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Internet of things towards a renewable energy systems future: Potentials, Limitations, and Future Trends

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Abstract

The rising growth of renewable energy systems has increased the demands for efficient monitoring, control, and management systems to cope with issues associated with intermittency, reliability, and energy efficiency. In this perspective, the Internet of Things (IoT) has gained prominence as an enabler of real-time data acquisition, smart analytics, and seamless connectivity for decentralized energy systems. This paper provides a thorough assessment of the implications of IoT applications for shaping a sustainable future for renewable energy systems through a critical evaluation of its pros, cons, and new trends. The research work explores the intensification of energy management, maintenance, fault detection, energy theft protection, and smart grid integration through IoT, aiming at enhancing operational efficiency and robustness of energy systems. In addition, actual applications of IoT technology for solar, wind, hydroelectric, and battery-based energy storage systems are examined through real-life examples of various applications of IoT technology. However, this study identifies important limitations of IoT technology, including issues of data privacy, security, scalability, increased energy consumption, and higher technology costs for sustainable applications of IoT technology. Finally, future research development of integrated applications of IoT with intelligence, machine learning, edge computing, blockchain technology, and next-gen communication systems is discussed. The result of this work reveals that with proper technological development, IoT technology has an important role to play for shaping a sustainable, efficient, and reliable future for renewable energy systems.

1.Introduction:

With the growing need for energy across the globe, along with the need to cut down greenhouse gas emissions, there has been a rapid shift towards the development of power systems based on renewable energy resources. Renewable energy resources like solar energy, wind energy, hydro energy, and biomass energy are well established alternatives to fossil fuel-based energy, but the implementation of these energy resources on a large scale faces various technological issues, such as handling intermittency, real-time monitoring, and energy management [1], [2].

In recent years, the Internet of Things (IoT) has been recognized as a revolutionary technology within modern energy systems. IoT helps create the interconnectivity of physical objects with the assistance of sensors, communication technology, and computing intelligence, which makes it feasible to monitor and control energy resources in real time [3], [4]. In the renewable energy domain, the role played by the Internet of Things has been vital in improving efficiency and helping achieve smooth interconnectivity of distributed energy resources [1], [2], [5], [6].

IoT technology has also gained significant attention for its incorporation with renewable and smart energy networks. There were certain early

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works that proposed the development of cyber-physical and Internet-of-Energy technologies for the integrated management of renewable energy resources, their storage, as well as their consumption through efficient communication and control systems [7, 8]. These ideas were further expanded into more sophisticated smart grid models that utilise IoT technology for facilitating mutual energy and information flow, as well as improving self-healing functionality within smart energy grids [9, 10]. Various researches were conducted, showing that IoT technology can enhance energy efficiency, reliability, and sustainability within energy generation, transmission, and supply systems [11, 12].

Besides grid-level implementations, IoT has been increasingly used in the context of wind/solar hybrid power systems, smart city developments, and sustainable urban energy management systems. Since IoT facilitates the monitoring of renewables as well as consumers in a real-time environment, it helps with smart dispatches, minimizing carbon emissions, and quality enhancement in a smart as well as sustainable city environment [13], [14]. Further developments on IoT architecture and vision have led to significant recognition regarding the role played by IoT in supporting transformations in various sectors like the energy sector [15], [16].

The fusion of IoT with other emerging and rapidly evolving digital technologies has also widened its applications. AI and machine learning have improved IoT systems by providing smart analytics, forecasting, control, and decision-making capabilities in a renewable dominant electricity network [17]-[19]. Edge computing has also been brought into use to address the issues of latency and scalability in IoT by processing data closer to its source, thus enhancing real-time processing and diminishing the need for communication in IoT applications [18], [20]. AI-based IoT applications have also been found to increase the intelligence of smart energy grids by a substantial margin [21], [22].

IoT-based fault identification and condition monitoring in renewable energy sources has become an important aspect in the sustainability of renewable energy resources. This technology facilitates early fault identification, accurate fault location, and remote predictive diagnostics in renewable energy sources, such as solar energy, wind energy, and city power [23], [24]. Successful implementations in smart domestic applications, industrial power systems, and environment monitoring have been highlighted in various publications to show the universal adoption of IoT technology [25], [26].

Energy efficiency and sustainability issues also promote the development of green and self-sustaining IoT solutions, where energy harvesting and energy-efficient transmission methods are utilized to ensure that the IoT system leaves a small environmental footprint [27], [28]. On the other hand, industrial and agricultural IoT applications have proven the scalability and reliability of IoT network architectures under various operating conditions [29]-[32]. Notwithstanding the abundant connectivity in the energy domain, there exist severe concerns regarding IoT security, privacy, and sustainability, which stimulate active research on secure IoT architecture designs and blockchain-enabled sustainability mechanisms [33], [34].

Advancements in communication technology, such as 5G and upcoming 6G communications, further enhance the importance of IoT in the renewable energy sector as it promotes ultra-reliable, low-latency, and high-capacity communication [35], [46]. Explainability in AI, network automation, and Industry 5.0 practices are currently influencing the design of next-generation IoT-based energy facilities [36], [48]. Recent research studies clearly highlight that the integration of IoT, AI, blockchain, and advanced communication technology is urgently required in order to acquire carbon neutrality, decarbonization, and sustainability in the energy sector [37], [42], [44]. Yet, several challenges exist in spite of the developments. These include the lack of compatibility, the high cost of installation, scalability, and the lack of frameworks for large-scale implementations [49]–[52]. Consequently, a broad knowledge on the prospects and future developments related to IoT is imperative for assisting researchers and practitioners in the field. Based on such considerations, this paper is intended to offer a full review on using IoT for renewable energy systems, with regards to technical capabilities and future research. By integrating recent progress on sensing, communication, intelligence, and security for IoT, this research is anticipated to play a role in fostering robust and sustainable energy solutions with the support of Internet of Things.

2.Potentials of IoT in Renewable Energy Systems:

The integration of Internet of Things (IoT) technologies into the renewable energy sector holds a lot of promises for improving the efficiency,

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stability, and sustainability of contemporary power networks. IoT makes possible the use of an interconnected network of sensors, smart meters, and intelligent controllers to acquire and control data in real-time, and the ability to do the aforementioned is paramount for managing the inherent variability and distributive nature of solar and wind energy technologies [1], [2], [6]. Figure 1. Demonstrates the potential of Iot in renewable energy systems.



Figure 1. IoT in renewable energy systems.

The most promising areas where the IoT can contribute are energy management systems. The real-time monitoring and tracking capabilities of the IoT will help optimize energy consumption to a large extent. The insights provided by smart energy management systems using the IoT technology will help optimize energy consumption and avoid inefficiencies. This is extremely necessary to ensure the increased integration of renewable energy resources into the power system. The energy management system using the IoT will help track energy consumption effectively [3], [9], [51]. Predictive maintenance is yet another important benefit that can be derived from the usage of the IoT paradigm within the energy and renewable sector. With the parameters of the system being monitored on a consistent regular basis, which may include temperature, voltage, vibration, and power, it becomes easier to predict system failures that may occur due to abnormalities. Therefore, predictive maintenance becomes more of a reality through analytical models and machine learning algorithms used on data produced by the IoT [7], [10], [23].

IoT is also an important factor involved in the integration of various forms of renewable energy with smart grids. IoT-based smart grids facilitate two-way communication and control, that is, real-time balance of supply and demand, energy routing, effective coordination of distributed energy resource systems, and energy storage systems, thereby increasing grid flexibility, stability, and resilience, especially for a grid with a dominant share of renewable energy sources [8], [12], [44]. The integration of IoT with modern communication networks further boosts intelligence levels in the grid and its operational reliability [42].

Microgrids are another crucial area where IoT has a significant potential. IoT-based control and management systems allow microgrids to work independently or in conjunction with the macro-grid and even improve the resilience related to energy in remote or rural areas or areas prone to natural disasters. By employing intelligent sensing and distributed control systems, IoT helps in the reliable operation and optimal power sharing in a microgrid [14], [49], [50].

Furthermore, IoT also improves energy storage management in a way that is very important in reducing the intermittency of renewable energy resources. This is because IoT-based energy storage management, in terms of the state of charge, temperature, and aging behavior of batteries, can help in the optimization of charging and discharge operations, thus improving energy storage system efficiency and longevity [10], [52].

Engagement of consumers is another major potential that can be achieved through the use of IoT technology. Smart home energy management solutions and consumer engagement platforms based on IoT allow consumers to track their energy usage in real time, receive notifications, and take appropriate actions to save energy. Engagement of consumers in managing energy through IoT can lead to energy conservation [25],[41]. Finally, IoT also aids in environmental monitoring and sustainability analysis by enabling the continuous tracking of environmental indicators, including pollution, air quality, and efficiency levels. These data-driven observations help optimise the functional use of renewable energy resources, ensuring that IoT also plays a significant role in environmental sustainability as a mechanism to mitigate climate change [17], [26], [38]. Table 1 demonstrates the potentials of IoT in renewable energy.

Table 1. Potentials of IoT in Renewable Energy Systems

Potential	Description	Benefits
Enhanced Energy Management	Real-time monitoring and control of energy production and consumption	Optimized energy usage, reduced wastage, better utilization of

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		renewable resources
Predictive Maintenance	Continuous monitoring of system health to predict equipment failures	Reduced downtime and maintenance costs, extended lifespan of infrastructure
Integration with Smart Grids	Seamless integration with smart grids for efficient energy distribution	Improved grid reliability, flexibility, and stability, maximized use of renewable energy
Development of Microgrids	Support for localized energy systems that operate independently from the main grid	Increased energy security and resilience in remote or disaster-prone areas
Improved Energy Storage Management	Optimization of energy storage systems for efficient charging and discharging	Enhanced energy storage efficiency, prolonged lifespan of storage devices
Increased Consumer Engagement	Active participation of consumers in energy management through smart devices	Energy conservation, reduced energy bills, informed decision-making at the household level
Environmental Monitoring	Tracking environmental parameters to optimize system performance	Minimized environmental impact, data for climate change mitigation strategies

3.The Role of IoT in Fault Detection in Renewable Energy Systems:

The integration of Internet of Things (IoT) technology into the renewable energy sector has brought about a paradigm shift in monitoring, diagnosis, and maintenance techniques, especially regarding fault detection. Effective fault detection is required for ensuring the efficiency, reliability, and long-termustainability of renewable energy sources such as photovoltaic, wind energy conversion, hydroelectric, and battery energy storage systems. Because of the distributed and dynamic nature of renewable energy resources, traditional approaches fail, making it imperative to resort increasingly to the use of IoT technology [1], [7], [12].

3.1. Real-Time Monitoring

IoT makes possible the continuous and real-time monitoring and tracking of renewable energy sources using sensor networks distributed and integrated within energy system devices. The sensors detect important operating parameters including temperature, voltage, current, vibration, solar irradiation, speed, and output power. The information is communicated to central and edge-based remote monitoring systems using communication networks for analysis to detect unusual operating parameters suggesting possible faults [2], [3], [7]. Real-time monitoring helps improve visibility and detect possible degradation in energy system performance before major faults occur.

3.2. Predictive Maintenance

Predictive maintenance solutions can be achieved by using data obtained from sensors that are IoT-capable, and this can be utilized to implement predictive maintenance solutions that can foresee failures related to equipment. Data analysis techniques, machine learning, and artificial intelligence can be utilized to foresee failures based on past and current data, and this can be applied to equipment associated with renewable energy to ensure that there are no unforeseen breakdowns. For instance, data pertaining to wind turbines can be utilized to foresee any failures related to bearings or gearboxes to take corrective measures [7], [10], [24].

3.3. Fault Localization

IoT technology also ensures fault localization with a high degree of accuracy in MLRE. Moreover, in the case of photovoltaic plants, IoT-based sensors can easily identify irregularities in the voltage drop or current mismatch in the module or string level, which helps to immediately localize the faulty module in the photovoltaic system. This has become possible since it was difficult to manually inspect the large-scale solar farms [2], [23], [40].

3.4. Enhanced Data Analytics

The large amount of data produced by IoT devices makes it possible to apply advanced data analytics and artificial intelligence tools for fault identification. Machine learning algorithms can identify complex patterns and relationships among data points across higher-dimensional data spaces that cannot otherwise be easily identified by conventional techniques involving thresholds. These tools allow early identification of slight faults, degradation, and inefficiency, which improves predictive maintenance techniques [10], [21], [24], [36].

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3.5. Remote Diagnostics

The IoT fault detection system enables remote diagnostics, making it possible to observe the fault condition of the system without having to physically go to the site. This is very effective, especially for offshore wind energy plant infrastructure, distant solar power stations, and geographically distributed energy storage systems. The method is efficient and removes the need for physical site inspection, hence enhancing safety and saving on operational expenses [7], [14], [50].

3.6. Integration with SCADA Systems

The IoT technologies could easily be integrated into the conventional Supervisory Control and Data Acquisition (SCADA) systems to improve the fault detection and system control capabilities. Although the SCADA system has the ability to monitor and control a system centrally and remotely, the capabilities for sophisticated sensing and analysis offered by the IoT technologies complement its abilities. The integration of the technologies therefore allows for aholistic perspective of the system performance for improved and efficient system control [34], [42], [50].

3.7. mproved Reliability and Efficiency

The advantages provided by IoT technology to renewable energy systems in the matter of monitoring and fault detection are enormous. It helps to improve the reliability and efficiency of the renewable energy systems. It is also able to prevent cascading failures, and the system can continue to operate under optimal conditions. The early warning alert given by the IoT technology helps to prevent failures in battery energy storage systems, such as cell temperature, cell voltage, and state-of-charge imbalances [10], [52].

4.Case Studies and Real-World Applications:

Various research work and implementation examples available in literature have established the efficiency and effectiveness of the usage of IoT-based fault detection and condition monitoring techniques for different types of renewable energy projects. These examples showcase how different IoT solutions improve the efficiency and performance of a project by offering remote monitoring and diagnosis capabilities [1], [2], [7], [10].

4.1. Solar Energy Systems

In solar photovoltaic systems, the usage of IoT-based monitoring systems is common for monitoring various parameters like irradiance, module temperature, voltage, current, and power. Real-time data acquisition helps in the early identification of any degradation in performance due to reasons like shading, dust accumulation, hotspot identification, or aging of the module. Various research papers have stated that the usage of IoT-based fault identification systems can lead to a remarkable boost in power output as it facilitates maintenance work on a timely basis and cleaning operations as well [2], [23], [40]. Predictive maintenance techniques utilizing performance data can further minimize downtime by predicting failures prior to their occurrence. Moreover, IoT-based fault identification facilitates the immediate identification of malfunctioning units in a solar farm setup [2], [23].

4.2. Wind Energy Systems

Wind power plants make extensive use of IoT sensors for detecting mechanical and electrical-related variables like vibration, temperature, rotational speed (in RPM), and power generation. These are considered essential for the early diagnosis of any mechanical issues in the turbine blades and gearbox. Predictive models of maintenance using machine learning algorithms based on IoT have been proven helpful in preventing failure and increasing the life of wind turbines [7], [10], [12]. Moreover, the use of IoT in remote diagnosis enables the diagnosis of the status of the wind turbine even in offshore locations [7], [14].

4.3. Hydroelectric

In hydroelectric power plants, the application of IoT technology involves monitoring the flow rates of the water, the level of water pressure, vibration in the turbines, and the functioning of the generator. This makes it easier to detect issues like blockages, cavitation, and mechanical failure in a more effective manner. Maintenance methods that utilize predictive models, which are data-driven in the context of IoT, can reduce instances of forced downtimes, thus minimizing the cost associated with maintenance [8], [49]. Fault localization, which relies on performance deviation analysis, improves efficiency in this process.

4.4. Energy Storage in Batteries

Battery energy storage systems (BESS) play a very important role in the integration of renewable

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energy sources and require trustworthy system operation for the stability of the power grid. IoT-based monitoring systems measure important variables like temperature, voltage, state of charge, and charge/discharge cycles for cells and battery packs. Also, early indication of irregularities in the system, such as temperature and voltage imbalances, enhances the safety and avoids catastrophic failures. Predictive maintenance methods using IoT inputs can extend the battery life through forecasting the patterns of battery degradation and failure events [10], [52]. Again, the remote diagnostic and control function avoids manual site visits and optimizes the use of distant storage resources [52].

Table 2 presents a detailed insight into the case studies and real-world implementation of IoT in the detection of faults within different renewable energy resources, such as solar energy, wind energy, hydro energy, and energy storage systems.

Table 2. IoT-Based fault detection application in renewable energy systems.

Renewable Energy System	IoT Application	Monitored Parameters	Fault Detection and Benefits
Solar Energy Systems	Real-time Monitoring	Irradiance, temperature, electrical output	Detects issues like shading, dirt accumulation, panel degradation; allows for timely cleaning and maintenance
	Predictive Maintenance	Voltage, current, performance metrics	Predicts panel failures, enabling proactive maintenance and reducing downtime
	Fault Localization	Voltage drops, performance anomalies	Precisely identifies faulty panels in large installations, speeding up repair processes
Wind Energy Systems	Vibration Monitoring	Vibration levels, temperature, RPM	Predicts mechanical failures in blades, bearings, and gearboxes; allows for repairs before catastrophic failures
	Predictive Maintenance	Performance metrics, load levels	Enables timely maintenance, extending the lifespan of turbines and improving efficiency
	Remote Diagnostics	Operational data, fault codes	Allows for remote assessment and troubleshooting, reducing the need for physical inspections
Hydroelectric Systems	Flow and Pressure Monitoring	Water flow rates, pressure levels, turbine performance	Detects blockages, inefficiencies in water usage, and performance issues; enables timely interventions
	Predictive Maintenance	Wear and tear indicators	Predicts equipment failures, reducing downtime and maintenance costs
	Fault Localization	Performance deviations	Quickly identifies problematic components within the system, facilitating efficient repairs
Battery Energy Storage	Health Monitoring	Temperature, voltage, state of charge	Detects issues like overheating, voltage imbalances; ensures optimal performance and safety
	Predictive Maintenance	Battery cycle count, charge/discharge patterns	Predicts battery cell failures, prolonging battery life and improving reliability
	Remote Diagnostics	Battery health data, performance metrics	Allows for remote monitoring and management, reducing the need for on-site inspections

5. IoT for Detection of Energy Theft:

Energy theft is one of the pressing issues arising in contemporary energy systems, leading to heavy economic losses, compromising the quality of power, and making the energy distribution network unreliable. Additionally, the growing integration of DER and smart grids makes energy theft detection using traditional approaches more complicated. In

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the above-stated issue, using IoT technology is a promising solution for energy theft detection, monitoring, and prevention with the aid of real-time data processing [53], [54], [55], [56].

5.1. Real-Time Monitoring

Smart meters empowered with IoT technology are the main constituents of a system that can detect energy theft. These devices enable the monitoring of usage at a high resolution in a real-time environment. They continuously collect usage information at a detailed level regarding every aspect related to user or feeder levels. All this information is then relayed instantly to a utility control center for analysis. It helps in picking abnormal usage patterns that may be a result of possible theft or usage profile irregularities [57].

5.2. Advanced Analytics and Machine Learning

The enormous amounts of data being created by IoT devices are processed through sophisticated data analytics techniques and machine learning algorithms for the purpose of identifying suspicious activity patterns related to energy theft. Machine learning techniques are capable of training on known activity patterns from the past and are effective in differentiating between genuine and suspicious activity patterns. The use of artificial intelligence improves the clarity of the results and minimizes the false alarm rates, making the use of IoT technology for theft protection more robust [53]-[55].

5.3. Tamper Detection

The IoT-based energy theft detection system also has tamper detection features that can be achieved by sensors integrated into smart meters and distribution devices. These sensors can detect any form of tampering, bypassing, or unauthorized access, which instantly alerts the concerned energy authorities [11], [34], [49]. The early detection of tampering ensures quick measures to prevent continuous energy thefts [55], [60].

5.4. Automated Alerts and Response Mechanisms

IoT systems can automatically produce alerts and trigger corresponding actions upon identification of potential energy theft. Automatic alerts enable utility companies to investigate alarm occurrences, while remote control functions enable actions like suspension of affected links until resolution of identified energy thefts. These actions automatically reduce response times and minimize associated economic losses [34], [50], [51], [55]-[60].

5.5. Remote Monitoring and Control

IoT technology makes it possible to remotely monitor and control distribution networks, giving utility companies the ability to manage extensive infrastructure remotely from central command centers. Real-time monitoring of network conditions facilitates quick identification of network locations that are susceptible to electricity theft. This remote-control function makes it possible to cut off the affected network or divert the power flow without physically being in the location, thereby increasing efficiency and safety [9], [50].

5.6. Data Integration and Interoperability

The advantage of using the IoT for theft detection is its capability to combine data from multiple, differing systems such as smart meters, distribution sensors, customer information systems, and SCADA systems. This is the advantage of taking a big data approach to data collection, where the data is viewed holistically, and therefore there is a better chance to accurately determine whether there has been theft. Another advantage is the interoperability of the devices and systems using IoT technology [3, 31, 34].

6. IoT Applications in Energy Theft Detection:

IoT technology has become an important facilitator in ensuring the efficiency of energy theft identification in modern power distribution systems, utilizing real-time supervision, smart analysis, and remote-control capabilities. Various modern smart meters enabled with IoT technology offer continuous high-resolution monitoring of electricity usage, allowing utilities to identify irregular patterns of usage, which may signify unauthorized usage or potential meter bypassing activities [53]-[55]. Advanced analysis and machine learning algorithms used in processing data from IoT technology can significantly enhance identification accuracy, detect irregular patterns and distinguish between random variations in user consumptions and fraudulent activities [10], [24]. Physical manipulation sensors designed in smart meters and power distribution units enable the identification of any potential manipulations in the initial stages, automatically sending notifications to power utility operators [59]. Automatic notification and response systems significantly reduce response time, where instantaneous actions can be processed to remotely cut or cap potential

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sources to halt further losses [58], [60]. In addition, remote monitoring and central command supervision made possible in utilities utilizing IoT technology enable utilities to supervise large-scale power distributions coming from central command centers, where data consolidation from diverse sources of IoT technology offer an overarching perspective of the energy system, thereby ensuring enhanced efficiency and effectiveness in energy theft identification and prevention strategies [3], [31].

Table 3. IoT Applications in Energy Theft Detection

IoT Application	Description	Benefits
Real-Time Monitoring	Continuous monitoring of energy consumption using smart meters	Detects unusual consumption patterns indicative of theft
Advanced Analytics	Machine learning algorithms analyze consumption data for anomalies	Identifies suspicious activities with high accuracy
Tamper Detection	Sensors on meters and equipment detect physical tampering	Alerts utility companies to attempts to bypass or manipulate meters
Automated Alerts	Systems send alerts and trigger automated responses upon detecting theft	Enables swift action to prevent further theft and mitigate losses
Remote Monitoring and Control	Enables remote surveillance and control of energy networks	Facilitates immediate actions like shutting down compromised connections
Data Integration	Combines data from various sources for comprehensive analysis	Provides a holistic view of the energy network, enhancing theft detection and prevention

7. Limitations of IoT in Renewable Energy Systems:

Although there are significant advantages to integrating the Internet of Things (IoT) technology into renewable energy resources, key limitations must also be addressed. The major challenge that lies ahead is related to the security of the massive amount of information generated by the adoption of IoT technology in energy production, as demonstrated in Table 4. This is because the amount of information is susceptible to hacking, that may affect the reliability of energy production. In addition, the adoption will also affect consumers, as their privacy may not be adequately protected [11], [33], [49].

Another significant drawback is the high cost associated with implementing IoT for renewable energy systems. This involves the setup cost of sensors, smart meters, communication infrastructure, data storage systems, and analytical tools. In the case of smaller renewable energy systems, especially in developing countries, the cost involved may become a barrier to their adoption. This can be made more economic by proper planning, the use of government subsidies, or any economic incentive programs [1], [6], [49], [51].

Interoperability and standardization challenges are further hindering the seamless incorporation of IoT solutions in the renewable energy field. The coexistence of disparate devices, communication protocols, and industry-specific platforms can lead to compatibility issues, causing impediments to the exchange of information among them. It becomes essential to implement universal standards for intercommunication and coordination among energy assets that are IoT-enabled [3], [31], [34].

The performance of IoT-based energy systems also depends to a great extent on data quality and reliability of sensors used. Inaccurate, incomplete, or noisy data from sensors can lead to incorrect data analysis, inefficient control decisions, and suboptimal system performance. It becomes a prerequisite to calibrate, maintain, and verify IoT sensors to ensure data quality and efficient performance of systems [3], [12].

Scalability is a challenge that is even more serious, especially as the systems for engaging with renewable sources become more complex. The ever-increasing number of devices that are connected into IoT systems raises new demands on communication abilities as well as processing and storage systems. Without a structured approach to scalability, system performance could be compromised as it is scaled up [5], [18], [20].

Moreover, the energy consumption levels of IoT devices have sparked concerns, particularly within the context of renewable energy sources where the optimal use of clean energy is required. Consuming excessive energy through the use of energy-wasteful sensors and network modules may counterbalance certain sustainability efforts. This situation calls for energy-efficient devices, energy-efficient network modules, and energy harvesting technologies, which can resolve this problem effectively [27], [28], [45].

Technological complexity is another challenge in IoT adoption. The development of sensor

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networks, reliable data transfer, interfacing with existing energy management and/or SCADA systems, and advanced levels of analysis using IoT technology require technical knowledge. A company lacking qualified technical staff may struggle to implement and maintain IoT technology, underscoring the importance of training and collaboration with technology companies [31], [34], [50]. Lastly, the challenges posed by regulations and policies are also an area of importance. The policies and regulations related to the use of IoT technology, data protection, and renewable energy are still evolving. It is an area of concern for any individual to follow the current policies and regulations in the field. There is a need for joint efforts from policymakers, companies, and researchers to develop favourable policies and regulations for integrating IoT technology with renewable energy systems [6], [47], [49].

Table 4. Limitations and Solutions of IoT in Renewable Energy Systems

Limitation	Concern	Solution
Data Security and Privacy	Vulnerability to cyberattacks and unauthorized access	Implement robust cybersecurity measures such as encryption and secure communication protocols
High Implementation Costs	High initial and ongoing costs for deploying IoT infrastructure	Financial planning and potential subsidies or incentives for IoT adoption
Interoperability Issues	Lack of standardization leading to compatibility problems	Development of universal standards and protocols for IoT devices
Data Quality and Reliability	Inaccurate or incomplete data affecting system effectiveness	Regular calibration and maintenance of IoT sensors
Scalability Challenges	Difficulties in scaling IoT solutions for large systems	Investment in robust infrastructure and careful planning for scalability
Power Consumption	Cumulative power consumption of numerous IoT devices	Optimization of IoT device energy efficiency and careful planning of deployment
Technical Complexity	High level of expertise required for implementation and maintenance	Training programs and partnerships with specialized technology providers
Regulatory and Policy Challenges	Evolving regulatory environment and lack of clear guidelines	Engagement with policymakers to develop clear regulations and standards

8.Conclusion

This paper has presented an analysis of the technical role of the Internet of Things (IoT) in developing and improving the renewable energy sector for a brighter and efficient future. Through this analysis and the various studies and works that have been reviewed and presented in this paper, the role of the Internet of Things has remained significant and crucial to the improvement of the various aspects of the renewable energy sector. The Internet of Things has played an important part in the improvement of the renewable energy sector. This is mainly attributed to its ability to facilitate intelligent control. In fact, the analysis further reveals that the IoT solution plays an enabling role in overcoming the natural challenges faced by RE power generation, like variability and intermittent energy generation, through the implementation of smart grid and microgrids, and efficient energy storage management. Practical applications in solar power, wind energy, hydro energy, and battery energy storage systems establish the feasibility of the IoT solution.

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