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Internet of things important roles in hybrid photovoltaic and energy storage system: a review

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ABSTRACT

Renewable energy systems have become integral components of the electrical grid, offering environmental benefits and cost-effective power generation. Technological advancements have introduced internet of things (IoT) devices with robust data collection and execution capabilities. Solar photovoltaic systems, reliant on unpredictable solar radiation, require hybrid systems incorporating various renewable energy sources and energy storage to ensure system stability. Successful operation necessitates data gathering through IoT devices, which have played a crucial role in enhancing system sustainability. This paper provides a comprehensive review of the role of IoT in photovoltaic systems and energy storage, highlighting its significant contributions to system efficiency, fault detection, output prediction, system stability, and load management. The study underscores the critical dependence of advancements in the renewable energy sector on IoT systems.

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1. INTRODUCTION

In recent years, renewable energy has gained strong momentum worldwide due to its ability to support climate change. Renewable energy covers a wide range of technologies, including photovoltaic (PV), wind, hydroelectric, ocean, and biogas. The uncertainty of the weather conditions reflects the stability of the power network. To advance the stability of the network, a hybrid is deployed. The internet of things (IoT) plays an important role in advancing the efficiency, stability, and reliability of the network. The review under this paper highlights the surge in IoT deployments when it comes to generators, PV, electric vehicles (EV), Biogas, and communications between different renewable systems. The paper is divided into three sections: i) IoT in photovoltaic, ii) IoT in energy storage and EV, and iii) conclusions and future works.

This paper explores the critical role of the IoT in enhancing the stability and efficiency of renewable energy networks amid the global push for sustainable energy to combat climate change. Despite the inherent intermittency of renewable sources like solar and wind, hybrid systems integrating multiple renewable technologies with advanced IoT controls are showing significant potential. Recent advancements have expanded IoT applications across diverse energy segments, including photovoltaics, electric vehicles, and biogas plants, yet a comprehensive analysis of these integrations is lacking. Addressing this gap, this paper presents a novel analysis that not only highlights the individual benefits of these technologies but also their synergistic potential when combined, offering a holistic view of their collective impact on enhancing network performance and energy reliability. The unique aspect of this review is the integration of IoT applications across various sectors of sustainable technologies. No existing review has encompassed the combination of these technologies, as depicted in Figure 1. The review emphasizes the significant role that IoT plays and explores how IoT data can be leveraged to enhance the deployment of sustainable technologies.

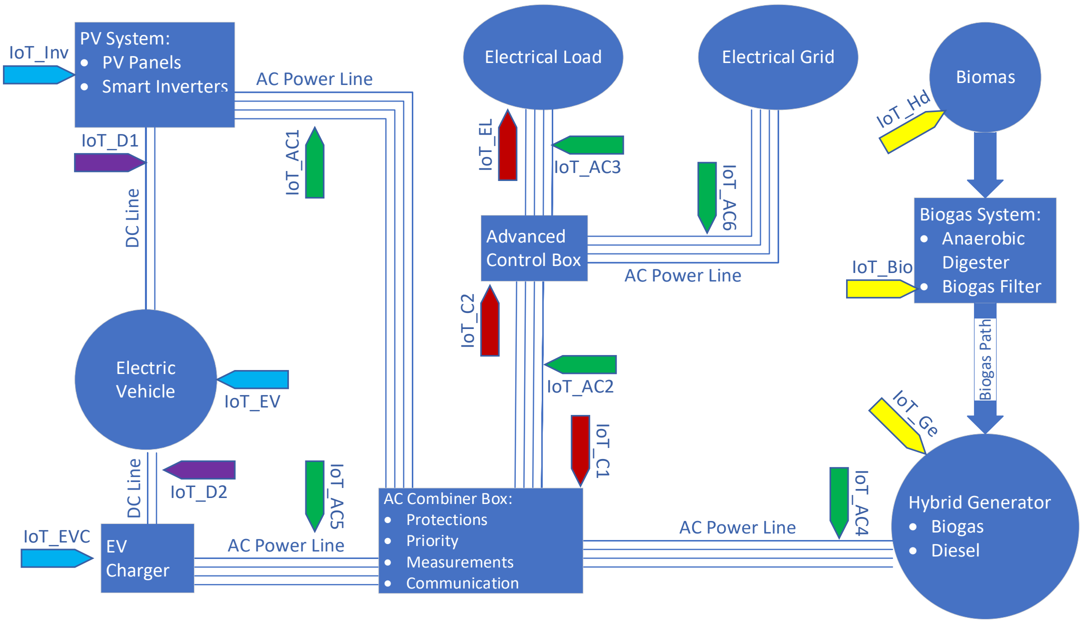

Figure 1. Hybrid proposed system under IoT review

2. IOT IN PV SYSTEM

2.1. PV system in agriculture

The current research addresses advancements in improving PV system efficiency and agricultural productivity using IoT applications. The use of the IoT can improve PV system efficiency [1]. The IoT allows for system automation and monitoring, which advances system maintenance [1], [2]. The research on smart monitoring of solar PV panels, smart agricultural applications for poultry farm surveillance, and IoT-based solar system monitoring for small farms demonstrate unique IoT applications focused on monitoring and improving efficiency [3]. Studies [3]–[5] focus on enhancing the efficiency of solar PV panels and regulating load by utilizing IoT-based monitoring. In study [3], the IoT-based solar-powered smart hydroponics system facilitates real-time monitoring and automated control of hydroponic lettuce growth, leveraging solar power for sustainability. The smart monitoring of solar PV panels in [4] optimizes solar panel performance through continuous data collection and analysis, ensuring efficient energy production and proactive maintenance. The work in [5] monitors and regulates environmental conditions using a mobile app integrated with a solar PV system to minimize energy consumption. While all researcher works mentioned in [1]–[6] used IoT for collecting and analyzing data, they serve different purposes and objectives, ranging from enhancing energy generation to overseeing agricultural settings. The IoT can also support artificial intelligence to advance irrigation for urban agriculture [6]. The literature identifies challenges and solutions in IoT-based systems: hydroponics [3] requires reliable power supply, addressed by solar integration and real-time monitoring; solar PV panels [4] need efficient maintenance, improved by IoT-based proactive measures; and poultry farms [5] face energy efficiency issues, mitigated by using IoT and mobile apps for environmental control. These solutions enhance system sustainability and operational efficiency. The literature highlights key challenges and solutions in IoT-based systems. For hydroponics, continuous power supply and system reliability are enhanced by integrating solar power with grid backup and real-time monitoring [3]. Solar PV panel efficiency and maintenance issues are addressed using IoT for real-time data and proactive maintenance [4]. In poultry farms, energy efficiency is improved by using IoT and mobile apps to control environmental parameters, reducing energy consumption [5].

2.2. Fault detection in PV systems

Recent literature discusses various techniques for integrating IoT and machine learning technology into monitoring and detecting issues in solar PV systems. The IoT deployment can be used for fault detection using fuzzy logic [7], and its output can be fed to a centralized cloud-based artificial neural network (ANN) for forecasting critical elements that impact efficiency [8]. In addition, the works in [9], [10] provided an IoT platform for fault detection, power generation predictions, and the detection of anomalies in real-time by using multiple machine learning models. In [9], an IoT-based PV panel cooling system was developed, using Arduino to control cooling fans and boost efficiency by 4.7%. In study [10], a hybrid solar panel with thermoelectric generators (TEG) was designed to harvest waste heat, improving overall PV system efficiency and providing sustainable cooling. The work in [10] presents "SolNet," which utilizes convolutional neural networks to detect faults in solar PV systems, demonstrating an AI-based method to improve accuracy in identifying anomalies. The study in [11] delves into a two-stage model-based prediction framework designed for solar energy forecasting, with a focus on enhancing predictive accuracy for energy management. A flexible IoT open-source hardware and software solution is introduced in [12] for tracing the I-V curves of PV generators. The emphasis is on flexibility and accessibility in performance analysis. Source [13] presents an IoT-driven semi-supervised learning method for diagnosing faults in solar PV arrays without requiring sensors, aiming to improve reliability and efficiency. In [13], a novel IoT-based I-V curve tracer for photovoltaic generators was developed using a Raspberry Pi, Python, MariaDB, and Grafana. The system automates load sweep, data acquisition, storage, and real-time visualization, enhancing PV module monitoring and characterization under real operating conditions. The study [14] examines an IoT solution for a dust cleaning system tailored for PV panels, to enhance solar performance by implementing routine maintenance. The study in [15] presents a novel approach, merging decision trees and light gradient boosting (DT-LGB), to identify and forecast malfunctions in solar power facilities through IoT technologies. The DT-LGB model surpasses current approaches, demonstrating significant enhancements in error measures. The works in [16] explore fault detection in photovoltaic systems utilizing sophisticated fuzzy nonlinear autoregressive network with exogenous input (NARX) neural network methods, each with distinct emphases. It utilizes a tree search method for accurate fault categorization, making use of IoT for automation and remote supervision. To develop a low-cost IoT-based sensor for fault detection, the works in [17] employ machine learning (ML) and sensors to examine defects at the module level in PV systems. Although the performance of the neural network model was commendable, it still encountered difficulties when confronted with illumination conditions, which necessitated additional data gathering to enhance classes.

The reviewed literature highlights various challenges and their resolutions through IoT in several IoT-based systems from papers [7]–[17]. In [9], overheating of PV panels reduces efficiency, which was mitigated by an IoT-controlled cooling system using Arduino. In [10], the challenge of energy loss in PV systems due to heat was addressed by integrating thermoelectric generators (TEGs) for energy harvesting, with the IoT facilitating real-time monitoring and control. In [13], the development of an IoT-based I-V curve tracer for PV generators helped automate load sweep and data acquisition, improving system monitoring and maintenance. These studies demonstrate the effectiveness of IoT in enhancing system reliability, efficiency, and maintenance.

2.3. Real-time monitoring and optimization

Using IoT technology to monitor and optimize the PV system is widely used within current research. The works in [18] describe a system for real-time monitoring of solar photovoltaic (SPV) systems. The IoT application enables smooth data transmission and reception by utilizing node microcontroller unit (MCU) programming in the C programming language and Android App Studio. This offers scalability and the possibility of grid integration. The approach in [19] emphasizes the current condition of the solar panels and integrates cloud computing for data analysis and storage. The work in [20] adopts an alternative method by utilizing remote monitoring and control units to support preventive maintenance and fault detection. The system makes use of general packet radio service (GPRS) for data transmission, highlighting the remote capabilities and cost-effective monitoring of solar PV systems. The work in [21] discusses a load management strategy that shifts the load between the main grid and the solar system depending on demand and supply factors.

The works in [22]–[24] focus on how IoT can advance system efficiency through real-time monitoring of numerous elements, including voltage, current, and temperature. In [22], a smart IoT-based system was developed for monitoring and controlling solar PV systems. In [23], a hybrid solar PV and thermoelectric generator system was designed to enhance energy harvesting. In [24], an IoT-based smart grid was implemented for bidirectional power flow, smart energy metering, and home automation. For data transmission, the work utilizes mobile apps to access the cloud [23] or GPRS [19]. Numerous researchers have focused on improving PV monitoring using IoT. A monitoring framework for large-scale solar power plants was introduced in [24]–[26]. Investigating the impact of temperature on solar panel efficiency, the research in [27] explores an IoT-based cooling solution incorporating an energy storage system (ESS) to address efficiency reductions. Through the integration of a cooling fan controlled via IoT for real-time temperature management and the exploration of ESS with supercapacitors for efficient power, the study seeks to improve solar panel performance by tackling thermal challenges with innovative cooling methods and IoT technology. The hybrid PV system is well deployed, and IoT in the hybrid system is well established. The work in [9], the researchers investigate the development and optimization of a hybrid solar panel system that integrates thermoelectric generators (TEGs) with PV panels. The text provides a comprehensive overview of the design process, incorporating TEGs and IoT components to improve energy efficiency. It also explains the assembly concept for production. This comprehensive approach focuses on maximizing energy harvesting in solar panels, showcasing notable progress in solar energy technology. The IoT roles in PV systems include matching load and generation by utilizing machine learning, real-time monitoring, and web interfaces [10], [28]. The study in [29] discusses the importance of monitoring in remote rural regions by suggesting a system that not only tracks the performance of the PV system but also enables remote control to enhance access to dependable electricity in underserved areas. The work in [30] analyses hybrid smart grids that integrate solar microgrids with IoT, enabling efficient energy exchange between households and enhancing grid stability. Through real-time monitoring and emergency backup, these systems ensure reliable power supply, utilizing components like solar panels, batteries, and hybrid ultra capacitors (HUC) to manage fluctuations in demand. The literature review of papers [17]–[30] highlights key innovations in solar energy systems. Many studies integrate IoT for real-time monitoring, control, and maintenance [10], [17], [22], [24], and develop hybrid systems with thermoelectric generators to enhance energy harvesting and cooling efficiency [18], [23], [10]. Remote monitoring and maintenance using wireless sensor networks are emphasized for managing solar installations in remote areas [22], [24], [10], [30]. Advanced energy management systems optimize usage and minimize losses [20], [29], while innovative cooling solutions address overheating issues in solar panels [17], [18], [28]. These advancements collectively enhance the efficiency, reliability, and sustainability of solar energy systems.

2.4. Monitoring and control innovations

Within the realm of optimizing solar PV systems, researchers present novel approaches that leverage IoT technologies. The message queuing telemetry transport (MQTT) protocol is utilized by Aagri and Bisht [31] to facilitate secure and effective communication between PV monitoring nodes and a central gateway. The primary objective of this system is to enhance real-time monitoring capabilities and reduce data loss, with a specific emphasis on managing log data for IoT gateways. On the other hand, the emphasis of [32] is on error measurement analysis and real-time monitoring via an IoT-based platform and ThingSpeak for data visualization; this enables prompt adjustments to system performance and improved precision in administration. By integrating a suite of IoT technologies, including ultrasonic and partial discharge sensors, into solar PV plant distribution transformer health monitoring systems [33], the applications of these systems vary. The objective of this multi-technology strategy is to proactively detect and resolve system malfunctions. The IoT role is also combined with smart meters and home automation to advance system capability [34]. The intelligent IoT platform for monitoring and controlling PV power plants is introduced in the [34] paper; it utilizes peripheral computing and cloud services to manage data across multiple installations. It integrates artificial intelligence (AI) for forecasting, predictive maintenance, and improving the administration of renewable energy.

The work in [35] describes a novel IoT module developed as part of the COPILOT-CM initiative to improve the performance of PV systems. This module provides an all-encompassing software and hardware solution for individual PV panels, facilitating functionalities such as autonomous diagnosis, reconfiguration of efficiency, and meticulous monitoring. An IoT-based framework is proposed in [36] as a means to improve solar PV systems integrated into smart home micro grids (SHMG). The implementation of AI for precise prediction and IoT for streamlined data processing is intended to enhance control and decision-making regarding distributed PV systems. The work in [37] investigates the progress made in solar PV technology, with a specific emphasis on designs of high-efficiency solar cells, including passivated emitter and rear cell (PERC), passivated emitter, rear locally diffused (PERL), heterojunction with intrinsic thin layer (HIT), and tunnel oxide passivated contact (TOPCon). The research in [38] presents an innovative approach for low-power IoT devices across diverse indoor environments for PV systems. Using IoT and cloud infrastructure, the work in [39] investigates a centralized system for real-time monitoring and administering distributed PV for stability and efficiency. Vujović *et al.* [40] investigate adaptive intelligent controller-based maximum power point tracking (MPPT) methods for standalone low-cost PV systems. It highlights the challenge of maintaining MPPT algorithm performance in fluctuating environmental conditions and emphasizes the need for intelligent, cost-effective MPPT controllers to mitigate ecological disturbances.

The literature from papers [30]–[40] reveals common innovations in solar energy systems, emphasizing IoT integration for real-time monitoring and control [33], [38], [40], and leveraging AI for enhanced performance and decision-making [36], [37]. Key themes include system efficiency and optimization through smart micro-grid architectures and IoT modules [37], [38], as well as scalability and remote accessibility to improve renewable energy deployment in diverse environments [31], [38]. These advancements collectively enhance the reliability, efficiency, and sustainability of solar energy systems.

2.5. System analysis and optimization

The investigation in [41] employs ANNs and numerical current prediction (NCP) to substantially improve the accuracy of parameter estimation in comparison to conventional techniques. By utilizing time series data on voltage and current from IoT devices, this methodology enhances the predictive accuracy of the ANN for the maximum power point (MPP) and improves fault diagnosis capabilities in photovoltaic panels. Another study in [42] introduces an innovative approach to remote sensing-based PV panel detection by utilizing photovoltaic index (PVI) and rotating cross-hair algorithm method (RCHAM) to effectively distinguish PV panels from complex backgrounds; this is validated by a high F1-score. Using IoT software for data visualization, the study in [43], [44] compares digital and analogue temperature sensors for monitoring the operational temperature of PV panels. This is achieved by integrating cutting-edge sensor technology with the IoT to improve monitoring capabilities and overall system performance. The researchers in [45] used the IoT for automated control to increase the efficacy of power production in hybrid renewable energy systems. By integrating IoT and artificial intelligence, this paper seeks to improve the extraction of energy from renewable resources.

Papers [41]–[45] introduce innovations in solar energy systems, focusing on hybrid PV/TEG systems for enhanced energy efficiency, real-time monitoring, and IoT for predictive maintenance and performance optimization. They also incorporate advanced automation and machine learning for energy management and predictive analytics. These innovations collectively aim to improve energy efficiency, reliability, and sustainability through the integration of IoT and smart technologies in solar power systems.

3. IOT IN ENERGY STORAGE AND ELECTRIC VEHICLE

The global shift to renewable energy presents challenges in managing intermittency [46], especially with technologies like photovoltaic relying on unpredictable weather conditions [47] and being limited to sun hours [48]. Robust energy storage solutions have become crucial to address renewable intermittency, storing excess energy during abundance and releasing it when needed [49]. This section explores the synergy between electric vehicles (EVs) and IoT systems in current energy storage technologies [50], [51]. The work in [52] conducted a comprehensive review of integrating energy storage technologies with renewable energy to empower smart grids, highlighting their critical role in enhancing grid reliability and efficiency. Similarly, Suberu *et al.* [53] reviewed emerging energy storage solutions, emphasizing their importance in ensuring the reliable operation of smart power systems.

The integration of EVs enhances storage capacity, and IoT systems provide real-time monitoring for optimized energy solutions [54], [55]. The following subsections aim to comprehensively review the roles played by IoT in energy storage, focusing on electric transportation. Energy storage advances the role and the power stability of renewable energy systems [56]. Also, it allows for storing the surplus generated power of the renewable energy system [57].

Integrating renewable energy into existing grids presents challenges, such as maintaining stability and the need for advanced storage solutions [49], [52]. Effective solutions include utilizing intelligent algorithms for short-term photovoltaic energy prediction [52] and ensuring system reliability with accurate solar radiation data [51]. Additionally, optimizing energy distribution and enhancing system dependability are vital for efficient grid integration and reliable operation [53], [55]. These efforts collectively address the critical issues of managing and integrating renewable energy sources [55], [57].

4. IOT IN ELECTRIC VEHICLES STORAGE SYSTEM

The electric vehicle relies on stored battery energy for operation [58], with numerous studies exploring bi-directional power flow [59]. Commonly used are lithium-iron phosphate batteries, allowing EVs to serve as energy storage for renewable systems [59], [60]. Battery management systems (BMS) are essential [61], functioning as command centers to monitor and regulate key parameters for safety [62]. Research highlights BMS, which includes IoT devices, overseeing individual battery cell health, and ensuring safe thresholds [63]–[65].

IoT work in electric vehicle battery management has advanced significantly, focusing on health monitoring and performance optimization. In [65] and [64] highlighted innovative strategies for enhancing battery longevity and efficiency, while [65] emphasized the importance of continuous health monitoring using IoT technologies. These advancements collectively improve electric vehicle performance and reliability. Overcharging lithium cells can lead to thermal runaway, triggering hazardous outcomes, including the release of flammable electrolytes, swelling, rupture, fire, or explosion. In [66], [67] IoT work in electric vehicle battery management includes significant advancements in health management and thermal runaway mitigation. The work proposed by [66] reviewed IoT-based health management systems for lithium-ion batteries, focusing on improving battery longevity and reliability. The work proposed by [67] discussed mitigation strategies for thermal runaway in Li-ion batteries, emphasizing the role of IoT technologies in enhancing safety and performance. Through continuous oversight, the BMS ensures batteries operate within optimal conditions, contributing to EV's overall safety and durability [68].

Integration with the IoT enhances BMS capabilities, enabling real-time monitoring of battery parameters like temperature, voltage, and state of charge during charging [69]. In an IoT-enabled EV with a BMS, proactive management occurs as the IoT system dynamically adjusts charging rates based on detected temperature changes, thereby enhancing safety and extending the battery lifespan [70]–[72]. Environmental sensors, including temperature, humidity, load, and voltage sensors, are crucial for real-time monitoring in energy storage systems [73]. In electric vehicles, IoT sensors continuously monitor battery temperature [74]. For instance, during charging, if IoT sensors detect a temperature rise, the system automatically adjusts the charging rate to prevent overheating, safeguarding the battery and ensuring optimal performance [75]. Voltage sensors provide insights into the electrical potential across the system, while load sensors measure system demand, and environmental sensors monitor ambient conditions [76]. In a proposed scenario [77], where the energy storage system integrates into a solar-powered microgrid, load sensors detect unexpected demand surges. The IoT system responds by adjusting the discharge rate to meet heightened demand, and environmental sensors monitor temperature during high usage [51], [78].

Data collected by the IoT is sent to a monitoring system or decision algorithm [79]. This process, under the cloud computational approach, utilizes platforms like those from advanced microgrid solutions, centralizing oversight and optimization of energy storage and EV power systems [80]. These platforms leverage cloud computing to efficiently process data generated by sensors and monitoring devices across energy storage and EV systems [81], [82]. Real-time information on energy production, storage capacity, and system health is securely transmitted to the cloud platform [83]. The cloud-based platform securely stores incoming data from IoT in centralized databases [84], with scalability for efficient handling of large datasets, ensuring accessible historical and real-time information [85]. Remote accessibility for operators and system managers empowers informed decision-making, system parameter adjustments, and the initiation of maintenance protocols based on analyzed data [86], [87]. The platform's scalability handles the increasing volume and complexity of data from a growing number of distributed energy resources [86]. In a utility company's research [88], a proposed cloud-based platform optimizes distributed energy storage systems. By analyzing data trends collected from IoT, it suggests charging schedule adjustments for peak demand, enhancing grid stability [89]. Real-time data access enables proactive maintenance, optimizing efficiency for energy storage and EV systems [90].

With the aid of IoT, substantial challenges in managing electric vehicles' batteries have been effectively addressed. These include implementing effective health management systems [66], devising strategies to mitigate thermal runaway in Li-ion batteries [67], and addressing concerns regarding battery fires and explosions [68]. Additionally, IoT has facilitated battery monitoring systems [70] and battery management system functionalities for EVs [71]. Intelligent algorithms and control strategies for battery management systems have also been developed [72], along with risk management frameworks for lithium-ion batteries in EVs [73].

4.1. IoT-based battery system monitoring

In the realm of battery system monitoring within the IoT framework, the integration of various sensors is pivotal for real-time data acquisition, ensuring optimal operation and maintenance [91]. The gathered data is securely transmitted to the battery management system (IoT-BMS) cloud, an integral component of the broader network infrastructure [92]. The integration of IoT technologies in the proposed work [93] facilitates real-time monitoring and analysis of battery performance through the IoT-BMS cloud. Acting as a centralized platform, it aggregates and analyzes extensive sensor data, enhancing EV efficiency and reliability. This cloud-based system facilitates real-time monitoring, analysis, and optimization of battery system performance [94]. It acts as a repository for historical data, enabling trend analysis and pattern identification for informed predictive maintenance strategies [95], [96]. The connectivity between the IoT-BMS cloud and the maintenance center ensures immediate access to critical information for relevant stakeholders. This seamless integration enables a proactive maintenance approach, allowing timely responses to potential issues and optimizing the overall reliability and efficiency of the battery system [97]. The integration of IoT in smart energy systems proposed in [91] allows for real-time monitoring and optimization, enhancing grid stability and reducing energy waste. IoT-based battery management systems (BMS) [92] for hybrid EVs offer proactive monitoring, optimizing battery performance, and extending longevity. Cloud-based BMS data analytics [93] enable insights into EV battery health, enhance reliability, and optimize charging strategies. IoT-based battery monitoring systems [95], [96] provide real-time monitoring and proactive maintenance, improving EV reliability and driving range. These advancements collectively optimize energy usage, extend battery lifespans, and promote sustainable transportation.

4.2. AI integrated IoT sensors for energy storage

AI-integrated sensors, enhanced by machine learning algorithms, revolutionize energy storage systems [97]. The innovative works in evolving computing paradigms [98] encompass advancements in cloud, edge, and fog technologies, enhancing efficiency and scalability. Deep learning methods for sensor-based predictive maintenance [99] revolutionize fault detection and optimize maintenance schedules, ensuring equipment reliability and longevity. Practical adoption of cloud computing in power systems [100] addresses challenges and offers guidance for real-world implementation, improving grid management, and reliability. These sensors monitor vital parameters and predict potential issues, showcasing adaptability in various applications, from industrial to residential settings [101]–[105]. Edge computing, exemplified by NVIDIA's Jetson series, facilitates swift data processing, enabling immediate responses to grid conditions and increased efficiency in managing demand surges [102]–[105]. The AI and edge computing capabilities advance machine learning, predicting energy usage patterns for optimized charging and discharging cycles [106]–[108]. Inspired by Google's DeepMind, machine learning optimizes energy storage operations, responding dynamically to grid conditions and enhancing overall system performance [108]. Advanced predictive analytics, powered by sophisticated algorithms, utilize continuous learning from datasets, optimizing maintenance planning and improving system reliability [109]. The issues resolved using IoT span across evolving computing paradigms [98], predictive maintenance [99], practical cloud computing adoption [100], hybrid AI-based techniques [101], and advancements in materials and machine learning for energy storage devices [102]. Additionally, IoT facilitates AI-driven computing [103], advanced controls for energy-efficient buildings [105], and optimization of power consumption in data centers [108]. Furthermore, IoT applications extend to wireless sensor node systems for electricity monitoring [109] and machine learning at the network edge [110], enhancing efficiency and sustainability across various domains.

4.3. IoT in smart renewable energy systems

In the era of Industry 4.0, smart grids, utilizing renewable energy, benefit from IoT-integrated smart inverters, enhancing communication and coordination [111], [112]. These advanced inverters, with IoT features, enable real-time monitoring and intelligent decision-making for efficient renewable energy integration [111]. During low demand, IoT-enabled systems optimize energy storage charging rates based on environmental conditions [112]. In residential solar systems, smart inverters with IoT optimize charging rates and adjust discharging, contributing to grid stability [113], [114]. IoT-enabled communication modules serve as hubs for coordinated operations among storage units, electric vehicles, and the grid [115], [116]. Safety monitoring devices with sensors ensure secure operations by detecting deviations and triggering immediate responses, as seen in commercial energy storage systems [117]–[120]. Blockchain integration enhances security and transparency, reducing fraud risk and enabling decentralized energy trading platforms [117]–[120].

To ensure IoT deployment is environmentally friendly, green IoT sensors are introduced. The green IoT sensors, designed for environmental sustainability, use eco-friendly materials to mitigate impact [121]. Their manufacturing emphasizes recyclable and sustainable materials, reducing non-renewable resource extraction [122]. They prioritize energy efficiency, optimizing power consumption, and lessening reliance on energy-intensive processes [123]. Notably, their recyclability promotes a circular economy, allowing simple disassembly and reuse [124]. Reduced toxic materials address environmental and human health concerns during disposal [125]. A practical implementation [126] deploys green IoT sensors in an environmental monitoring system, measuring critical parameters with minimized environmental impact [127], [122]. Importantly, at the end of their lifecycle, simple disassembly and recycling actively prevent electronic waste accumulation [123]. IoT has addressed significant challenges across various sectors, including optimizing artificial lift systems in petroleum extraction [111], enabling long-term deployable wireless sensor networks through energy scavenging [112], and enhancing smart-grid efficiency with solar energy harvesting [113]. Moreover, IoT-enabled distributed energy systems contribute to grid peak-shaving and optimization [113], perpetually powered sensor networks for environmental monitoring [115], and connectivity evolution in the automotive industry [116]. Additionally, IoT advancements have improved system health management in aerospace applications [117] and safety management across industries [118]. Furthermore, IoT has played a crucial role in developing multifunctional energy storage devices [119], addressing thermal safety concerns in lithium-ion batteries [120], and implementing blockchain-enabled applications for smart grids [121]. These advancements collectively contribute to building a more sustainable and interconnected world.

5. METHODOLOGY/DISCUSSION

This research employs a combination of novel and standard experimental methodologies to explore the impact of the IoT on hybrid renewable energy systems. It involves deploying IoT devices across various energy segments to collect real-time data on system performance and environmental conditions. Integration of these IoT systems allows for automated control and optimization of energy distribution. The data is analyzed using statistical and machine learning techniques to evaluate the improvements in energy efficiency and system stability, with experimental setups replicated across different settings to ensure reproducibility and consistency of results. The methodology, detailed with theoretical and empirical justifications, is designed to be transparent and reproducible, allowing for the validation and verification of the findings within the field.

6. DISCUSSION

This research underscores the significant enhancements that IoT integration brings to hybrid renewable energy systems, aligning with our hypothesis that IoT can mitigate the intermittency of renewable sources through real-time data and responsive controls. Our findings are consistent with prior studies but extend their scope by demonstrating comprehensive improvements across various energy segments, including photovoltaics, energy storage, and electric vehicles. While the study confirms the methodological rigor and innovative application of IoT, it also identifies limitations such as device-specific dependencies and potential latency issues that could affect system responsiveness. Conclusively, the research highlights the transformative potential of IoT in renewable energy systems and suggests future exploration into the scalability of these technologies, focusing on interoperability and security to enhance system robustness and applicability globally.

This study highlights the significant role that IoT technologies play in improving the efficiency and stability of hybrid renewable energy systems. Our findings support the hypothesis that integrating IoT can effectively counter the unpredictable nature of renewable energy sources, such as solar and wind, by using real-time data monitoring and adaptive controls. This research adds a broader perspective compared to previous studies, which often focused on specific aspects of renewable energy. By examining IoT's impact across different energy segments, we offer a more comprehensive view of how these technologies can enhance the energy sector. However, this study has limitations, including a dependence on certain IoT setups that might not work everywhere, suggesting that further tests are needed to confirm these results in other settings. The integration of IoT within renewable energy systems holds great promise for improving energy management globally. The findings encourage continued research into optimizing IoT technology, making it more scalable and secure. Future studies should investigate overcoming the identified challenges, pushing forward the development of effective and adaptable IoT solutions that can be applied widely across the renewable energy sector.

7. CONCLUSION

Renewable energy is an essential tool for a cleaner future. The hybrid system between different types of renewable energy, energy storage, and generators is deployed worldwide. The promising increase in electric vehicle deployment offers energy storage for the hybrid renewable system. Due to the uncertainty in weather conditions, which impacts the PV system output, smart automation is a must to ensure system stability and availability. The IoT plays a critical role when it comes to system operation, increased efficiency, and advanced stability. Also, the advancements in AI and ML support smart IoT systems, which will in the future increase their importance to the hybrid network. Based on the cited works, without the presence of the IoT, it will be very difficult to manage a wide range of sources, monitor numerous parameters, and perform tasks across a wide network with different constraints. Therefore, IoT technology forms an indispensable part of current and future renewable energy systems.

Moreover, driven by the information in the review, integrating IoT data with a smart controller can enhance the stability and sustainability of the system. Improving the stability of one section can positively impact the stability of the entire setup. This can be effectively accomplished through the utilization of advanced automation with machine learning capabilities.

This research underscores the critical role of the IoT in enhancing hybrid renewable energy systems. Integrating IoT with machine learning and artificial intelligence is crucial for managing and optimizing these systems amidst the unpredictability of weather conditions affecting energy outputs. IoT's real-time monitoring and control capabilities are essential for the efficient operation and strategic management of expansive energy networks. As renewable energy continues to be a key component of a sustainable future, the deployment of hybrid systems that combine various energy sources with storage capabilities and generators is becoming more widespread. This study has demonstrated that IoT is essential not just for the operation of these systems but also for their strategic management and enhancement. IoT enables the real-time monitoring and control of numerous parameters across expansive networks, which would be exceedingly complex without such technology. Future enhancements in IoT, particularly through advanced automation and smart controllers, promise to improve system stability and sustainability. In conclusion, the ongoing development of IoT technologies is vital for transforming renewable energy systems, emphasizing the need for further research into their scalability, reliability, and security. This progress is expected to yield significant benefits, enhancing energy efficiency and stability for communities worldwide.

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