Designing a Renewable Energy System for Industrial IoT with Artificial Intelligence

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Abstract. This paper reviews the integration of renewable energy systems with Industrial IoT (IIoT) through Artificial Intelligence (AI). It examines various studies focusing on the design and monitoring of solar-powered wireless sensor nodes in diverse IIoT settings, particularly outdoors. A proposed distributed network architecture, underpinned by open-source technologies, aims for efficient solar power harvesting and data acquisition on solar radiation and ambient parameters. This data aids in devising estimation techniques to predict solar panel voltage outputs, optimising energy utilisation of solar-powered sensor nodes. The discourse extends to photovoltaic plants, emphasising continuous monitoring and fault detection for operational safety and reliability. Reviewed works advocate embedding AI and IoT for remote sensing, fault detection, and diagnosis, addressing challenges posed by undetectable faults. Furthermore, the paper explores AI's transformative potential in the broader energy sector, impacting electricity production, distribution, energy storage, and efficiency. The synergy of AI, IIoT, and renewable energy systems is underscored as a conduit for enhancing energy management, operational transparency, and deploying cost-effective solutions for complex industrial challenges, significantly bolstering the efficiency and intelligence of industrial production and services.

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1 Introduction

The swift progression of technology, together with the rapid global population growth, has sparked a crucial dialogue concerning energy sources and their exploration. This dialogue is further intensified by the increasing deployment of the Industrial Internet of Things (IIoT) and smart technology systems in outdoor settings. At the heart of this discussion is the utilisation of solar energy, a highly esteemed and applicable renewable energy source, particularly within the domains of IIoT and smart technology systems. The urgency of this consideration stems from the broad implementation of sensor networks and the need for a significant number of sensor nodes and smart devices within these systems. The adoption of solar-powered sensors and smart devices has emerged as a key solution, leading to a myriad of research initiatives aimed at enhancing the operational lifespan of these devices through solar energy.

A notable aspect of using solar energy to power sensor nodes is the extension of their operational time. To optimally utilise solar-powered sensor nodes in various scenarios, it's crucial to identify the most suitable locations for node deployment, thereby enabling the estimation of solar panel outputs in specific areas. This strategic positioning aids in modelling sensor node operations and devising adaptive energy-saving modes based on the estimated outputs. This short paper reviews the studies proposing an approach centred on a wireless sensor network for gathering data on solar radiation, utilising a variety of sensors to assess solar panel performance, especially in outdoor IIoT scenarios. This approach represents the diverse strategies employed to efficiently harness solar energy within industrial settings.

This short paper reviews the studies tackling the challenge of estimating the energy supply of solar-powered wireless sensor networks across a range of IIoT environments. The system offered in the reviewed studies is crafted to collect data suitable for applying nonlinear regression techniques for solar panel output estimation. The estimated outputs are vital in determining optimal energy-efficient operational modes of solar-powered sensor nodes, thus achieving efficient solar power harvesting effects. The proposed distributed wireless sensor network system architecture, rooted in open hardware and open-source technologies, is designed to capture solar radiation data and other ambient parameters. This architecture highlights the importance of design and platform efficiency of sensor nodes deployed within this network, aiming to improve energy efficiency and extend the node lifecycle.

The burgeoning photovoltaic (PV) market, driven by the reduced cost of PV modules and renewable national energy targets, emphasises the importance of solar power generation. The remarkable growth in solar PV development calls for robust fault detection and diagnosis (FDD) algorithms to ensure the security and reliability of PV parks. The emergence of web-based monitoring for isolated and inaccessible solar PV parks aims to reduce operational and maintenance costs, thereby highlighting the need for innovative solutions like the application of Artificial Intelligence (AI) techniques and Internet of Things (IoT) in PV system monitoring and remote sensing. These technological advancements are anticipated to significantly enhance fault diagnostics, prognostics, and overall operational efficiency, marking a substantial step towards achieving safe, highly efficient, and eco-friendly industrial production/service.

The integration of AI and IoT in solar energy systems, as explored in various studies, presents a promising avenue for advancing the efficiency and reliability of renewable energy sources in industrial settings. The fusion of AI algorithms with IoT-enabled devices facilitates real-time monitoring, fault detection, and predictive maintenance, which are crucial for ensuring the optimal performance of solar-powered systems in industrial environments. Moreover, the application of machine learning and deep learning techniques in analysing vast datasets from solar PV systems contributes to more accurate forecasting, better decision-making, and enhanced control optimisation. This convergence of technologies not only augments the capabilities of solar energy systems but also propels the industrial sector closer to achieving sustainability and energy independence. Through a thorough review of the existing literature and studies, this paper underscores the pivotal role of AI and IoT in revolutionising solar energy systems for industrial applications, thereby contributing to the broader discourse on renewable energy and industrial sustainability.

2 Review and discussion

In the study by Dobrilovic et al. (2023), emphasis is placed on evaluating the performance of energy-efficient solar-powered sensor nodes for deployment in Industrial IoT environments [1]. The narrative explores the imperative of harnessing renewable energy sources, notably solar energy, to energise sensor nodes and smart devices within industrial frameworks. This urgency is propelled by the widespread integration of sensor nodes and smart gadgets in such domains. The paper advocates for a distributed wireless sensor network system architecture, grounded in open-source hardware and software technologies. This architecture is envisioned to capture solar radiation data along with other ambient parameters like solar panel and ambient temperature, light intensity, among others. The amassed data is chiefly channelled towards devising estimation techniques using nonlinear regression to forecast solar panel voltage outputs. These forecasts are pivotal for realising energy-efficient functionalities of solar-powered sensor nodes in outdoor Industrial IoT infrastructures. Furthermore, the data avails a resource for scrutinising and monitoring the impact of various ambient parameters on the efficiency of solar panels and, consequently, the energising of sensor nodes.

The study encapsulated various parameters pivotal to the performance and efficiency of solar panels. The table below provides a structured summary of these parameters, shedding light on their measurement units, distribution nature, methods employed for data collection, and the results obtained. Additionally, it elucidates the benefits and challenges associated with each parameter, thereby offering a nuanced understanding of the factors influencing solar panel performance. This tabulation serves as a foundational reference, aiding in the exploration of optimising solar energy harnessing, which is quintessential for the seamless integration and operation of renewable energy systems in industrial IoT frameworks. Through such detailed analyses, the study by Dobrilovic et al. (2023) contributes significantly to the body of knowledge, paving the way for further research and innovation in designing energy-efficient, sustainable, and intelligent renewable energy systems for Industrial IoT with Artificial Intelligence.

Table 1. Analysis of Solar Panel Performance Parameters

Parameter	Description	Measurement Unit	Method of Data Collection	Results	Benefits	Challenges

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Solar Radiation	Amount of solar energy received per unit area	W/m^2	Solar radiation sensor	Accurate measurement of solar radiation	Enables precise energy harvesting predictions	Sensor calibration and maintenance
Ambient Temperature	Temperature of the surrounding environment	°C	Temperature sensor	Reliable ambient temperature data	Aids in understanding environmental effects on solar panel performance	Sensor accuracy in varying conditions
Solar Panel Temperature	Temperature of the solar panel's surface	°C	Temperature sensor	Consistent temperature readings	Helps in monitoring and maintaining optimal panel operating conditions	Temperature fluctuations affecting accuracy
Light Intensity	Amount of light incident on the solar panel	Lux	Light intensity sensor	Accurate light intensity data	Facilitates better understanding of light conditions for energy harvesting	Sensor sensitivity and calibration
Voltage Output	Voltage generated by the solar panel	V	Voltage sensor	Reliable voltage output data	Essential for calculating energy output and efficiency	Electrical interference and sensor accuracy
Current Output	Current generated by the solar panel	A	Current sensor	Consistent current output readings	Crucial for energy output calculations	Sensor accuracy and electrical interference
Power Output	Power generated by the solar panel	W	Calculated as Voltage Output × Current Output	Accurate power output calculations	Direct measure of solar panel performance	Dependence on accurate voltage and current readings
Efficiency	Ratio of output power to incident solar energy	%	Calculated as (Power Output / (Solar Radiation × Panel Area)) × 100	Reliable efficiency calculations	Provides insight into solar panel performance and areas for improvement	Accurate measurement of all contributing parameters

The study by Dobrilovic et al. (2023) particularly focuses on the performance of the voltage sensor under various light conditions. The light sources examined include solar radiation, incandescent, CFL, and LED bulbs. The table delineates the average voltage readings as captured by the sensor and a Digital Multimeter (DMM) across these diverse light sources, alongside the Root Mean Square Error (RMSE) to gauge the accuracy of the readings. This tabulation is instrumental in discerning the efficacy and precision of the voltage sensor, which is pivotal for the data acquisition system proposed for solar-powered Industrial IoT environments.

The following points provide a concise summary of the key findings from Dobrilovic et al. (2023)'s study. The study delves into the efficacy and precision of voltage sensors under diverse lighting conditions, offering insights into the broader application of solar-powered sensor nodes in the realm of Industrial IoT:

- **Voltage Sensor Evaluations**: The study elaborates on the precision of voltage sensor readings under a variety of light sources. As detailed in Table 4 of the study, average voltage readings from both the sensor and a digital multi-meter (DMM) are presented under conditions of solar radiation, incandescent, CFL, and LED bulbs. The Root Mean Square Error (RMSE) values highlight a strong correlation between the sensor and DMM readings, validating the accuracy of the voltage sensor.
- **Reliability of the Voltage Sensor**: The research accentuates the consistent performance of the voltage sensor, especially when exposed to different light sources. Figures 10 to 12 in the study offer a side-by-side comparison of the voltage sensor and DMM readings under the influence of incandescent, CFL, and LED bulbs. The congruence in these readings emphasises the sensor's dependability and its suitability for the proposed measurement framework.
- **Voltage Sensor and Digital Multi-meter Comparison**: An extended analysis is presented graphically in Figure 9, showcasing the collective measurements from both the voltage sensor and DMM across three bulb types. This representation confirms the consistency in readings across varied light sources, reinforcing the credibility of the voltage sensor.
- **Consolidation of Results Across Light Sources**: The study provides a comprehensive overview of the voltage sensor's consistent performance across diverse light sources. As depicted in Table 4, the RMSE values, ranging between 0.11 to 0.17 V, signify a commendable level of precision, reflecting the platform's robust performance throughout the testing phase.
- **Correlation Between Voltage and Other Sensor Readings**: The research also probes into the interplay between voltage sensor readings and other sensor values. While the specifics of this relationship aren't elaborated upon in the extracted content, it remains a pivotal facet in gauging the overall efficacy and precision of the sensor nodes under varied environmental conditions.
- **Study's Key Contributions**: The study culminates by spotlighting the significant strides made towards a distributed wireless sensor network system architecture, rooted in open-source hardware and technologies. This advancement is paramount in promoting the adoption of solar-powered sensor nodes within Industrial IoT contexts, resonating with the overarching theme of our review article centred on crafting renewable energy systems for Industrial IoT, augmented by Artificial Intelligence.

The insights gleaned from Dobrilovic et al. (2023) serve as a cornerstone in comprehending the performance dynamics of solar-powered sensor nodes, especially the precision of voltage sensors under an array of lighting conditions. This empirical evidence is invaluable to our review article, shedding light on the reliability of solar-powered sensor nodes, a fundamental component in the blueprint of renewable energy systems tailored for Industrial IoT, enriched by Artificial Intelligence.

Through the studies by Mellit et al. (2021) and Ahmad et al. (2022) our review aimsto understand their contributions to the field of renewable energy systems, particularly focusing on the integration of Artificial Intelligence (AI) and Internet of Things (IoT) in enhancing the efficiency and monitoring of solar photovoltaic (PV) systems [2,3].

Study by Mellit et al. (2021) [8-11]:

- **Objective**:
  - The study endeavours to tackle the hurdles and put forth intelligent solutions for the monitoring and fault detection in PV systems.
  - It delves into the utilisation of AI and IoT in amplifying the efficiency and safety of PV systems..
- **Key Findings**:
  - The paper highlights the remarkable growth in the PV market and the corresponding need for effective Fault Detection and Diagnosis (FDD) algorithms to ensure the reliability and safety of PV installations.
  - It categorises fault detection methods into manual, semi-automatic, and automatic, with a focus on the latter due to its real-time online monitoring capabilities.
  - The application of AI and IoT is emphasised as a significant advancement in fault detection, diagnosis, and remote monitoring, which could lead to cost reduction and improved accuracy in PV system management.
  - The study also furnishes a thorough comparison of AI techniques, encompassing machine learning and deep learning, in regard to cost implementation, complexity, accuracy, and real-time applicability.
- **Recommendations**:
  - The paper advocates for the incorporation of AI and IoT techniques into simplistic hardware for economical and technically viable solutions, particularly in remote locales.
  - It also propounds a technology transition from laboratories to industrial sectors for large-scale deployment of smart monitoring systems.

Study by Ahmad et al. (2022) [12-15]:

- **Overview**:
  - The study emphasizes the significance of industrial development in relation to the power system's growth, stability, and technical advancement.
  - The role of artificial intelligence (AI) in the energy market is becoming increasingly prominent.
  - The research explores seven disparate energetics systems and their applications, encompassing electricity generation, power delivery, electric distribution networks, energy storage, energy conservation, novel energy materials and devices, energy efficiency and nanotechnology, and energy policy and economics.
- **Key Findings**:

    - AI is instrumental in addressing challenges in power systems engineering that were previously considered complex.
    - The study pinpoints the principal catalysts in current AI technologies, including fuzzy logic systems, artificial neural networks, genetic algorithms, and expert systems.
    - Developed nations are capitalising on AI to meld with smart meters, smart grids, and Internet of Things devices, ushering in enhancements in efficiency, energy management, and the adoption of renewable energies.
    - AI has engendered significant advancements in how power system devices monitor data, interact with systems, analyse input-output, and present data.
    - There's a call for more investment in global research into AI and data-driven models to further harness its potential in the energy sector.
- **Implications for Industry 4.0**:
    - Industry 4.0, which encompasses advanced analytics, connectivity, and automation, is poised to be a major driver of economic growth.
    - AI is projected to contribute significantly to the manufacturing sector by 2035.
    - The study also touches upon the potential of AI in improving sustainability in the context of Industry 4.0.

Insights from the two studies:

- **Technological Advancements**:
    - Both studies underscore the importance of integrating AI and IoT technologies in managing and monitoring PV systems. However, Mellit et al. provide a more detailed exploration of AI techniques and their applicability in fault detection and diagnosis.
- **Fault Detection and Diagnosis (FDD)**:
    - Mellit et al. delve into the categorisation of FDD methods and the significance of automatic methods enabled by AI and IoT. The study by Ahmad et al. might also have insights into FDD, but the information could not be extracted.
- **Industry Application**:
    - The study by Mellit et al. emphasises the need for technology transfer to the industrial sector for large-scale deployment of smart monitoring systems. The perspective of Ahmad et al. on industrial application remains unclear due to the unavailability of extracted information.

Through the authors' studies, we found out that the integration of AI and IoT in PV systems is pivotal for advancing fault detection, diagnosis, and remote monitoring, which are crucial for ensuring the reliability, safety, and cost-effectiveness of renewable energy systems. The detailed exploration by Mellit et al. provides a solid foundation for understanding the current challenges and future directions in this domain. Through the study by Ahmad et al. (2022), we found out that the integration of AI in the energy sector is not just a trend but a necessity. The advancements brought about by AI in power systems engineering are transformative, offering solutions to previously complex challenges. As we move towards a more interconnected world with Industry 4.0 at the forefront, the role of AI in ensuring energy efficiency, sustainability, and smart management cannot be understated.

In another study by Chen et al. (2016), the focus was on the development of an efficient and cost-effective solution for complex problems in the industrial applications of the Internet of

Things (IoT) [4]. The paper delves into the concept of an industrial intelligent ecosystem, which facilitates the collection of vast amounts of data from various devices that dynamically collaborate with humans. This collaboration is essential for improving the efficiency of industrial production and services.

Key findings from the study include [16-19]:

- **Collaborative Sensing Intelligence (CSI) Framework**: The paper introduces a CSI framework that combines collaborative intelligence and industrial sensing intelligence. This framework aims to enhance the cooperativity of analytics by integrating vast spatio-temporal data from different sources and time points.
- **Industrial IoT (IIoT)**: The study emphasizes the importance of IIoT in collecting massive data daily. Collaborative analysis of this data can lead to efficient and cost-effective solutions, ensuring safe, efficient, and eco-friendly industrial production and services.
- **Collaborative Intelligence (CI)**: The paper defines CI as the ability to acquire information or knowledge from massive data to construct a problem-solving network. This network aims to automate industrial production or improve its performance.
- **Industrial Sensing Intelligence (ISI)**: ISI is defined as the ability to dynamically mine and analyse massive spatio-temporal data collected from industrial ecosystems. This intelligence can improve industrial automation.
- **Challenges and Open Research Issues**: The study also highlights the challenges and open research issues in deploying the CSI framework in the dynamic environment of the industry.

Relating this to our review article, "Designing a Renewable Energy System for Industrial IoT with Artificial Intelligence", the findings from Chen et al. emphasize the importance of collaborative intelligence in the IoT domain. The integration of vast amounts of data from various sources, combined with intelligent analytics, can significantly enhance the efficiency and effectiveness of renewable energy systems in the industrial sector. The concepts of CI and ISI, as presented in the study, can be pivotal in designing AI-driven renewable energy systems for IIoT, ensuring a sustainable and efficient energy solution for the future.

Furthermore, a broader look into the realm of AI in renewable energy systems integration reveals a transformative change in modern power systems. The integration of power electronic converter-interfaced renewable energy sources and smart grid technologies is driving this change. As we move towards a higher percentage of renewable energies, the necessity for coordinated design, control, and protection schemes becomes paramount to ensure reliable and resilient system operation under any contingency. The development of AI methods has significantly facilitated the transition towards smart renewable energy systems design, emphasizing intelligent data-driven control and optimization, fault classification, detection, and diagnosis, among other aspects. This transition is crucial for achieving the objectives outlined in our review article, further underscoring the relevance of the findings from Chen et al. (2016) in shaping the discourse on designing renewable energy systems for Industrial IoT with Artificial Intelligence.

3 Future Scope of Research

The realm of renewable energy systems intertwined with Industrial IoT (IIoT) and Artificial Intelligence (AI) is a burgeoning field with a plethora of avenues yet to be explored. The confluence of these technologies holds the promise of revolutionising industrial operations by fostering sustainability, efficiency, and intelligence. Here are some pointers for future research in this domain:

- **Development of Robust Algorithms**: There's a pressing need for the development of more robust, efficient, and self-learning algorithms that can seamlessly integrate with IIoT to optimise the harnessing of renewable energy resources.
- **Real-time Monitoring and Control**: Research into real-time monitoring and control systems that leverage AI to ensure optimal energy utilisation and predictive maintenance in industrial settings is crucial.
- **Security and Privacy**: As IIoT and AI become integral to renewable energy systems, addressing the security and privacy concerns associated with data handling and communications is imperative.
- **Interoperability**: Ensuring interoperability among diverse systems and technologies within the industrial ecosystem is a significant area for future research.
- **Energy Storage and Management**: Innovations in energy storage and management solutions that can efficiently handle the intermittent nature of renewable energy sources are essential.
- **Scalability**: Research into scalable architectures that can accommodate the growing demands of industrial operations while maintaining energy efficiency is vital.
- **Human-machine Collaboration**: Exploring the dynamics of human-machine collaboration in an AI-driven IIoT environment to enhance decision-making and operational efficiency.
- **Policy and Regulation**: Understanding the implications of policy and regulation on the deployment and operation of AI and IIoT in renewable energy systems is crucial for widespread adoption and standardisation.

4 Knowledge Gaps

The journey towards fully realising the potential of integrating renewable energy systems with IIoT and AI is fraught with knowledge gaps that need addressing. These gaps often serve as roadblocks to the seamless adoption and optimisation of these technologies in industrial settings. Here are some identified knowledge gaps:

- **Standardisation**: Lack of standard protocols and frameworks for the integration of renewable energy systems with IIoT and AI technologies is a significant knowledge gap.
- **Performance Metrics**: There's a need for well-defined performance metrics to evaluate the efficiency, reliability, and sustainability of AI-driven renewable energy systems in industrial environments.
- **Data Quality and Availability**: The availability of high-quality, real-time data is crucial for the effective application of AI algorithms, yet there's a gap in the methodologies for data collection, processing, and analysis.
- **Technological Literacy**: The lack of technological literacy among stakeholders in understanding, deploying, and maintaining AI and IIoT technologies in renewable energy systems is a notable gap.

- **Cost-Efficiency Analysis**: Comprehensive cost-efficiency analysis of deploying AI and IIoT technologies in renewable energy systems across different industrial sectors is lacking.
- **Long-term Impact Assessment**: There's a gap in the assessment of long-term impacts, both positive and negative, of integrating AI and IIoT with renewable energy systems on industrial operations and the environment.
- **Human Factors**: Understanding the human factors, including the change in job roles, training needs, and the human-machine interface, is a significant knowledge gap.
- **Deployment Challenges**: Identifying and addressing the challenges associated with the deployment of AI and IIoT technologies in existing industrial infrastructures is essential to bridge the knowledge gap.

The exploration into the future scope of research and the identification of knowledge gaps provide a structured pathway for researchers, policymakers, and industry practitioners to navigate the complex landscape of renewable energy systems integrated with IIoT and AI. Through a concerted effort to address these areas, the vision of achieving a sustainable, efficient, and intelligent industrial ecosystem can be brought closer to reality.

5 Conclusion

The expedition into the realms of Renewable Energy Systems, Industrial IoT, and Artificial Intelligence has unfolded a tapestry of insights, innovations, and opportunities. The confluence of these technologies is not merely a stride towards modernisation but a leap towards a sustainable and intelligent industrial ecosystem. As we delve into the intricacies and examine the studies at hand, several key findings emerge that resonate with the core essence of our discourse:

- **Optimisation of Solar-Powered Sensor Nodes**: The meticulous design and monitoring of solar-powered sensor nodes, as elucidated in the studies, underscore the potential for optimising energy harvesting in industrial settings. This optimisation is pivotal for extending the operational longevity of sensor nodes and ensuring energy efficiency.
- **Real-Time Monitoring and Fault Detection**: The integration of AI and IoT for real-time monitoring and fault detection in photovoltaic plants is a significant stride towards enhancing the reliability and safety of renewable energy systems in industrial environments.
- **Collaborative Sensing Intelligence Framework**: The proposition of a Collaborative Sensing Intelligence framework heralds a new era of collaborative analytics, fostering a dynamic interaction between humans and machines, thereby enhancing the efficiency of industrial production/service.
- **AI-Driven Control and Optimization**: The deployment of AI-driven control and optimization schemes is instrumental in navigating the complexities of renewable energy systems, ensuring seamless integration and operation in an industrial IoT framework.
- **Data-Driven Renewable Energy Systems**: The emphasis on leveraging massive spatio-temporal data for enhancing the operations of renewable energy systems is a testament to the transformative power of data analytics in this domain.

- **Security, Privacy, and Interoperability**: Addressing the challenges of security, privacy, and interoperability is crucial for the widespread adoption and seamless operation of AI and IIoT technologies in renewable energy systems.

The synthesis of these findings paints a promising yet challenging landscape. The journey towards harnessing the full potential of renewable energy systems, augmented by the intelligence of AI and the connectivity of IIoT, is laden with both opportunities and hurdles. The insights gleaned from the reviewed studies serve as a beacon, guiding the discourse and actions towards a sustainable, efficient, and intelligent industrial future. Through a meticulous examination and understanding of these findings, the pathway towards achieving the envisioned objectives becomes clearer, setting the stage for further exploration, innovation, and transformation in the industrial sector.

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