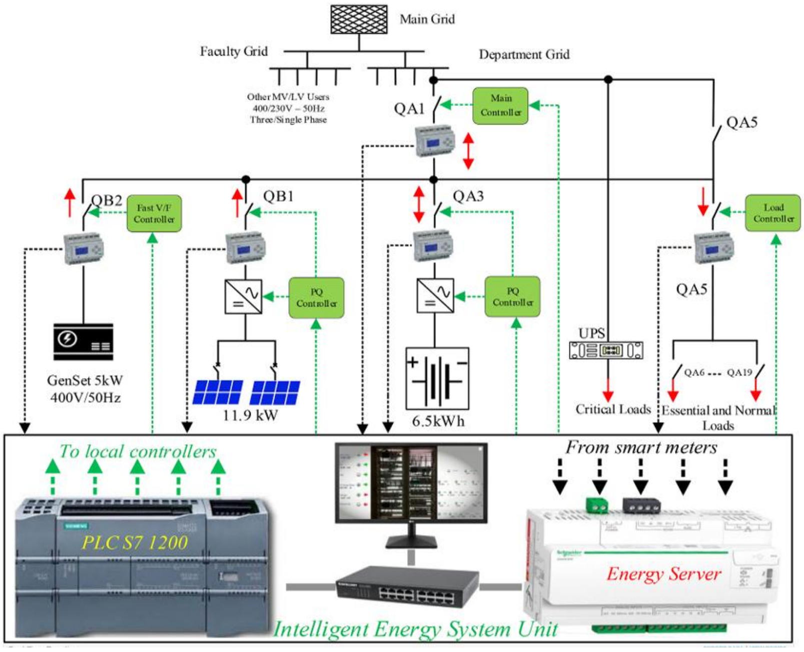

Figure 10. Schematic of a PV system integrated with a building energy management system.

This integration has been examined from multiple dimensions. Educationally, the inclusion of renewable energy topics within science, technology, engineering, and mathematics (STEM) disciplines has been shown to enhance public awareness and support the transition toward clean energy [39]. On a practical level, home energy management models incorporating PV systems, batteries, heat pumps, and thermal storage have been developed. While batteries play a central role in enhancing self-consumption, surplus electricity often still needs to be exported to the grid. Under existing tariff structures, maximizing self-consumption may not always be economically optimal [40].

At the community level, operational models for distributed energy systems have been proposed. These allow for cost savings and revenue generation by responding to grid frequency fluctuations, despite the inherent uncertainty in PV generation. Virtual energy storage models (which consider fluctuations in indoor and outdoor temperatures) have also been introduced to enable more efficient load scheduling while maintaining occupant comfort [41,42].

Advanced BEMS models now combine cogeneration, electrical and thermal storage, and demand forecasting to simultaneously lower carbon emissions and energy expenses [43]. Predictive centralized control strategies have demonstrated a 13.5% reduction in energy costs compared to traditional rule-based systems [44]. For off-grid settings, integrated energy management systems incorporating PV forecasting, time-of-use tariffs, and direct load control achieved a 44% cost reduction, a 46% drop in emissions, and a 113% increase in solar energy utilization relative to diesel generators [45].

Modern smart technologies have played a transformative role. Adaptive neuro-fuzzy inference systems (ANFIS) improved power quality and system stability [46], while LSTM-based machine learning models achieved 97% forecasting accuracy for PV production, reducing grid losses [47]. Optimization-based scheduling methods (incorporating PV and battery systems) have delivered up to 59.06% reductions in electricity costs, 57.42% lower emissions, and a 17.40% decrease in the peak-to-average ratio [48].

These capabilities have been further enhanced through Internet of Things (IoT) and cloud computing technologies, which enable real-time energy monitoring and control. In one study, IoT-based energy management across four buildings resulted in energy savings ranging from 15 to 49% [49]. On a smaller scale, such systems also improved grid stability and solar utilization, with energy loss reduction of up to 100% during sunny conditions and 42.6% under cloudy skies [50]. IoT-based load management has also been proposed for electric vehicle charging stations to alleviate grid stress during peak hours [51].

Literature reviews have confirmed that IoT integration within smart energy management systems is essential for improving energy monitoring, enhancing efficiency, and ensuring photovoltaic system reliability [52]. Broader studies have also addressed the limitations of conventional grid integration and proposed new market mechanisms to increase consumer flexibility. These were complemented by comprehensive analyses of demand-side management (DSM) strategies and their role in improving renewable energy integration [53].

DSM techniques have included smart scheduling of home appliances to boost on-site solar energy use and reduce reliance on the grid [54]. Battery-integrated solar systems using DSM strategies have proven effective in lowering operational costs and enhancing management efficiency. Comparative evaluations of four DSM approaches integrating PV panels, batteries, and electric vehicles have highlighted the strengths and limitations of each method [55]. Additionally, IoT-based DSM systems for residential buildings have shown promise in lowering costs and maximizing solar energy utilization [56].

Advanced optimization algorithms, such as Grey Wolf Optimization, have also been employed to improve smart microgrid performance by enhancing demand-side flexibility and solar energy efficiency. Case studies in smart buildings have demonstrated the effectiveness of intelligent control strategies and solar-PV integration in boosting energy performance [57]. More broadly, recent reviews on DSM in smart distribution networks have emphasized the critical role of renewable integration, especially solar, in improving system efficiency and reducing costs [58].

Together, these efforts reflect the diverse range of strategies being developed to align solar energy generation with consumption patterns in buildings. They highlight the importance of integrating storage systems, applying IoT technologies, and leveraging advanced optimization techniques to achieve optimal performance, cost-effectiveness, and sustainability.

3.8. Impact of PV System on Governmental Buildings

Numerous studies have demonstrated the substantial environmental and economic benefits of integrating photovoltaic (PV) systems into governmental and institutional buildings. In Riyadh, Saudi Arabia, a feasibility study showed that incorporating PV systems into government facilities led to an annual carbon emission reduction of 1.2 tons and a 48% decrease in net current costs [59]. Similarly, research conducted in Dubai confirmed that PV integration significantly lowered energy consumption, thereby reducing operational expenses and enhancing building energy efficiency [60].

In Algeria, a building-integrated photovoltaic (BIPV) case study demonstrated the potential to save 9.45 megawatt-hours annually, with a payback period of 4.95 years and yearly cost savings of approximately $370.48. This translated into a reduction of 5.37 tons of CO_2 emissions per year [61]. In Bangladesh, hybrid systems combining solar PV and biomass reduced carbon emissions from 1,920,065 kg/year to 839,600 kg/year, with a projected payback period of 6.52 years [62].

At Universiti Tun Hussein Onn Malaysia (UTHM), a 6.9 MW solar PV system was capable of generating approximately 8,529 MWh annually, achieving an efficiency of 11.86% and a performance ratio of 0.78 [63]. A separate 19 MW rooftop solar installation highlighted the importance of utilizing building rooftops to reduce fossil fuel dependence and energy costs. In regions with harsh or unstable climates, performance can be improved by adjusting the panel tilt angle, and implementing design models that consider both environmental and economic factors has been strongly recommended [6].

Further evidence from Iraq suggests that converting 546 government buildings to solar-integrated systems could produce around 62,353 kWh annually, resulting in a reduction of approximately 167,662 tons of carbon dioxide emissions per year [64]. The design of a 1 MW grid-connected PV system in Iraq demonstrated an energy production cost of $0.22/kWh and a payback period of nine years [65].

Optimization studies revealed that a modified distribution strategy achieved the lowest net present cost ($33,747), outperforming other configurations such as solar tracking ($40,336) and periodic charging ($34,826). It also registered the lowest unmet energy load at 87 kWh/year, compared to 143 and 118 kWh/year, respectively, thereby improving system reliability. Furthermore, this strategy reduced carbon emissions to 3,913 kg/year, significantly lower than emissions under other strategies (4,550 and 7,845 kg/year), showcasing its environmental superiority.

In Iraq's oil sector, the cost-effectiveness of solar systems was compared to traditional diesel generators used in oil field operations [66]. Although the initial investment for a 1 MW solar plant was found to be 37–40% higher than that of conventional generators, the operational cost was substantially lower (approximately $0.0183/kWh compared to $0.10/kWh for generators). The solar plant had a payback period of around nine years and a lifespan of up to 25 years, whereas diesel generators typically last no more than ten years. In addition to long-term economic benefits, the PV system also offered significant environmental advantages, emitting no direct carbon emissions, in contrast to conventional sources that emit between 185 and 265 grams of CO_2 per kWh.

3.9. Challenges and Solutions for PV System Implementation in Iraq

The implementation of photovoltaic (PV) systems in Iraq faces a wide range of technical, environmental, institutional, and economic challenges, many of which are unique to the country's harsh climatic conditions and unstable infrastructure. A significant issue affecting PV performance is dust accumulation, as demonstrated in a multi-region study covering Baghdad, Basra, Mosul, and Najaf [3]. Dust composition was found to vary significantly across locations, directly influencing energy conversion efficiency. For instance, high concentrations of silica, clay, and silt were found in the deserts surrounding Karbala and Najaf, while Baghdad and Al-Faw exhibited elevated levels of fine particles, lead, and sulfur, attributed to fossil fuel combustion.

Empirical data showed that dust accumulation of 100 g/m² caused reductions in output current by 15.2 to 25.66% and output voltage by 10.85 to 26.1%, resulting in overall power losses ranging from 31.12 to 45.06%. These findings support the implementation of region-specific cleaning strategies, such as daily dry cleaning in Al-Faw and bi-monthly washing in other cities. Interestingly, another study reported that under certain conditions, dust may have a paradoxically beneficial effect [67]. During dust storms, the decrease in ambient temperature can reduce thermal losses in PV modules, slightly mitigating performance degradation. For example, while clean panels experienced energy losses of up to 24%, dust-covered panels under dust storm conditions lost only 6%, suggesting that aggressive cleaning during such events may not always be necessary.

Mathematical models were developed to assess the combined effects of dust and wind speed on PV output in Najaf, revealing that power output may decline by 20-40% in highly polluted environments [68]. Wind played a dual role: while moderate speeds (2-5 m/s) helped cool panels and improve performance, wind carrying fine particles increased surface contamination. Additional analysis in Nasiriyah confirmed that wind alone is insufficient for effective panel cleaning, and that temperature increases above nominal values reduced efficiency by 0.4-0.5%/ per °C. Moreover, high solar irradiance levels, while increasing energy production, also elevate module temperature, leading to efficiency losses. Humidity was also found to cause material degradation and reduced electrical conductivity. Experimental results showed that combining air and water cooling enhanced panel efficiency by up to 18% in hot regions.

Long-term assessments have shown that the performance and reliability of PV systems in Iraq can be significantly improved through design adaptations based on local conditions [68]. A review of three decades of renewable energy trends identified economic constraints, policy gaps, and low public awareness as major barriers to adoption. Iraq’s potential to reduce fossil fuel dependency by 30% by 2030 through green hydrogen projects and international collaboration has been acknowledged [69]. However, successful implementation requires strategic policy planning, institutional reforms, and funding mechanisms [70].

Comparative insights from Spain’s renewable energy transition show that regulatory frameworks and financial incentives were key to their progress in solar and wind energy deployment, despite facing their own integration and cost-related challenges [71]. In contrast, Iraq continues to struggle with weak infrastructure, political instability, and a lack of incentives and expertise [72]. Nonetheless, the country possesses vast undeveloped land and some of the world’s highest solar radiation levels, offering significant potential for solar PV and wind energy expansion.

Efforts to address these challenges include proposals to optimize panel installation for desert environments, such as adjusting panel elevation and tilt angles. Studies suggest that a reflectivity index of 0.5, typical of desert sand, may reduce the need for reflective enhancements, particularly for bifacial modules [68]. However, systemic issues persist in Iraq’s electricity sector. Sandstorms alone can reduce energy generation by up to 62% in some regions. Despite plans to expand generation capacity by 12 GW by 2030 (approximately 23% of projected capacity), Iraq lags behind neighboring countries in implementing effective renewable energy policies [73].

Other technical reviews emphasize the detrimental effects of extreme temperatures, with some areas reaching up to 70°C, which can significantly reduce PV efficiency despite an average daily solar radiation of 5.00-5.50 kWh/m²/day. Lastly, the importance of community engagement and private sector participation was emphasized. Supportive mechanisms such as feed-in tariffs, net metering, and investor incentives are crucial to scaling up PV adoption in Iraq’s residential and public sectors [74].

3.10. The Proposed Methodology

This study proposes an integrated methodology for designing and analyzing photovoltaic (PV) systems (both on-grid and off-grid) by utilizing real load data and advanced simulation tools, including PVsyst and MATLAB. The objective is to achieve a technically sound, economically viable, and environmentally sustainable PV system that supports net-zero energy goals through the integration of energy storage and building energy management systems (BEMS) [10]. The approach is grounded in Iraq's favorable solar potential, with irradiance levels ranging from 2,000 to 2,500 kWh/m²·yr, and supported by an 82% decline in global PV technology costs since 2010 [10].

The methodology begins with a comprehensive evaluation of the target site, taking into account temperature, solar radiation, wind patterns, humidity, and electrical infrastructure. Iraq's climatic conditions (particularly high ambient temperatures and frequent dust storms) pose significant challenges to PV performance [8,10]. Empirical findings show that dust accumulation of 100 g/m² can reduce current, voltage, and output power by up to 45%, varying by region (e.g., daily cleaning in Al-Faw vs. biweekly cleaning in Baghdad) [15].

Temperature increases beyond nominal values decrease PV efficiency by 0.4-0.5% per °C, while moderate wind speeds enhance panel cooling and performance. High humidity contributes to material degradation and insulation loss [24,25]. In bifacial systems, panel height and surface albedo significantly influence efficiency; a reflectivity value of 0.5, similar to desert sand, has been identified as optimal [19].

Due to Iraq’s weak grid stability, the integration of large PV systems requires careful design and modeling [10]. The process involves the collection of site-specific meteorological data, selection of system components (panels, inverters, storage), and calculation of optimal tilt angle and azimuth orientation [18]. PVsyst is employed to simulate annual energy production, analyze losses due to shading, wiring, and thermal effects, and compute economic metrics such as the levelized cost of energy (LCOE) and payback period [2,9]. MATLAB is used to simulate dynamic system responses under different grid scenarios [2,7].

Several case studies support this methodology. For example, a 10 MW PV plant in Dohuk and a 1 MW grid-connected system in Baghdad have been modeled using real load data to assess performance and cost-efficiency [13,18]. Similarly, a 1 MW system in Morocco evaluated physical and environmental variables impacting output, while other studies in low-irradiance zones optimized the reflector-array ratio using time-calibrated data [9,16].

Battery integration (especially using lithium-ion technology) has been emphasized due to its 85–95% efficiency and an 80% price reduction since 2010 [1,12]. When paired with smart control systems, energy stability improves by up to 50%, along with enhancements in power quality [13][16]. However, challenges remain, including state-of-charge (SOC) management, protection protocols, system reliability, and safety [17,20]. Studies on BEMS integration show that exporting excess energy to the grid improves economic returns [21], while Integrated Energy Management Systems (IEMS) have demonstrated 44% cost reduction, 46% lower CO_2 emissions, and 113% higher solar energy utilization compared to diesel-only systems [21].

Cost evaluations in Iraq show that solar-generated energy is economically viable, with the LCOE for a 1 MW system estimated at $0.22/kWh and a payback period of nine years [11]. In the oil sector, although upfront costs for solar plants are 37-40% higher than conventional generators, the operational cost is only $0.0183/kWh, compared to $0.10/kWh for diesel [11], with lifespans extending to 25 years for solar systems.

Simulations using HOMER Pro affirm that grid-connected microgrids yield lower LCOE than isolated systems [13]. Hybrid configurations in other regions show success in balancing demand, reducing fossil fuel use, and enhancing resilience [8]. Yet, Iraq continues to face regulatory and infrastructural constraints, including a lack of legal frameworks and limited financial incentives [8,19].

Site-specific factors, such as cleaning frequency, panel slope, and elevation, play a crucial role in desert environments. Field studies have demonstrated the effectiveness of raising panel height and adjusting reflectivity to maximize performance in harsh conditions [15,19].

Analytical Tools Employed are as follows:

(i) PVsyst: for energy yield simulation, system loss analysis, and financial modeling [2,9].
(ii) MATLAB: for dynamic simulation and system behavior analysis under varying operating scenarios [2,16].
(iii) Time-based load forecasting tools: to improve system planning and operational efficiency [7,16].

Expected outcomes of the methodology are in as follows:

(i) Optimized PV system design that incorporates storage and intelligent control mechanisms [2].
(ii) Economic feasibility indicators, including LCOE, annual energy yield, and performance ratios.
(iii) Environmental impact assessment, demonstrating emissions reduction and sustainability contribution [14,21].
(iv) Replicable implementation guidelines for similar climatic and infrastructural contexts [13,19].

3.11. Discussions on Recent Research Findings

In environments such as Iraq, recent research illustrates how integrating photovoltaic (PV) systems with intelligent storage and control technologies can significantly enhance the efficiency and stability of energy infrastructures. Strategic project site selection—based on environmental factors such as solar radiation, climate conditions, and existing infrastructure—has proven essential in ensuring long-term productivity and cost-effectiveness. Given Iraq's high solar irradiance and the substantial decline (over 80%) in PV technology costs over the past decade, investing in solar energy represents a strategic opportunity.

However, operational challenges remain, particularly related to dust accumulation and elevated temperatures. Field studies have confirmed that these factors can severely impact panel efficiency if not addressed through proactive maintenance and cleaning protocols. Design considerations such as optimal tilt angle, panel elevation, and the use of dust-resistant materials and coatings are critical for mitigating these environmental impacts and maintaining stable performance.

Simulation-based economic models demonstrate that integrating lithium-ion batteries into PV systems improves energy self-sufficiency, stabilizes grid performance, and reduces reliance on diesel generators. Although such systems improve long-term financial viability by reducing operating costs, their high initial capital costs remain a barrier, highlighting the need for government subsidies and favorable regulatory frameworks.

From an environmental standpoint, widespread deployment of PV systems results in substantial reductions in carbon dioxide emissions, aligning with both national sustainability goals and international carbon neutrality commitments. Comparative studies of grid-connected, off-grid, and hybrid configurations suggest that hybrid or grid-connected systems with storage offer the most efficient and cost-effective solutions where infrastructure allows.

Ultimately, these findings underscore that the success of PV implementation in Iraq is not solely dependent on technical design but also on the institutional and regulatory environment. Strong collaboration between research institutions, government agencies, and the private sector is essential for establishing clear legal frameworks, financial incentives, and streamlined grid-connection procedures to ensure long-term sustainability and national-scale deployment.

Finally, this study adds new information regarding solar energy, as reported elsewhere [75-79].

4. CONCLUSIONS

Based on literature reviews and simulation results, the proposed PV system design has proven to be both effective and economically viable for the Iraqi context, particularly in government buildings. Regional studies consistently demonstrate that solar energy systems can function optimally when environmental factors such as dust and high temperatures are addressed through appropriate design (especially panel tilt, elevation, and orientation). Accurate climatic and load data are essential in system modeling, as shown by models such as Väisänen's, which confirm that real-time data improves design accuracy, minimizes energy losses, and enhances system stability.

The implementation of such systems in urban centers and public institutions would significantly reduce the load on Iraq's national grid. From environmental, economic, and strategic perspectives, investment in solar infrastructure is well justified, provided it is supported by regulatory and legislative frameworks. Although initial construction costs are high, the system's low operating expenses and absence of fuel costs result in substantial long-term savings. In Iraq, where power outages are frequent, integrating storage systems (such as batteries and capacitors) offers critical flexibility and resilience, reducing dependence on conventional power sources.

Simulation outcomes further suggest that deploying PV systems in government institutions such as schools, ministries, and universities would lower grid dependency and emissions, making them ideal candidates for renewable energy transitions. Nevertheless, the absence of supportive legislation (such as feed-in tariffs, net metering, and simplified licensing procedures) remains a major obstacle. This affirms that institutional reform is as crucial as technical innovation. Moreover, these initiatives can serve as pedagogical models within universities and technical colleges, supporting the development of a skilled national workforce in the renewable energy sector.

This study proposes the expansion of PV system applications in Iraq to encompass a broader range of educational and healthcare institutions, transforming them into decentralized hubs for energy generation. Such an approach would alleviate pressure on the national grid while promoting sustainability. Future efforts should also focus on incorporating artificial intelligence (AI) in areas such as load forecasting, energy demand management, and real-time data analysis. Additionally, aligning international best practices with local realities is essential to enhance implementation effectiveness.

Lastly, achieving the full potential of PV systems in Iraq requires coordinated action across the public and private sectors. This includes establishing robust policies, offering financial incentives, and fostering an investment-friendly environment to scale up solar capacity and contribute meaningfully to carbon emissions reduction.

5. AUTHORS' NOTE

The authors declare that there is no conflict of interest regarding the publication of this article. The authors confirmed that the paper was free of plagiarism.

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