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Recent Advances in Photovoltaic Energy Harvesting, Power Optimization, and IoT Technologies for Photovoltaic Systems: A Review

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ABSTRACT: Photovoltaic (PV) systems have emerged as a key renewable energy technology due to their sustainability, scalability, and environmental benefits. Recent advances in PV energy harvesting, power electronic control, and Internet of Things (IoT) technologies have significantly enhanced system efficiency, reliability, and operational performance. However, the rapid expansion of research in these areas has created a need for a comprehensive and up-to-date review. This paper presents a systematic review of recent developments in PV energy harvesting, power optimization, and IoT technologies for PV systems based on studies published between 2023 and 2026. The literature reviewed is divided into three sections, namely: PV energy harvesting technologies, power electronic control and maximum power point tracking (MPPT) techniques, and IoT based PV monitoring and management system. The review presents a major development regarding the ability of thermal management, hybrid PV/thermal systems, nano-coating technologies, indoor PV systems and integration with energy storage solutions. MPPT techniques have progressed from traditional to adaptive, predictive, optimization and hybrid techniques in power optimization with several studies showing efficiencies of more than 99% in tracking. In addition, the Internet of Things technologies have provided real-time monitoring, fault diagnosis, predictive maintenance and remote management with cloud connected and edge enabled platforms. While these developments have taken place, issues concerning scalability, interoperability, cyber security, standardization, and validation in field remain. Further investigations are desired to combine energy harvesting, advanced MPPT control, energy storage management and IoT enabled monitoring in a combined PV system. This review provides a structured overview of current developments, challenges, and future opportunities for next-generation photovoltaic systems.

KEYWORDS: Photovoltaic Systems, Energy Harvesting, Power Optimization, Maximum Power Point Tracking (MPPT), Power Electronic Control, Internet of Things (IoT), Photovoltaic Monitoring, Photovoltaic Management.

1. INTRODUCTION

Recently, the global demand for energy has been growing and there are growing concerns about climate change, environmental degradation and the exhaustion of fossil fuel resources, which has forced the shift to renewable energy technologies [1]. Solar energy stands out as one of the most promising and adopted renewables, which has, as an advantage, the abundance, sustainability and environmental friendliness [2]. The PV (Photovoltaic) systems are a direct conversion of solar radiation into electric energy and, in the last decade, have grown in a remarkable way, due to the constant technological improvement, the reduction of installation costs and the favourable governmental policies [3, 4]. The PV installed capacity is rising sharply in recent years, indicating the important role that PV plays in sustainable electric power generation and energy security for the world [5, 6]. Thus, PV technology is widely included in contemporary energy infrastructures, such as large-scale grid connected PV power plants to residential PV systems, remote monitoring stations, wireless sensor networks, smart buildings, and portable electronics [7, 8].

The last few years have seen the evolution of PV systems not only from traditional electricity generation to more efficient, adaptive and application oriented energy solutions [9, 10]. Advanced materials and combination PV/thermal systems, cooling methods, nano-coatings and integration with energy storage have been the subjects of significant research efforts to improve PV energy harvesting [11]. Meanwhile, power electronic converters and maximum power point tracking (MPPT) techniques have been introduced to optimise maximum energy extraction with different irradiance, temperature and shading conditions [12]. Additionally, with the fast expanding Internet of Things (IoT), PV systems monitoring, fault diagnosis, predictive maintenance, remote supervision, and performance optimization have also been introduced as new opportunities [13, 14]. Modern PV systems are increasingly becoming interconnected and data-driven energy platforms with unprecedented levels of efficiency, reliability, and operational flexibility, through the integration of sensing devices, communication networks, cloud computing platforms and edge processing technologies [15, 16].

A number of review studies have recently been conducted on various aspects of PV technologies. Khernane et al. [17] summarized the renewable energy harvesting methods for WSN and presented the significance of PV harvesting in smart agriculture and remote sensing applications. Kumar et al. [18] have classified the MPPT techniques extensively, differentiated the existing techniques based on classical, optimization based and hybrid and discussed their pros and cons in various operating conditions. In the same way Mazumdar et al. [19] presented a review on evolution of conventional and advance MPPT in which they discussed about the suitability of them for maximum extraction of PV power in uniform and partial shading conditions. Wang et al. [20] discussed PV monitoring technologies in the context of IoT PV systems subjected to extreme environments, including sensing technologies, condition monitoring, fault diagnosis, and reliability enhancement. Shukla et al. [21] recently explored the uses of IoT technologies in PV systems, including cloud, edge, and fog computing architectures, as well as a predictive maintenance framework and advanced monitoring. The studies presented above in totality offer important insights into particular research directions and the increasing relevance of PV harvesting, PV power optimization and IoT technologies in modern energy systems.

However, with these contributions, existing review papers focus on PV energy harvesting, MPPT control strategies or IoT enabled monitoring systems as independent research fields [22]. In fact, the success of modern PV installations is now more and more reliant on the synergy between efficient energy harvesting technologies, advanced power optimization solutions and a monitoring infrastructure based on IoT. While many studies have been conducted on PV energy harvesting, MPPT techniques, and IoT-based monitoring techniques, very few studies have focused on combined PV, MPPT, and IoT-based monitoring techniques. While modern PV systems are more dependent on the interaction between these technologies, a comprehensive review that simultaneously covers energy harvesting, energy power optimization, and PV management using IoT has not yet been conducted [23]. In addition, the fast development of new harvesting techniques, powerful MPPT algorithms, monitoring platforms in the edge and cloud, and integrated PV management systems require a new evaluation of recent advances, challenges, and lines of future research. The above considerations lead to the necessity of the present review.

The aim of this review is to analyse in details the recent advancements in PV energy harvesting, power optimization, and IoT technologies pertaining to PV systems. In particular, in this review, the innovative PV energy harvesting methods from recent years such as thermal management methods, indoor PV technologies, hybrid PV systems, and integrated energy storage methods are discussed. Furthermore, the review discusses the development of power electronic control and MPPT techniques for energy extraction maximisation for different environmental conditions. Besides, the recent developments of IoT PV monitoring and management technologies are explored, including real-time PV monitoring, fault diagnosis, predictive maintenance, remote PV supervision, and smart PV system operation.

However, to accomplish these goals, relevant studies in the period 2023–2026 were selected and categorized based on the following three major research themes: PV energy harvesting, power electronic control and MPPT techniques, and IoT-based PV monitoring and management. The system architecture, operating principles, implementation platforms, performance indicators, and advantages, limitations, and practical applications of the selected literature were analyzed. The main contributions of this review can be summarized as follows:

- Providing a comprehensive review of recent advances in PV energy harvesting technologies, including thermal management, indoor PVs, hybrid systems, and energy storage integration.
- Presenting a comparative analysis of modern power electronic control and MPPT techniques used to maximize PV energy extraction.
- Examining recent IoT technologies for PV monitoring, fault diagnosis, predictive maintenance, and system management.
- Identifying current challenges, research gaps, and future research opportunities for next-generation PV systems.

The rest of this paper is structured as follows. The development of PV systems and energy harvesting techniques in recent years is discussed in section 2. Power electronic control and MPPT techniques for PV energy extraction and system efficiency improvements are discussed in section 3. In Section 4, a brief overview of the recent advancements in PV monitoring and management systems using the IoT is provided. The reviewed literature is discussed in detail in Section 5, with the main trends, challenges and future research opportunities presented. Last, Section 6 provides a summary and conclusion to the paper.

2. PHOTOVOLTAIC SYSTEMS AND ENERGY HARVESTING

PV energy harvesting is the process of converting light energy into electrical energy by use of a semiconductor-based solar cell [24]. It is one of the most significant renewable energy technologies due to its potential for small, self powered electronic systems as well as large scale power generation, its environmental friendliness and its potential for scaling up. The parameters influencing the energy harvested from PV systems are primarily solar irradiance, temperature, shading, dust accumulation, cell material, converter efficiency and effectiveness of MPPT. Hence, in addition to efficient solar cells, the design of PV energy harvesting systems along with power conditioning, energy storage, and control strategies play a crucial role in enhancing the efficiency of PV energy harvesting.

Nowadays, new research indicates that PV energy harvesting can be performed on much more than traditional solar panels outdoors. It has come to indoor PVs for low-power IoT devices and PV/thermal collectors for simultaneous electrical and thermal energy generation, building-integrated PV systems, wireless sensor networks, portable energy storage systems, and self-powered electronic devices. Indoor PV is, for instance, proposed for IoT sensor and low power electronics under artificial light sources, and PV/T systems for energy harvesting are proposed to lower the PV temperature and to harness useful thermal energy. Other works are dedicated to dust reduction, nano-coatings, MPPT algorithms as well as integration of energy storage to enhance the PV system's practical efficiency in real environmental conditions.

Therefore, this section discusses some of the recent literature on PV energy harvesting in terms of PV system architectures, methods to improve PV energy harvesting efficiency, indoor and outdoor PV applications, PV/T, environmental effects, MPPT-based PV energy harvesting, and integration of PV energy harvesting with energy storage. This gives the background to understand how with the support of IoT-based monitoring and power electronic control the performances of energy harvesting in modern PV systems can be further enhanced. Figure 1 shows the different types of PV energy harvesting technologies, their applications, and important ways to improve their performance.

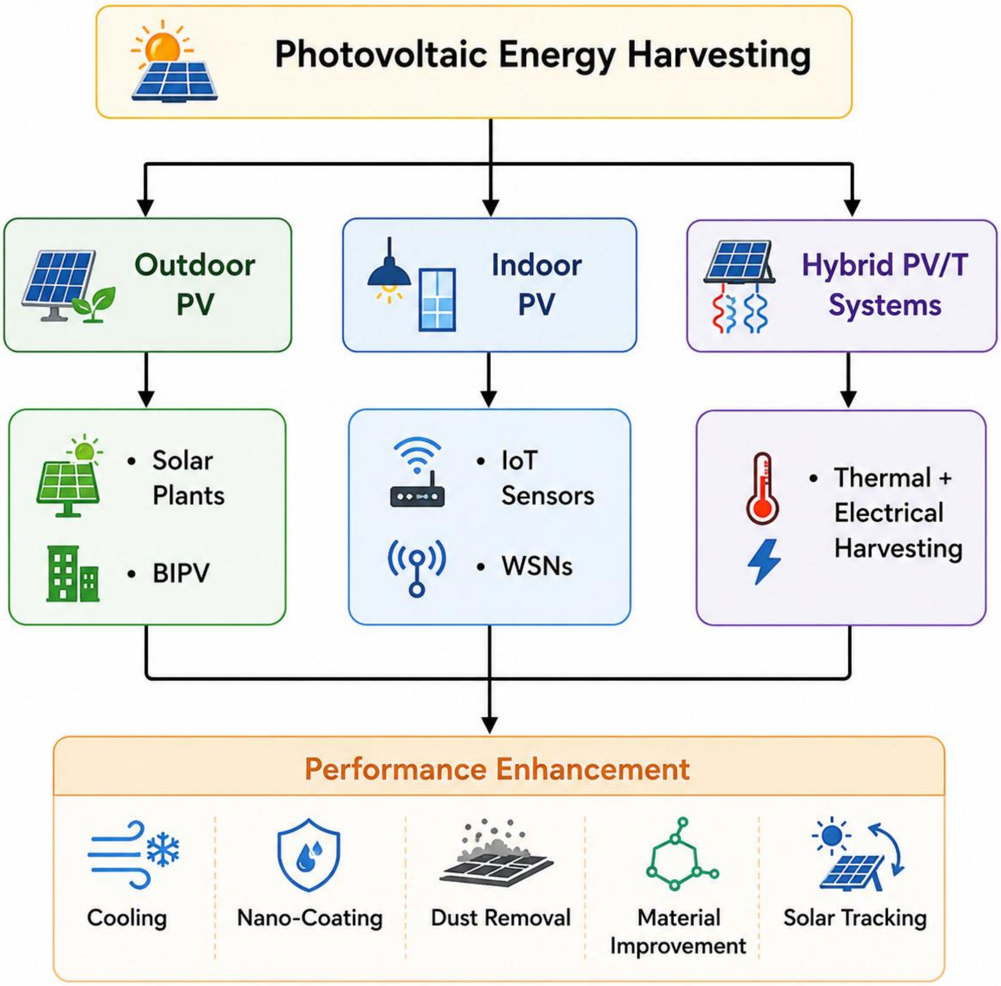

Figure 1: Classification of PV energy harvesting technologies and applications

Prasetyo et al. (2023) [25] studied temperature rise in PV systems, a factor that affects electrical efficiency and hinders solar energy harvesting potential. They aimed to enhance PV performance by adopting a hybrid PV/thermal (PV/T) collector system that can cool PV panel and generate useful thermal energy in the process. The authors suggested various riser arrangements with different coolants like water, nanofluids of TiO_2, SiO_2, and Al_2O_3. A thermal simulation of the system was performed in ANSYS with controlled thermal simulation conditions with solar irradiance of 1000 W/m2. The results indicated that at a mass flow rate of water of 0.5kg/s, the semicircular collector configuration had the highest electrical efficiency of 11.98%. The contribution of this study is that the PV/T cooling design is proven to have the capability to reduce PV panel temperature and hence improve energy harvesting. The study, however, was primarily simulation-based and primarily thermal behavior based, not real time monitoring and power electronic control. This work is applicable to the present review as it draws attention to the role of thermal management as one of the significant methods for promoting PV energy harvesting.

To enhance the performance of MPPT in solar PV systems in changing environmental conditions, Hussain et al. (2023) [26] worked on it. Their work aimed to compare six training algorithms of artificial neural networks for the energy harvesting using MPPT. The Levenberg–Marquardt, Bayesian regularization, resilient backpropagation, gradient descent momentum, BFGS and scaled conjugate gradient algorithms were evaluated by the authors using MATLAB/Simulink and the ANN toolbox. The solar irradiance, temperature, voltage data set of 1000 samples was used for training, validation and testing of the model. Results indicated that Levenberg–Marquardt and BFGS performed better than did SCG and GDM. The comparative evaluation of ANN based MPPT techniques in enhancing the PV energy extraction is the main contribution. In this study, however, the hardware implementation was not done and it was only simulated and algorithmic comparison was made in between them and with IoT based monitoring. It is useful in this review as a reference in order to improve PV system for energy harvesting based on MPPT.

Furthermore, Khan et al. (2024) [27] investigated the challenge of harnessing maximum power from PV systems under nonlinear conditions due to fluctuations in solar irradiance, temperature, and partial shading. They aimed to improve the MPPT controller performance using a new Energy Valley Optimizer algorithm. The proposed method was compared with P&O, whale optimization, cuckoo search and particle swarm optimization algorithms. Several case studies have been developed and tested with the system such as partial shading, variable temperature, variable irradiance, and field atmospheric data. A process-in-loop test was also conducted with the Arduino MKRZERO board, which confirmed the controller. The results indicated 30% faster tracking time, 80% faster settling time and 4-8% higher power efficiency of the proposed method. The main contribution is to validate advanced MPPT controller through simulation and microcontroller testing. The method can, however, be more algorithmically complex than traditional MPPT methods. The paper is very relevant as it relates PV energy harvesting to actual implementation of the MPPT control.

Moreover, Khernane et al. (2024) [17] discussed Renewable Energy Harvesting Techniques for Wireless Sensor Networks Applied to Precision Agriculture. The research problem was the short lifetime of the battery-powered wireless sensor nodes, particularly in a remote agricultural application where accessing the wireless sensor nodes to replace batteries is also challenging. The goal was to review different renewable energy harvesting technologies such as solar, vibration, thermal and radio frequency for IoT based agricultural monitoring systems to maintain a sustainable solution. The review indicated that PV energy harvesting has higher power density than other ambient energy sources and can be used in wireless sensors and smart farming applications. Its main contribution is a discussion on renewable harvesting as an approach for prolonging the lifetime of sensor networks in agriculture. The paper, however, is wide, and shallow in terms of PV power electronics and MPPT control. It is applicable for this study as it facilitates PV harvesting towards IoT based and remote monitoring applications.

Additionally, Elnozahy et al. (2024) [28] studied the issue of dust deposition on building integrated PV panels that leads to reduction of solar radiation absorption and consequently harvested energy. The aim was to enhance PV energy harvesting by applying a self-cleaning, anti-reflection and anti-static hydrophilic nano-coating materials. The authors studied and compared 3 types of panels: dusty, manually cleaned, and nano-coated, under natural dust conditions. As a result of the experiments, it was found that nano-coated panel had a higher maximum output power of 18% than the manually wiped panel and the efficiencies of nano-coated, manually wiped and dusty panels were 11%, 9% and 6%, respectively. The main contribution is the experimental demonstration of the significant improvement of PV performance due to surface treatment in dusty environments. But, the research is primarily carried out in the material improvement aspect without incorporating IoT monitoring and active control. It is relevant because environmental losses (dust) have a significant impact on the efficiency of PV energy harvesting.

Similarly, Chakraborty et al., (2024) [29] presented a review of the role of indoor PVs as an energy harvesting solution for low power electronics, wireless sensors, and IoT applications. Major research issues considered in the study were the reliance of electronic devices on batteries, its contribution to the maintenance cost of electronic devices, and its effect on long term autonomous operation of the electronic device. The aim was to present an organized overview of the indoor PV technologies and assess their potential for energy harvesting in low light artificial indoor environments. Various PV material types such as amorphous silicon, organic PVs, dye-sensitized solar cells and perovskite solar cells were mentioned along with their efficiency, stability, spectral-matching and device design. The study pointed out that indoor PV devices have demonstrated high efficiency of PVs under artificial light, including some of the emerging PV technologies which have a PVs efficiency of over 30%. The significant contribution of this work is a thorough discussion on indoor PV as a practical energy source for IoT and low power systems. However, the study is mainly about the materials of the device and indoor applications, while power electronic control and implementation of MPPT are less discussed. This article is relevant since it brings PV energy harvesting from outdoor solar energy systems to indoor self-powered IoT applications.

Likewise, Silva et al. (2024) [30] studied the design of a self-powered indoor energy harvesting system based on the organic PV technology. The issue being addressed was that traditional batteries would need to be replaced regularly for low power consuming electronic devices, which would not be sustainable. The goal was to create an electrical power supply system which allows to operate a commercially available electronic lock with a source of energy in the form of OPV panels. The system under the proposal consisted of an OPV energy harvester, charging control circuit, supercapacitor storage unit and boost converter. Bench and real-scenario tests were carried out to assess the system performance under the indoor lighting environment. It has been concluded that the system could function autonomously for a minimum daylight illuminance of 250 lux for 12 hours per day. The most important contribution is the practical demonstration of the energy harvesting by OPV technology for a real low power electronic load to be used inside. But this study is confined to a certain application and no study of large scale PV system and advanced MPPT control has been undertaken. This is relevant to the present review as it demonstrates that PV harvesting can be applied to self-powered devices and to indoor IoT-related applications.

Subsequently, efficient PV energy harvesting in CubeSat missions, where space, weight and power constraint are the main issues, is presented by Dwaza et al. (2025) [31] and a highly reliable MPPT strategy is required. The aim was to compare the conventional Perturb and Observe, Particle Swarm Optimization and hybrid P&O–PSO MPPT method for CubeSat PV modules. The authors have created a MATLAB R2025a/Simulink model from PV module datasheet Azur Space 3G30C and combined it with DC–DC boost converter. The proposed hybrid P&O–PSO method used the advantages of both P&O and PSO, simplicity of P&O and global search of PSO. The simulation results indicated that the hybrid approach produced lesser oscillations around global maximum power point, better tracking accuracy over varying temperature conditions and also stable output parameters as compared to standalone P&O and PSO approaches. The main contribution is a hybrid MPPT strategy, which is appropriate for constrained aerospace PV use. The work was simulation based and was related to CubeSat conditions and not terrestrial IoT based PV monitoring. The relevance of this study is to show the value of the optimized MPPT control to maximize PV energy harvesting under constrained conditions.

More recently, Badawi et al. (2026) [32] studied the PV energy harvesting coupled with energy storage and wireless power transfer in small-scale portable applications. The research problem was that of the solar harvesting, battery storage and resonant wireless power delivery combined in a small enclosure would result in conversion loss, thermal instability and frequency detuning. The goal was to create and optimize a portable energy storage system that uses solar power to charge a lithium-ion battery and wirelessly transmit high efficiency energy to the user. The proposed system comprised of 5 V monocrystalline PV array, 10,000 mAh lithium ion battery, adaptive MPPT, thermal management using CFD modeled ventilation and graphite spreaders, and direct frequency stabilization using Phase-Locked Loop (PLL) for resonant inductive power transfer (RIPT). Under irradiance levels of 100–1200 W/m², the experimental validation showed a wireless transmission efficiency above 85%, a restorative gain in the wireless power transfer stage of 12.3% at 15 W load, thermal stabilization of 48 °C under a 15 W load, and a full solar recovery cycle of 23.6 cumulative solar hours at standard test conditions. The novel element is the concept of integrated design of solar harvesting, storage, thermal management and wireless power delivery. But the system is geared towards portable energy modules and not grid connected PV systems. It is relevant since it demonstrates the integration of PV harvesting with storage and sophisticated power delivery for stand-alone applications.

Lastly, Fernandez et al. (2026) [33] mitigated the drawbacks of the traditional MPPT techniques, particularly the steady-state oscillations and slow convergence in varying irradiance and temperature conditions. The goal was to improve PV energy harvesting by developing a predictive controller that could be implemented with a low-resource hardware. The proposed method involved the power of two quantized recurrent neural network (RNN) controllers based on FPGA for the DC–DC converter control signal and updating the control signal only when there was a noteworthy difference between the measured and predicted voltage and currents. Performance was evaluated with a dataset-driven method with year-long climatic information from various geographical locations. The results indicated the annual energy yields to be as high as 99.90% of the ideal maximum with the assumed conditions, and the number of internal controls to be 20-40 times less than with traditional P&O methods. However, the controller also attained the aggregated efficiency of over 98% under strong sensing-noise condition. The main contribution is the design of a hardware efficient predictive MPPT controller for edge oriented PV systems. The study is based on model assumptions and evaluation based on data, however, and needs to be validated in real deployments. It is relevant as it connects PV energy harvesting, MPPT control and edge hardware implementation to the overall trend of PV control systems based on IoT. The literature reviewed shows a variety of methods that can be used to improve the energy harvesting process of PV systems, as also compared in Table 1.

Table 1: Quantitative comparison of recent PV energy harvesting studies

Reference	Year	Harvesting Type	Proposed Approach	Quantitative Performance	Main Contribution	Limitation
Prasetyo et al. [25]	2023	Hybrid PV/T	PV/T collector with water and nanofluid cooling	Electrical efficiency = 11.98%; active cooling improved PV performance	Simultaneous electrical and thermal energy harvesting	Simulation-based study
Hussain et al. [26]	2023	MPPT-based PV harvesting	ANN algorithms for MPPT	Regression value = 1.0 (LM, BR, RP, BFGS); performance error as low as 9.98×10^{-17}	Comparative evaluation of ANN-based MPPT methods	No hardware validation
Khan et al. [27]	2024	PV energy harvesting	EVO-based MPPT controller	30% faster tracking; 80% faster settling; 4–8% higher power efficiency	Improved MPPT under partial shading conditions	Higher computational complexity
Khernane et al. [17]	2024	Renewable harvesting for WSNs	Solar, thermal, RF, and vibration harvesting review	Solar harvesting reported power density ≈ 15 mW/cm³, highest among surveyed sources	Demonstrated suitability of PV harvesting for smart agriculture	Review-only study
Chakraborty et al. [29]	2024	Indoor PV harvesting	Indoor PV technologies	Indoor PV efficiencies exceeding 30% reported under optimized lighting conditions	Assessment of PV technologies for IoT devices	Limited discussion of control systems
Silva et al. [30]	2024	Indoor OPV harvesting	OPV-powered self-sustaining system	Self-powered operation achieved at ≥250 lux for 12 h/day	Practical indoor PV energy harvesting implementation	Application-specific design
Elnozahy et al. [28]	2024	Outdoor PV harvesting	Nano-coated PV panels	Output power increased by 18%; efficiency improved from 6% (dusty) to 11% (nano-coated)	Dust mitigation and self-cleaning enhancement	Focused on surface treatment only
Dwaza et al. [31]	2025	Space PV harvesting	Hybrid P&O–PSO MPPT	Improved tracking stability and reduced oscillations compared with standalone methods	MPPT optimization for CubeSat applications	Simulation-based validation
Badawi et al. [32]	2026	Portable PV harvesting	Integrated PV-storage-WPT system	Wireless power efficiency >85%; thermal stabilization at 48°C	Integration of harvesting, storage, and wireless transfer	Portable-scale application
Fernandez et al. [33]	2026	Predictive MPPT harvesting	FPGA-oriented predictive controller	Annual energy yield up to 99.90%; 20–40× fewer control updates	Low-computation predictive MPPT strategy	Requires field deployment validation

Table 1 presents the current research trends of PV energy harvesting based on the following aspects: advanced materials, thermal management techniques, indoor PV technologies and hybrid PV/T technologies for enhancing the energy conversion efficiency. Cooling has been used to achieve significant improvements in power generation and harvesting efficiency, and PV designs have been optimized, and nano-coatings have been developed, indicating the ongoing development of energy harvesting technologies for various applications.

3. POWER ELECTRONIC CONTROL AND MPPT TECHNIQUES

Power electronic control is a key element of PV systems, enabling efficient conversion of energy, voltage regulation, and maximizing power output under different environmental conditions [34]. The output characteristics of PV modules are strongly related to the solar irradiance, temperature and shading; so the operating point of a PV system varies continuously throughout the day. Therefore, power electronic converters and advanced control algorithm are needed to achieve stable operation and energy harvesting efficiency.

MPPT has become one of the most significant control mechanisms to optimize PV performance among the different control techniques. MPPT algorithms are in constant operation to tune the PV array's operating voltage or current to the maximum available power as environmental conditions change. The most widely-used methods include the traditional techniques (Perturb and Observe (P&O) and Incremental Conductance (INC)), and the more advanced optimization-based and predictive control techniques. Normally these methods are done by using DC-DC converter and inverter control systems, which are located between PV source and electrical load or grid.

In recent years, the MPPT accuracy, the MPPT tracking speed, the convergence behavior, the power conversion efficiency and the Anti-Partial Shading performance are the main research directions of MPPT. Moreover, the power electronic control architectures are getting more efficient and reliable due to the development of digital controllers, embedded systems, FPGA-based implementations, and optimization algorithms. In this regard, this section summarizes recent advances in power electronic converter, control method, and MPPT technique which can help improve the PV energy harvesting and the overall performance of PV system. The general relationship between PV generation, sensing, MPPT control, power electronic conversion and energy delivery is shown in Figure 2.

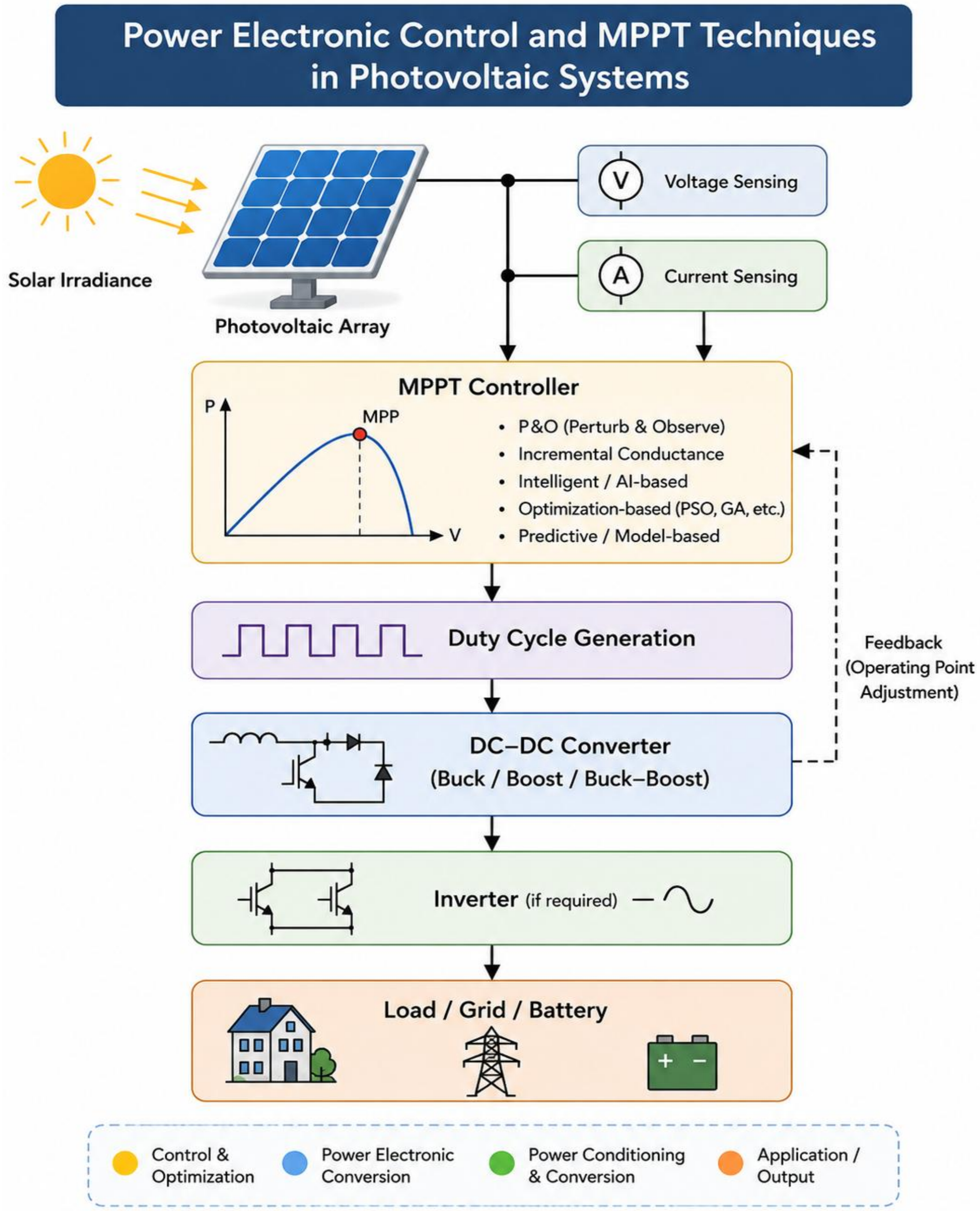

Figure 2: General architecture of power electronic control and MPPT in PV systems

Kumar et al., 2023 [18], provided a detailed survey of various classic and modern MPPT algorithms for solar PV system under uniform and partial shading. The primary research issue was how to achieve maximum power extraction from PV systems under variable irradiance and temperature conditions particularly under partial shading in which several local maximum power points occur. The goal was to categorize and assess the MPPT techniques based on their appropriateness for various operating conditions. The authors classified MPPT techniques into four categories: classical, optimization-based, and hybrid techniques. They used a structured literature review and comparative analysis by selection criteria including tracking speed, complexity, accuracy, cost, implementation difficulty and performance in partial shading. The study results revealed that classical techniques are simple and inexpensive, but are unable to provide good tracking under partially shaded conditions, and the optimization-based techniques were found to be able to provide good tracking globally but incur high computation intensity. The primary contribution of this work is the systematic classification of MPPT algorithms and highlighting the pros, cons, and research gaps. The study, though, is review based and does not introduce new experimental validation. It is pertinent to the current review as it gives theoretical background for understanding the evolution of MPPT techniques in PV system.

Furthermore, Ali et al. (2023) [35] studied the performance of generalized PV system under varying environmental conditions and using Perturb and Observe (P&O) MPPT algorithm. The problem addressed by the research was that PV output varies continuously as a function of solar irradiance and cell temperature and it is hard to keep PV operating at the MPP. The main goal was to design and model a general PV model that consists of PV array, DC-DC converter, DC-AC inverter, MPPT control, and grid synchronization. The maximum power point tracking was given by P&O algorithm and the synchronization of the inverter to the grid was accomplished by feedback control. The system was designed and simulated in MATLAB/Simulink under sudden change in weather conditions. The results showed that the P&O based MPPT could track the maximum power point well in the simulated PV system and could run the PV system on the grid. The principal contribution is the modeling and simulation of PV, boost converter control, inverter synchronization and MPPT in a single generalized simulation model. The P&O method, however, still has the drawbacks of oscillating around the MPP and lower performance in rapidly changing and partially shaded conditions. It is relevant as it is a conventional MPPT which can be compared with newer optimization based and robust MPPT.

Following this review, Ghazi et al. (2024) [36] tackled the problem of enhancing MPPT performance in large-scale grid-connected PV systems through various advanced reinforcement learning techniques. The research problem was the conventional MPPT and PID based control may not give the optimum tracking in different weather condition and in grid connected mode. The aim was to design a deep reinforcement learning MPPT strategy for a 100 MW PV plant based on Dandelion Optimizer which was connected to a 33 kV distribution system. The proposed method used a Dandelion Optimizer algorithm along with Proximal Policy Optimization and Deep Deterministic Policy Gradient algorithms to optimize the PV voltage reference. The system was simulated on MATLAB/Simulink with real input data of the typical summer and winter day. A comparison between the proposed methods and the DO-PID, PSO and Incremental Conductance with PI control methods was made. Results indicated that the efficiencies of DC–DC boost converter were achieved to 84.25–85.90% in summer and 92.77–95% in winter, and the efficiencies of voltage source converter were achieved to 78.33–81.10% in summer and 86.70–89.50% in winter. Optimized implementation of reinforcement learning for MPPT in large scale grid connected PV system is the main contribution. The method is however a complicated one and still needs to be validated in the field. This work is relevant as it shows how classical MPPT transitioned to adaptive and learning based power electronic control.

Similarly, Mazumdar et al. (2024) [19] provided an overview of the conventional and artificial intelligence-based MPPT techniques in PV system. Challenges of obtaining maximum power extraction under uniform irradiance, and also under partially shaded conditions were the research problem because of the nonlinear I–V and P–V characteristics of PV modules. The aim was to give a comprehensive up to date review of MPPT development, classical, soft-computing and artificial intelligence based approaches. The authors reviewed the conventional methods like the P&O, Incremental Conductance, Constant Voltage and Hill Climb and strong methods like fuzzy logic, neural network, and bio-inspired optimization algorithms. A review-based approach was adopted and various datasets and control strategies reported in the previous studies were summarized. Results indicated that conventional techniques are appealing because of their simplicity and fast convergence, however, they have a problem in identifying the local and global maximum power points under partial shading conditions. The wide comparison of MPPT methods and their appropriateness for various PV operating conditions is the main contribution. The study is however, descriptive and a new controller is not tested. This is relevant as it helps to classify the MPPT techniques and it is important to understand that a large number of advanced control techniques have been employed in modern PV systems.

In the same year, Mohamed et al., 2024 [37], proposed a global MPPT controllers to enhance the PV system performance under partial shading conditions. The problem in the study was that partial shading results in several peaks in the P–V curve, which causes classical MPPT controllers to fall at a local maximum PMP and not the global maximum PMP. The goal was to enhance the tracking accuracy, convergence speed and stability through a set of optimized global MPPT controllers. The authors compared the performance of PI, fractional-order PI, and fuzzy logic controllers along with modified Incremental Conductance (IC) and Fractional Open-Circuit Voltage (OCV) algorithms. A novel Atom Search Optimization Algorithm was used to tune the controllers. Extensive simulations were carried out in the system under various shading conditions. Results revealed that the ASOA based fuzzy IC MPPT controller exhibited excellent performance in terms of average power harvesting efficiency (APHE) of more than 97.9% and settling time. The major contribution is the incorporation of optimization-based tuning in fuzzy and conventional MPPT structures to enhance the dynamic response under partially shaded condition. But the study was a simulation and no hardware testing was conducted. This work shows how the MPPT performance in the shaded PV system can be improved through optimized control.

Meanwhile, Oliveira et al. (2024) [38] presented the drawbacks of traditional MPPT methods in PV systems under partial shading conditions when multiple peaks appear, making it impossible to harvest the GMPP. The purpose of this work was to investigate and implement a genetic algorithm (GA) based MPPT technique that can find the global optimum operating point of the MPPT more efficiently than the traditional ones. A combination of genetic algorithm and power electronic converter was proposed to perform a continuous search to find the global maximum power point (MPP) for a PV array under varying irradiance and temperature conditions. The simulation of the system has been performed and the results have been compared with the well-known Perturb and Observe (P&O) algorithm. The results showed that the GA-based MPPT method had better tracking performance and was more effective in tracking the global maximum power point under partial shading conditions as compared to the classical P&O method. The primary originality of the study is the use of evolutionary optimization for power extraction improvement in complex shading environment. But, the suggested algorithm consumes more computational power and processing time than the traditional MPPT techniques. The relevance of this study is that it illustrates the potential application of optimization based control techniques for overcoming the limitations of these traditional MPPT techniques in PV systems.

In another study, Yuan et al. (2024) [39] attempted to overcome the issue of tracking the global maximum power point in PV systems under partial shading conditions, where traditional MPPT algorithms may be stuck in the local maximum point. The aim was to design a segment cubic Hermite interpolation MPPT algorithm with high accuracy and fast speed. The authors suggested that the PV array with boost converter has to be integrated with a Hermite Interpolation Optimization (HPO) based MPPT controller. Modeling and testing was done using MATLAB/Simulink under four different irradiance (solar power) scenarios which include partial shading conditions. Evaluation was done comparatively with the Incremental Conductance and Particle Swarm Optimization algorithms. The average tracking efficiency was 99.84%, the average tracking speed was 0.28 s and the best tracking efficiency for partial shading was 99.99% with 0.23 s tracking time. The main contribution is with regard to the introduction of a mathematical interpolation based MPPT technique, which has a high tracking accuracy along with a fast convergence rate. Nevertheless, the method involves some more calculations than the simple conventional ones. This work is relevant as it offers an alternative high performance MPPT solution that can be used to enhance energy extraction when the environment is complex.

Additionally, Chellakhi et al. (2024) [40] analyzed the disadvantages of the conventional Perturb and Observe algorithm, such as the fixed perturbation step size, which leads to power oscillations, slow convergence and poor tracking rate. The goal was to design a simple, low cost and easily implementable MPPT controller having improved tracking performance. The authors suggested an improved indirect P&O scheme with the current perturbation and a flexible step-magnitude mechanism. The PID regulation structure was implemented in the controller in an Arduino Uno platform. Proteus software was used to simulate the proposed system, and the results were compared with that of the conventional P&O, Particle Swarm Optimization, Fuzzy Logic Control and Zone Voltage methods. The obtained results showed that the static and dynamic efficiency of tracking were 99.38% and 99.88% respectively, the tracking time was 0.19 s and the power fluctuation was very small. The novelty of this work is a simple and low cost MPPT solution which can deliver a similar performance as more complex optimization based methods. However, the validation was mainly based on simulations and was geared towards low cost embedded implementation. The relevance of this study is that it proves that considerable improvement in the MPPT can be made without the need to use a complicated algorithm.

Subsequent research by Abdelmalek et al. (2025) [41] tackled the issue of the effective tracking of the maximum power point of PV systems under both standard operating conditions and partial shading conditions. The goal was to design a hybrid MPPT algorithm based on optimization technique which can enhance the convergence speed and tracking accuracy. The authors introduced Grey Wolf Equilibrium Optimizer (GWEO) that is a mixture of exploration feature of the Grey Wolf Optimizer (GWO) and exploitation feature of the Equilibrium Optimizer (EO). The algorithm was tested using standard test conditions and 4 partial shading conditions, and compared with PSO, Whale Optimization Algorithm, Grey Wolf Optimization and Flower Pollination Algorithm. Experimental validation was carried out with a DSPACE platform and PV emulator. The results indicated that the average tracking times were 0.9 s in standard conditions and 0.975 s in partial shading and the efficiencies were 99.96% and 99.95% respectively. The main contribution is the development of a highly accurate hybrid optimization MPPT technique which has excellent performance under the complex shading condition. The algorithm however demands more computation and is not as easy to use as conventional methods. The work of this study is very relevant due to the application of the latest trend in the optimization of advanced PV power extraction technique that is hybrid metaheuristic.

Continuing this trend, EL-Ebiary et al. (2025) [42] studied adaptive MPPT control techniques for grid-connected PV systems under rapidly varying weather conditions. The problem studied was that, for fixed-parameter controllers, it is difficult to keep the controller parameters optimal under varying irradiance and temperature. The goal was to enhance the performance of the Incremental Conductance MPPT through adaptive control strategies and machine learning based initialization. Optimized Fractional order Adaptive PI controller (FOAPI) and Single Perceptron Adaptive PI controller (SP-API) with Incremental Conductance MPPT were proposed. In addition, machine learning regression models were used to estimate the initial duty cycle of the converter. Three case studies were carried out to assess the performance of the controller with various operating conditions. Results showed that this approach achieved better tracking accuracy, faster dynamic response and better adaptability to the environment than conventional approaches. The novelty is the use of adaptive control and machine learning in a grid connected MPPT. But it does need more tuning and computation effort on the part of the controller. The relevance of this work is to illustrate the trend towards employing data-driven control methods for optimizing the PV energy harvesting efficiency.

Lastly, Chnini et al. (2025) [43] studied the application of sturdier nonlinear MPPT controllers for embedded PV systems. The problem of research was the degradation of MPPT performance under nonlinear operating condition due to the irradiance and temperature variation. The goal was to create advanced MPPT strategies that are capable of yielding high efficiencies while keeping real time embedded implementation options open. Two nonlinear controllers, namely ANFIS combined with Fast Terminal Synergetic Control for boost converter and ANFIS combined with Backstepping Control for SEPIC converter have been proposed by the authors. Then a Processor-in-the-Loop validation framework was adopted, which is based on the ARM processor of the microcontroller STM32F407VG. Experimental results have shown that the tracking efficiency is more than 99.6%, the convergence speed is quick, and the tracking system has high robustness to adapt to different environments. The significant contribution of the work is that the developed advanced ANFIS-based MPPT strategies are successfully validated in real-time in an embedded environment, connecting the simulation with the actual implementation. However, more sophisticated design of the controller and computational capability are required in the system than conventional MPPT techniques. This study is very relevant as it demonstrates the way powerful MPPT algorithms can be implemented from simulation to real embedded PV application. Table 2 provides a comparative summary of recent power electronic control techniques and MPPT techniques for PV systems along with their control strategies, implementation platforms and quantitative performance indicators.

Table 2: Comparison of recent MPPT techniques for PV systems

Reference	Year	MPPT Technique	Control / Optimization Method	Environment / Platform	Quantitative Performance	Main Limitation
Kumar et al. [18]	2023	Review of MPPT methods	Classical, Optimization, Hybrid	Literature review	Comparative review only	No experimental validation
Ali et al. [35]	2023	Perturb & Observe (P&O)	Feedback-controlled PV system	MATLAB/Simulink	Effective MPP tracking under varying irradiance and temperature	Oscillations around MPP; reduced performance under PSC
Ghazi et al. [36]	2024	DO-PPO and DO-DDPG MPPT	Dandelion Optimizer + Deep Reinforcement Learning	MATLAB/Simulink, 100 MW grid-connected PV plant	DC–DC converter efficiency: 84.25–85.90% (summer), 92.77–95.00% (winter); VSC efficiency: 78.33–81.10% (summer), 86.70–89.50% (winter)	High computational complexity

Mazumdar et al. [19]	2024	Review of MPPT methods	Conventional and AI-based techniques	Literature review	Comparative review only	No hardware or experimental validation
Mohamed et al. [37]	2024	Global MPPT	ASOA-optimized Fuzzy IC, PI, and FOPI controllers	MATLAB-based simulations	Average harvesting efficiency >97.9%; settling time reduction ≈1.9%	Simulation-based evaluation
Oliveira et al. [38]	2024	Genetic Algorithm MPPT	Evolutionary optimization	Simulation environment	Superior GMPP tracking compared with conventional P&O under PSC	Higher computational burden
Yuan et al. [39]	2024	HPO-MPPT	Hermite Interpolation Optimization	MATLAB/Simulink	Average tracking efficiency = 99.84%; maximum efficiency = 99.99%; average tracking time = 0.28 s; fastest tracking = 0.23 s	Increased mathematical complexity
Chellakhi et al. [40]	2024	Improved P&O MPPT	Adaptive current perturbation + PID	Arduino Uno + Proteus	Static efficiency = 99.38%; dynamic efficiency = 99.88%; tracking time = 0.19 s	Primarily simulation-based validation
Abdelmalek et al. [41]	2025	GWEO-MPPT	Grey Wolf Equilibrium Optimizer	DSPACE board + PV emulator	Efficiency = 99.96% (STC); 99.95% (PSC); tracking time = 0.90 s (STC); 0.975 s (PSC)	Higher computational requirements
EL-Ebiary et al. [42]	2025	Adaptive IC-MPPT	FOAPI and SP-API adaptive controllers + ML initialization	Grid-connected PV system	Improved tracking accuracy and dynamic response under weather variations	Requires controller tuning and training
Chnini et al. [43]	2025	ANFIS-FTSC and ANFIS-BS MPPT	ANFIS-based nonlinear control	STM32F407VG Processor-in-the-Loop	Tracking efficiency >99.6%; rapid convergence and robust real-time performance	Higher implementation complexity

Table 2 tabulates the evolution of recent MPPT and control strategies with power electronics from traditional MPPT approaches to optimization based, adaptive, and robust control approaches. Most of the advanced techniques had efficiencies of tracking that are above 97% and some recent methods reported efficiency above 99%, indicating clearly the importance of the modern control algorithms in maximizing the PV power extraction and hence the overall PV system performance under the different operating conditions.

4. IOT-BASED PV MONITORING AND MANAGEMENT

Internet of Things (IoT) based monitoring technologies have become a vital tool for enhancing PV systems reliability, performance evaluation and operation [44]. Traditional PV monitoring relies on manual inspection or local data logging, processes that are expensive, time-consuming and not appropriate for remote locations. IoT-based systems include the integration of sensors, microcontrollers, wireless communication, cloud storage, and web and mobile interfaces, so that electrical and environmental parameters like voltage, current, power, irradiance, temperature, humidity, and battery condition can be monitored in real time.

These monitoring systems enable early detection of faults, predictive maintenance, remote supervision, and optimization of performance. The recent studies are about low cost monitoring devices, wireless data acquisition, cloud-based platforms, SCADA-IoT architecture and smart sensor based monitoring under harsh environmental conditions. In this context, this section discusses the latest research on PV monitoring using IoT, including the communication method, monitored parameters, system architecture, platform for implementation, performance outcomes, limitations, and relevance to improving PV system reliability and energy harvesting.

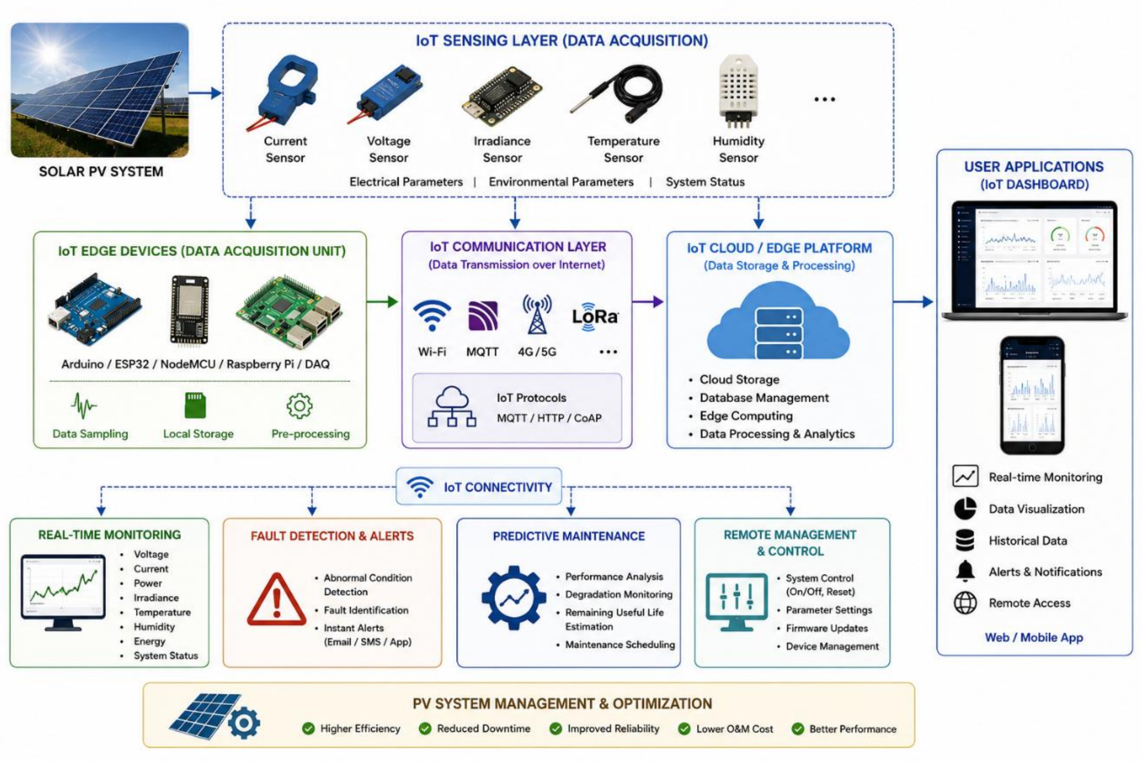

Figure 3: General architecture of IoT-based PV monitoring and management systems

Initially , Njoka et al. (2023) [45] assessed the remote monitoring of stand-alone solar PV in Kenya using a combination of Internet of Things (IoT) technologies. The research problem was operation and maintenance cost for off-grid PV systems in remote locations, where the cost and technical challenge of physically visiting PV sites is high. The goal was to evaluate the potential reduction in maintenance costs and increase in system reliability through the use of IoT monitoring platforms. The authors examined three solar PV sites that were remotely monitored and confirmed the results by data from four PV installer companies in Nairobi. These findings indicated that a large number of system issues can be monitored and many of them can be corrected remotely, yielding an annual cost savings of USD 2040 to USD 3096 per site. The cost of annual operation and maintenance was reduced by 47-95% compared with the systems monitored locally. The key value of this research is based on the economic feasibility of IoT monitoring of remote PV systems. The work concentrated primarily on cost and maintenance analysis, however, and was not detailed with regards to sensor architecture or real-time performance optimization. This study is relevant since it shows the practicality of IoT monitoring to minimize PV system maintenance cost and enhance long-term sustainability.

Moreover, Lakshmi et al. (2023) [46] explored the use of IoT in detecting fault and maintenance of solar panels with machine learning. The research problem was that PV system faults may lead to power loss and additional maintenance services, and the existing PV system fault detection methods are mostly time consuming and human labor intensive. The goal was to create a predictive model of fault detection using power generation and solar power plant weather data. After pre-processing the input data, the proposed approach was a Decision Tree with Light Gradient Boosting algorithm. The system was designed to detect major faults or anomalies of PV operation, as well as minor ones. The results indicated good prediction performance with MSE, RMSE and R2 of 8.74, 2.96 and 0.9939 respectively, which are 12.8%, 6.8% and 11.08% better than the existing method. The primary contribution is that PV fault prediction and maintenance support are provided using IoT-supported data and machine learning techniques with high accuracy. But the study relies on the performance of the models that are driven by the data, and high quality datasets are needed for reliable predictions. This work is relevant as it links IoT monitoring to predictive maintenance for PV system reliability.

Next, Hamied et al. (2023) [47] designed a monitoring system for an off-grid PV system that is used to power a greenhouse farm in a dry southern part of Algeria at low costs and using IoT technology. The difficulty of monitoring isolated PV installation in remote agricultural application, which may be influenced by fault occurrences to reduce the reliability of energy supply, was identified as the research problem. The main goal was to develop a low cost monitoring and fault diagnosis system which can be operated in real time in harsh climatic conditions. The proposed system measured PV current, PV voltage, solar irradiance and cell temperature and IoT technology was used to visualize the measured data remotely via a web page and SMS notifications. A fault diagnosis algorithm was implemented and validated in a low cost micro-controller in real time. Results indicated that the system was able to monitor the greenhouse PV installation well and it was able to detect selected defects with good accuracy. The total cost of the monitoring system was about EUR 73, and its average daily energy consumption was about 13.5 Wh. The key contribution lies in the development of practical and low-cost IoT monitoring solution for stand-alone agriculture PV systems. But, for larger PV installation, the system needs to be tested on the same application in the greenhouse and may need to be validated. This study is relevant because it shows that PV monitoring with IoT can guarantee PV reliability in remote and arid areas.

In addition, Alombah et al. (2023) [48] developed a Trio-PV Monitor, a smart IoT-based system for continuous monitoring of solar PV installations. The research problem was the lack of reliable, affordable PV monitoring tools with PV system information that is expensive and difficult to access, especially in developing countries. The aim was to build a monitoring tool that would allow data collection, storage, sharing and statistical analysis of PV related data in a flexible way. It was a system consisting of electronic hardware, desktop software, and a website. It measured six PV parameters: irradiance, panel temp, ambient temp, humidity, PV current and PV voltage. It was developed for PV plants of up to 90 kW and was tried on a 30 W solar PV-DC system. The results indicated that the system could be used for continuous monitoring and real-time visualization using a desktop application, and by using IoT could be remotely accessed from anywhere. The development of a flexible PV monitoring platform for the developing world is the major contribution. But the developed system was tested with a small 30 W PV module. Because of the relevance of this work, it offers a way to develop a low cost PV data acquisition and remote monitoring using IoT.

Similarly, Radia et al. (2023) [49] created a wireless data acquisition and control system based on IoT for the analysis of PV module performance. The need for reliable and inexpensive monitoring system of PV modules placed in remote areas having difficulty in manual monitoring is the research problem. The goal was to create a wireless IoT monitoring and control platform with easily available hardware and open source software. The proposed system consisted of nodeMCU boards, Raspberry Pi, MQTT Mosquitto Broker, InfluxDB, node-red and Grafana for PV data collection, data storage, data visualization and data analysis. Voltage, current, power, ambient temperature, humidity, panel temperature, coolant inlet and outlet temperature, and spectral irradiance were the monitored parameters. The system also included the use of OpenWeatherMap data and included threshold-based alerts and wireless ON/OFF and servo motor control. The results indicated that the operation was efficient under various testing conditions and PV and environmental parameters were accurately measured. The integration of wireless monitoring, open-source platforms, and remote control functions in a single PV performance analysis system is the main contribution. But there was insufficient demonstration of scalability for large PV plants. This study is relevant because it shows the importance of IoT, wireless sensor networks and open source tools in the monitoring and control of PV.

Furthermore, Demir (2023) [50] studied the problem of monitoring stand-alone PV systems in remote locations where maintenance operations are challenging and expensive. The goal was to create an affordable IoT monitoring platform with PV power estimation which can be integrated for early fault detection and maintenance planning. The proposed system was an IoT compatible data logger to collect electrical and environmental parameters such as PV voltage, PV current, battery voltage, battery current, temperature, humidity, pressure and solar radiation. These data were sent to a server and displayed on web and mobile interfaces. Moreover, machine learning models such as Linear Regression, Support Vector Machine, Decision Tree, Random Forest and KNN were used to forecast PV power and detect the likelihood of PV system irregularities. Results indicated that the Random Forest algorithm predicted with the highest accuracy of 87%, followed by Decision Tree (81%), KNN (79%), SVM (67%) and Linear Regression (64%). The key novelty lies in the implementation of IoT monitoring and prediction of PV power generation in an affordable platform for large PV installations. However, with the quality and quantity of the collected operational data, the prediction accuracy is still dependent. This study is relevant because it shows how the IoT monitoring can go beyond data acquisition and move towards predictive diagnostics and robust maintenance support.

Moreover, Given the growing demand for sophisticated supervisory control and monitoring systems for operation and maintenance of large PV utility plant, Ferlito et al. (2024) [51] discussed this. Research problem: Traditional SCADA systems tend to create a lot of communication overhead and don't have adequate scalability for modern large PV installations. The goal was to create an SCADA architecture using IoT with better monitoring efficiency, scalability, reliability and prediction capabilities. The suggested solution involved using microservices, edge computing, lightweight communication protocols, and data certification via blockchain. The aim of the system was to gather and process a vast amount of operational and environmental data, to lower latency and to provide real-time decision making. The results showed that the hybrid edge-cloud architecture enhanced the scalability, fault-tolerance, centralized management, and historical data storage reliability for predictive maintenance applications. The development of a modern IoT-SCADA framework, particularly for utility-scale PV plants is the main contribution. The study was however mainly focussed on the system architecture with only few quantitative field-performance measurements. This is a relevant piece of work, as it shows the evolution of the traditional monitoring system into a more powerful, scalable and cloud-based PV management platform.

Also, Wang et al. (2024) [20] discussed in detail the IoT-based green-smart PV systems under extreme climatic conditions. Research problem was that in harsh environment PV systems are prone to faults such as hot spot, bubble formation, potential-induced degradation and short circuit that impact negatively their long term performance and reliability. The goal was to discuss technologies for sensing, data-processing approaches, condition-monitoring methods, and smart materials applied to PV systems that are equipped with IoT. They have included a survey of state-of-the-art sensor technologies such as fiber-optic sensors, wireless sensors, and thermal monitoring devices as well as environmental sensing platforms that can withstand harsh climatic conditions. The study emphasized the importance of preventive maintenance, early fault detection, and environmental adaptation for the implementation of IoT based monitoring system in the industry which can be achieved by acquiring of data and real time data processing. The introduction of a smart PV monitoring framework that combines and balances sensing technology, data analytics and material reliability is the primary contribution. But the pieces are all review-oriented and don't create an experimental monitoring platform at all. This study is relevant since it gives a thorough knowledge of advanced IoT monitoring technologies that can be used for PV systems in challenging environments.

Later, an advanced IoT based monitoring system for real-time PV performance evaluation was developed by Alombah et al. (2025) [52]. The research problem was that in developing countries, where PV system performance information is often expensive and difficult to obtain, there are few affordable and reliable PV monitoring tools. The goal was to develop a smart monitoring device for PV which collects, processes, stores and remotely visualizes PV operating data. The following set of parameters were proposed for the monitoring in the proposed system: Irradiance, Panel temperature, Ambient temperature, Humidity, PV current, PV voltage. The resolution of the data delivered by the device was below one minute and it was used for PV installations up to 90kW. The prototype PV system of 30W has been tested in Dschang, Cameroon under two climatic seasons. It was found that the results were reliable, there was real-time graphical visualization, the sensors were weatherproof, and remote monitoring was achieved from any location using IoT connectivity. The most significant contribution has been the development and experimental validation of the comprehensive, low cost monitoring platform that can be used in developing countries. But validation was carried out on a relatively small PV installation. This study is relevant due to the fact that it is a practical realization of IoT-based monitoring system for long-term PV performance assessment.

Subsequently, Rao et al. (2025) [53] studied the design of a smart cloud-based monitoring system for the solar PV energy generation. The problem addressed in the research was the lack of efficiency of the conventional methods in monitoring PV systems, especially those located at remote places and where continuous supervision is required. The goal was to take advantage of IoT and cloud computing to track PV performance and offer real time visualization of PV operational parameters. The proposed system comprised data collecting units, communication gateways, cloud storage system and visualization interfaces accessible by the user. The data obtained from PV system were sent to cloud servers and users were able to view the voltage, current, and solar radiation information remotely. Experimental assessment demonstrated that the monitoring platform has reliable operation with an average monitoring data transmission time of 53.01 s and a satisfactory monitoring accuracy. The key added value is the fact that they have integrated cloud computing and IoT technologies into a practical solar monitoring framework. But, a relatively long transmission delay can be present, which may restrict some real-time control applications. This study is relevant given its emphasis on the use of cloud-based monitoring infrastructures of modern PV.

Another study by Rouibah et al. (2025) [54] presented a smart prototype for real-time monitoring of PV energy systems based on IoT. Research problem was the need of many existing PV monitoring solutions to be costly and complex to deploy, particularly in rural or resource-poor areas. The goal was to create an inexpensive and experiment-validated monitoring platform that can continuously monitor PV system performance. An embedded hardware based on Arduino, temperature sensor, irradiance sensor, voltage sensor, current sensor, Wi-Fi communication, DC-DC converter and incremental conductance MPPT controller were proposed in the present system. A web interface was created to allow remote monitoring of all parameters such as irradiance, temperature, voltage, current, load conditions and the MPP information. The experimental results validated the real-time operation, low cost implementation, reliable remote supervision and minimal human interventions. The novelty is the inclusion of monitoring, MPPT control, and IoT communication in a practical prototype that can be deployed in PV systems both in the home and in remote locations. A prototype was tested on a limited scale though and needs more cybersecurity and scalability enhancements. This study will be relevant because it shows IoT monitoring and PV power optimization in one integrated PV management framework.

Finally, Shukla et al. (2026) [21] presented a literature review of the use of IoT technologies for PV system monitoring, fault diagnosis, predictive maintenance and efficiency optimization. The research problem was the complexity of PV systems and the necessity of smart monitoring infrastructures to help the operation to be reliable and the energy efficiency to be high. The goal was to explore IoT systems, monitoring frameworks, and optimisation methods suitable for contemporary PV systems. The authors explored cloud, edge and fog computing architectures as well as technologies like adaptive MPPT, predictive maintenance, AI-based analytics and intelligent cleaning systems. The research pointed the advantages of the IoT that allows permanent communication between the sensing, communication, processing and decision-making layers and how it turns traditional PV systems into smart energy infrastructures. The biggest contribution is the identification of future research opportunities related to scalability, interoperability, cybersecurity and intelligent automation. It is still a review study without experimental implementation though. This study is relevant because it offers future insights into the evolution of PV monitoring technologies using IoT. Table 3 shows a comparative summary of recent monitoring technologies for PV systems based on IoT, their monitoring architecture, communication technology, and quantitative performance indicators.

Table 3: Quantitative comparison of recent IoT-based monitoring technologies for PV systems.

Reference	Year	Monitoring Architecture	Monitored Parameters	Communication Technology	Quantitative Performance	Main Limitation
Njoka et al. [45]	2023	IoT remote monitoring platform	PV system status, faults, operational data	IoT cloud platforms	Annual cost savings = USD 2040–3096; O&M cost reduction = 47–95%	Focus on economic analysis rather than system architecture
Lakshmi et al. [46]	2023	IoT + DT-LGB fault prediction	PV generation and weather data	IoT-enabled data collection	MSE = 8.74; RMSE = 2.96; R^2 = 0.9939; performance improvement = 12.8%	Requires high-quality training data
Hamied et al. [47]	2023	Low-cost IoT PV monitoring	PV current, voltage, irradiance, cell temperature	IoT web platform + SMS alerts	System cost ≈ €73; daily energy consumption ≈ 13.5 Wh	Evaluated on a small greenhouse PV system
Alombah et al. [48]	2023	Trio-PV Monitor	Irradiance, panel temperature, ambient temperature, humidity, PV current, PV voltage	IoT remote monitoring platform	Supports PV plants up to 90 kW; continuous operation ≈ 12 h/day	Validation performed on a 30 W PV system
Radia et al. [49]	2023	Wireless IoT DAQ system	Voltage, current, power, irradiance, humidity, temperatures	MQTT, NodeMCU, Raspberry Pi, Wi-Fi	Real-time monitoring with wireless control and alert functionality	Large-scale deployment not evaluated
Demir [50]	2023	IoT monitoring + ML prediction	PV, battery, and environmental parameters	Web and mobile interfaces	Random Forest accuracy = 87%; Decision Tree = 81%; KNN = 79%; SVM = 67%; LR = 64%	Prediction accuracy depends on dataset quality
Ferlito et al. [51]	2024	IoT-SCADA architecture	Utility-scale PV operational and environmental data	Edge-cloud architecture, microservices, blockchain	Improved scalability, fault tolerance, and low-latency operation	Limited quantitative field-performance results
Wang et al. [20]	2024	Green-smart IoT PV monitoring review	Environmental, climatic, and PV health parameters	Advanced sensor networks and IoT platforms	Comprehensive review of monitoring technologies under extreme climates	Review study without experimental validation
Alombah et al. [52]	2025	Advanced IoT PV monitoring system	Six PV operating variables	IoT remote monitoring platform	Data resolution < 1 min; PV plant capacity up to 90 kW	Tested on a 30 W prototype system

Rao et al. [53]	2025	Cloud-based PV monitoring system	Voltage, current, solar radiation	IoT + cloud computing	Average transmission time = 53.01 s	Transmission latency may affect real-time control
Rouibah et al. [54]	2025	Smart IoT PV prototype with MPPT	Irradiance, temperature, voltage, current, MPP data	Wi-Fi and web interface	Real-time monitoring and remote supervision with MPPT integration	Limited-scale experimental validation
Shukla et al. [21]	2026	IoT-enabled PV architecture review	PV performance, faults, maintenance indicators	Cloud, edge, and fog computing	Identified future architectures for self-optimizing PV systems	Review study without practical implementation

Indeed, the advancement of the IoT-based monitoring system has progressed from low-cost remote monitoring systems to cloud-based, edge-enabled and data-driven system as presented in Table 3. The key points highlighted in most studies include real-time data acquisition, fault detection, predictive maintenance, and remote supervision; new developments are now increasingly focussed on the scalability and interoperability of the data and automated decision support for next generation PV systems.

5. DISCUSSION

The literature surveyed illustrates the fast growth of PV systems from conventional energy generation technology to intelligent and highly optimized energy platform. The common goal in all the investigated themes, PV energy harvesting, power electronic control and MPPT, IoT-based PV monitoring and management, is to optimize the use of energy, improve reliability, adaptability, and operational efficiency. As the reviewed studies showed, the improvements are being achieved increasingly not through improving a single component of a PV system, but by combining harvesting technologies, control and management strategies and monitoring infrastructures.

A number of studies reviewed in this paper show that energy harvesting efficiency can be improved by various complementary methods for photovoltaic energy harvesting. Thermal management is an effective technique as shown by Prasetyo et al. [25], in which hybrid PV/T collector is used to enhance the electrical efficiency along with the recovery of useful thermal energy. Likewise, Elnozahy et al. [28] demonstrated that the use of nano-coating technologies could significantly cut down dust losses, and substantial increase in output power and conversion efficiency could be observed. The results of this work validate that temperature elevation and dust deposition are still significant problems for efficient PV performance. Concurrently, the works of Chakraborty et al. [29] and Silva et al. [30] highlight the need of the indoor PV technologies for low power electronics, wireless sensor networks, and IoT devices. The efficiency of indoor PV systems was greater than 30% under artificial light and they were capable of operating self-powered electronic devices. Further, Khernane et al. [17] highlighted the applications of PV harvesting to wireless sensor networks and smart agriculture, and Badawi et al. [32] showed the integration of PV harvesting with energy storage and wireless power transfer technologies. All these studies show that the research on PV harvesting is not only expanding from traditional solar power generation to application oriented and autonomous energy solutions, but that they are also becoming increasingly multifaceted.

The reviewed studies on the power electronic control and MPPT techniques clearly show the evolution of the conventional tracking techniques to the advanced optimization and adaptive control. Despite the above, classical techniques like Perturb and Observe are still popular because of their simplicity, lesser computation needs and easily implementable nature, as reported by Ali et al. [35] and as discussed in the review articles mentioned by Kumar et al. [18] and Mazumdar et al. [19]. These, however, still suffer from steady-state oscillations, slower convergence and decreased effectiveness in partial shading. More and more researchers have turned to optimization based and intelligent controllers as a result. Mohamed et al. [37], Oliveira et al. [38], Yuan et al. [39], and Abdelmalek et al. [41] reported significant improvements in tracking accuracy and efficiency with some methods reaching efficiency of more than 99%. Specifically, the Hermite Interpolation Optimization (HIO) technique suggested by Yuan, et al. and Grey Wolf Equilibrium Optimizer (GWEO) technique introduced by Abdelmalek, et al. [41] were found to perform very well under complex operating conditions. Likewise, Ghazi et al. [36], EL-Ebiary et al. [42], and Chnini et al. [43], discussed the emerging areas of adaptive control, reinforcement learning and intelligent nonlinear controllers in the advancement of PV power extraction. These methods offer great benefits in dynamic performance and robustness but in general they have higher demands on computational resources and more advanced implementation platforms. The algorithmic sophistication isn't the only factor that matters, as Chellakhi et al. [40] demonstrated: With proper design, low-cost embedded implementations can also provide high tracking performance.

The literature survey that has been performed on PV monitoring and management based on IoT technology shows a similar technological evolution. Initial research focused on cost of remote monitoring and maintenance. Njoka et al. [45]

reported the significant reduction in operation and maintenance cost by using remote supervision, which shows how economically beneficial it is to monitor with the help of Internet of Things. Similarly, Hamied et al. [47] and Alombah et al. [52] created low cost monitoring platform to collect operating data of PV systems and transmit it in real-time. More modern research has evolved and moved beyond just collecting data; monitoring systems now play a more dynamic role in research. Lakshmi et al. [46] applied machine learning algorithms for fault detection and prediction of maintenance; meanwhile, Demir [50] embedded predictive power estimation into a monitoring system based on the Internet of Things (IoT). Radia et al. [49] showed the feasibility of integrating open-source wireless communication, cloud-based visualization, environmental sensing, and remote-control capabilities. In addition, Ferlito et al. [51] suggested the scalable IoT-SCADA architecture for PV applications of scale using the concepts of edge and cloud computing to manage the utility-scale application. The recent works of Rao et al. [53], Rouibah et al. [54], and Shukla et al. [21], also showcase the convergence of cloud computing, edge processing, predictive maintenance, and intelligent systems management. The evolution of PV monitoring systems from passive observation to active decision support systems further suggests that they are becoming more than a simple tool for monitoring PV systems, but are also a tool for improving the efficiency and reliability of PV system operation.

A comparative analysis of the literature shows that PV energy harvesting, MPPT control and the monitoring technology in the IoT field are tightly connected. Although PV harvesting can be efficient, without optimum control strategies that are able to track the optimum operating point continuously, it is not possible to achieve a maximum system performance. Similarly, high level MPPT algorithms need accurate sensing and monitoring data to optimize their performance. The operational information from the monitoring systems that are built on the IoT is crucial for fault detection, predictive maintenance, performance analysis and adaptive control. Hence, future PV systems are anticipated to become energy platforms, with harvesting, control, communication and decision making closely intertwined. This integration is crucial where there is need of remote monitoring stations, smart agriculture, smart buildings, autonomous energy systems, and wireless sensor networks.

Although significant advances have been noted in the research studies reviewed, there are a number of limitations. First, many investigations involve a lot of simulation-based validation, especially on the MPPT optimization and advanced control algorithms. Model efficiencies often exceed 99%, but extensive field testing in realistic conditions is lacking. Second, optimization and intelligent control techniques are often more advanced, requiring more computation which can limit their use in low-cost embedded equipment. Third, cyber security, communication reliability, interoperability, scalability and data management issues remain challenges with IoT-enabled monitoring systems. Lastly, most of the studies are dedicated to energy harvesting, control or monitoring only, while only few studies are dedicated to a seamless integration of all three functions in a single PV architecture.

More research is thus needed on the development of integrated and holistic PV energy management systems, which integrate efficient harvesting technologies, adaptive power electronic control and intelligent monitoring infrastructures in an attractive framework. More focus is required on edge computing, lightweight control approaches, secure communication protocols, digital twins, predictive maintenance techniques and large-scale field trials. These will help to enable highly efficient, reliable, and independent PV systems that can meet the ever-increasing demand for renewable energy across all application areas of the smart city, industrial, agricultural, and IoT enabled infrastructure.

6. CONCLUSIONS

This review presented a comprehensive analysis of recent advances in PV energy harvesting, power optimization, and IoT technologies for PV systems, covering studies published between 2023 and 2026. The reviewed literature was systematically classified into three major research areas: PV energy harvesting technologies, power electronic control and MPPT techniques, and IoT-based PV monitoring and management systems. The analysis revealed that modern PV systems are increasingly evolving beyond conventional power generation platforms toward integrated energy solutions that combine efficient energy harvesting, advanced control strategies, and real-time monitoring capabilities.

A number of key trends were noted throughout the studies evaluated. The developments achieved in thermal management, hybrid PV/thermal systems; nano-coating technology, using PV technology in interior spaces, and integrating energy storage systems into PV energy harvesting are outstanding. These methods have shown significant energy conversion efficiency and system performance for various environmental conditions. MPPT techniques in power optimization have progressed from traditional methods like Perturb and Observe (P&O), Incremental Conductance (IC), optimization-based, adaptive, predictive and hybrid methods. Modern control strategies have been shown to be effective in maximizing PV power extraction in many recent studies with reported tracking efficiencies of over 99%. At the same time, PV monitoring has evolved from a data collection system to a cloud-based and edge-based system that can enable real-time monitoring, fault diagnosis, predictive maintenance, remote supervision and performance assessment. All of these advances suggest a highly dynamic and maturing research area with high technological convergence.

Yet there are a number of gaps to be filled. There are many proposed solutions that continue to depend on the validation by simulation or experimental prototypes of limited size, and there are still only limited large-scale deployments and long-term field testing. Moreover, issues of scalability, interoperability, cyber security, communication reliability, implementation cost, and standardization remain in the way of advanced PV system implementation. The review additionally uncovered that there was a major gap in research on integration of energy harvesting technologies, MPPT energy control, energy storage control, and IoT monitoring in a single PV platform. Besides this, there is no standard benchmarking procedure and consistent evaluations with identical operating conditions between different studies, which can make it difficult to compare performances.

Future research should be directed towards the development of highly integrated PV ecosystems, which should include efficient harvesting technologies, advanced power optimization strategies, energy storage management and IoT enabled monitoring in one operational unit. Other new technologies like edge computing, digital twins, low-power sensing platforms, secure cloud services, and standardized communication architectures will continue to improve PV system performance, reliability, and scalability. This review is useful for researchers, engineers and practitioners in the PV field, as it offers a structured classification of recent studies, quantitative comparison of significant technologies, an analysis of current trends, challenges and research opportunities. In the future, the integration of these advanced energy-harvesting strategies, high-performance power electronic control and IoT technologies will be essential to realize next generation efficient, reliable and sustainable PV energy systems.

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