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Smart Energy Meets Smart Security: A Comprehensive Review of AI Applications in Cybersecurity for Renewable Energy Systems

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ABSTRACT- The rapid adoption of renewable energy systems has brought forth a new set of cybersecurity challenges that require innovative solutions. In this context, artificial intelligence (AI) has emerged as a promising approach to tackle these challenges. This paper provides a comprehensive review of more than 19 studies that investigate the applications of AI in cybersecurity for renewable energy systems. By analyzing these studies, a range of opportunities and challenges associated with the integration of AI in this domain are identified. Notably, the findings indicate that over 75% of the studies acknowledge the significant potential of AI in enhancing the security of renewable energy systems. Among the various AI techniques employed, machine learning emerges as the most extensively utilized method, demonstrating an impressive detection rate of 85% and a false positive rate below 5%. However, certain challenges persist, including the limited availability of relevant data and concerns regarding the interpretability of AI models. To address these challenges, this paper concludes by providing recommendations for future research directions in this field, aiming to drive advancements in the intersection of smart energy and smart security.

Keywords: AI; Cyber Attack; Cyber Security; Renewable Energy; System; Threats.

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1. INTRODUCTION

Renewable energy systems are expanding rapidly due to their environmental benefits and decreasing costs. However, their digital integration and interconnectivity introduce new cybersecurity challenges [15]. Traditional approaches are inadequate for addressing the dynamic nature and distributed architecture of these systems [19]. Artificial intelligence (AI) offers potential solutions through the use of machine learning algorithms for real-time threat detection, risk assessment, and incident response. This paper comprehensively reviews AI applications in cybersecurity for renewable energy systems, including identifying opportunities and challenges, evaluating the effectiveness of AI techniques, and providing recommendations for further research [16]. The increasing adoption of renewable energy systems has ushered in a new era of clean and sustainable energy generation, encompassing solar, wind, hydroelectric, and geothermal sources, which mitigate the environmental impacts associated with traditional energy sources [1]. However, as these systems become more interconnected and digitized, they face a growing range of cybersecurity threats [2]. Securing renewable energy systems is crucial to ensure their reliable operation and protect critical infrastructure and sensitive data from malicious attacks. Traditional cybersecurity approaches are insufficient to address the unique challenges posed by these systems, necessitating innovative solutions. AI has emerged as a promising technology to augment cybersecurity efforts in the realm of renewable energy systems [3]. This paper aims to comprehensively review AI applications specifically tailored for securing renewable energy systems by examining more than 19 relevant studies. Through this review, we aim to identify opportunities and challenges associated with AI in safeguarding renewable energy infrastructure. Additionally, we evaluate the effectiveness of various AI techniques employed and offer recommendations for further research [15]-[20]. The review sheds light on the potential benefits of integrating AI into the cybersecurity framework of renewable energy systems, highlighting its role in enhancing threat detection, anomaly identification, and response mechanisms, thereby bolstering the security posture of critical energy infrastructures. Furthermore, we analyze the strengths and limitations of different AI techniques to provide practical insights into their feasibility and effectiveness in real-world applications [3]-[21]. The methodology employed in this review comprises four distinct stages: study selection, data collection, data analysis, and synthesis and reporting.

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2. SYSTEM MODEL

This section presents a comprehensive review of existing studies on AI applications in cybersecurity for renewable energy systems. The review encompasses over 21 relevant studies conducted in this field, aiming to identify the opportunities and challenges associated with AI integration in securing renewable energy infrastructure [3]. The reviewed studies collectively highlight the potential benefits of AI in enhancing the security of renewable energy systems [21]. More than 75% of the studies suggest that AI can significantly improve the overall cybersecurity posture. The majority of these studies leverage machine learning techniques, which prove to be the most widely utilized AI approach [4]. Machine learning algorithms demonstrate impressive capabilities in threat detection, achieving an average detection rate of 85% across the reviewed studies [22]. Moreover, the false positive rate remains below 5%, indicating the potential of AI to minimize false alarms and improve the efficiency of security operations [5].

One notable challenge identified in the literature is the scarcity of relevant data for training AI models in the context of renewable energy systems [22]. Limited availability of labeled data poses a significant hurdle in developing accurate and robust AI-based cybersecurity solutions [6]. Addressing this challenge requires the establishment of comprehensive datasets that capture the unique characteristics and threats specific to renewable energy systems. Interpretability of AI models also emerges as a significant concern in the reviewed studies [7]. While machine learning algorithms demonstrate high detection rates, the lack of interpretability hinders understanding the decision-making process behind these models [23]. Explainable AI techniques and methods are needed to provide transparency and insight into the reasoning of AI systems, enabling better trust and adoption in practical applications [24]. The reviewed studies emphasize the need for further research and development in AI applications for cybersecurity in renewable energy systems [17]. Recommendations include the exploration of ensemble learning techniques, integration of AI with other security measures, such as anomaly-based detection systems, and the development of robust evaluation frameworks to assess the performance and effectiveness of AI algorithms in real-world settings [8].

The literature review section provides a comprehensive analysis of recent studies on AI applications in cybersecurity for renewable energy systems. The review incorporates several key studies focusing on various aspects of this research domain. One study explores the prospects and challenges of implementing renewable energy-based microgrid systems in Bangladesh. The authors emphasize the need to address techno-economic vulnerabilities associated with renewable energy sources [25]. They discuss key issues related to microgrid planning, controlling, maintenance, and resilience [9]. The findings highlight the importance of overcoming these challenges to effectively deploy and secure renewable-based microgrids in the country. Another study investigates the role of cyber-physical systems (CPSs) as enablers of the circular economy for achieving sustainable development goals [26]. The review emphasizes the integration of CPS technologies within the circular economy framework. It showcases how CPSs, as Industry 4.0 tools, can enhance efficiency and reduce waste in circular economy practices [10]. The study also emphasizes the need for standardized assessment tools to evaluate and improve circulatory practices across different economic levels. In the context of inverter-based smart power systems, another comprehensive review focuses on cybersecurity aspects amid the rapid growth of renewable energy. The study examines the system structure, vulnerabilities, cyberattack types, and defense strategies in inverter-based smart power systems [18]-[27]. It delves into various detection and mitigation techniques and provides an overview and comparison of testbed and simulation tools for cyber-physical research [28]. The review also identifies ongoing challenges, unresolved problems, and potential future research directions in smart grid cybersecurity [11]. A comprehensive review of recent advances in smart grids presents an overview of key developments in this field [29].

The review encompasses intelligent energy curtailment, demand response integration, distributed renewable generation, and energy storage within the smart grid paradigm. It discusses advancements in energy data management, pricing modalities, network reliability, cybersecurity concerns, and emerging developments in pricing mechanisms.

The study provides a comprehensive understanding of the potential of smart grids in achieving sustainable future energy systems. Furthermore, a chapter on artificial intelligence models in power system analysis highlights the significance of AI technologies. The chapter emphasizes how AI techniques improve power system operations and productivity by controlling voltage, stability, power flow, and load frequency. It also discusses the automation of power system processes and the importance of selecting appropriate AI techniques for planning, monitoring, and control. The chapter briefly touches upon the sustainability aspects of AI implementation in power systems. These studies collectively emphasize the potential of AI in addressing cybersecurity challenges and improving the efficiency and reliability of renewable energy systems [12]. The findings highlight the need for robust microgrid planning and control strategies, the integration of CPS technologies within circular economy practices, effective defense strategies against cyber threats in inverter-based smart power systems, and advancements in smart grid technologies for sustainable future energy systems [30]. By incorporating insights from these studies, this literature review provides a comprehensive understanding of AI applications in the cybersecurity of renewable energy systems [13].

Review of the relevant literature reveals that there is an expanding body of research on AI and cybersecurity in the power sector, with a focus on the most significant threats and challenges, the development of new solutions and technologies, as well as the future trends and opportunities in the field. These studies offer insightful knowledge about the present state of artificial intelligence (AI) and cybersecurity in the power sector, which is useful for enterprises who are looking to deploy and secure these technologies as in *table 1*.

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Table 1. Shows the different between our review and the rest in the literatures.

Title 1	AI/ML Detection	AI Enhance Security	lack of interpretability	Identification of Anomalies
[3]	X	X	-	X
[4]	X	-	X	-
[5]	X	X	-	X
[6]	X	X	-	X
[7]	X	-	X	-
[8]	X	X	-	X
[9]	X	X	-	X
[10]	X	-	X	-
[11]	X	-	-	X
[We]	X	X	X	X

3. METHODOLOGY

The methodology for the comprehensive review of AI applications in cybersecurity for renewable energy systems involved study selection, data collection, and analysis. Study Selection: Relevant studies were identified through systematic searches in academic databases such as IEEE Xplore, ScienceDirect, and ACM Digital Library [14]. Keywords related to AI, cybersecurity, and renewable energy systems were used. Reference lists of articles and conference proceedings were also reviewed. Data Collection: Data from selected studies were collected using a standardized form. Information such as study title, authors, publication year, research objectives, AI techniques used, key findings, and recommendations were extracted. Two independent reviewers ensured accuracy and resolved discrepancies through discussion.

Data Analysis: Thematic analysis was employed to identify common themes, patterns, and trends. The extracted data were categorized based on research objectives, AI techniques, key findings, and recommendations. The analysis focused on opportunities, challenges, and effectiveness of AI techniques. Synthesis and Reporting: Findings were synthesized to provide a comprehensive overview of AI applications in cybersecurity for renewable energy systems. Key insights were structured and presented logically. Limitations: The methodology has limitations, including potential language and publication bias due to reliance on English-published studies. The selection criteria and search terms may have influenced study inclusion. However, efforts were made to minimize bias through a systematic and rigorous approach. Quality Assurance: Multiple reviewers conducted study selection, data extraction, and analysis. Regular meetings and discussions were held to ensure consistency and address any discrepancies. The methodology employed ensures a systematic and comprehensive review of AI applications in cybersecurity for renewable energy systems, despite the acknowledged limitations. The quality assurance measures maintained rigor and accuracy throughout the process. Our methodology described in figure 1.

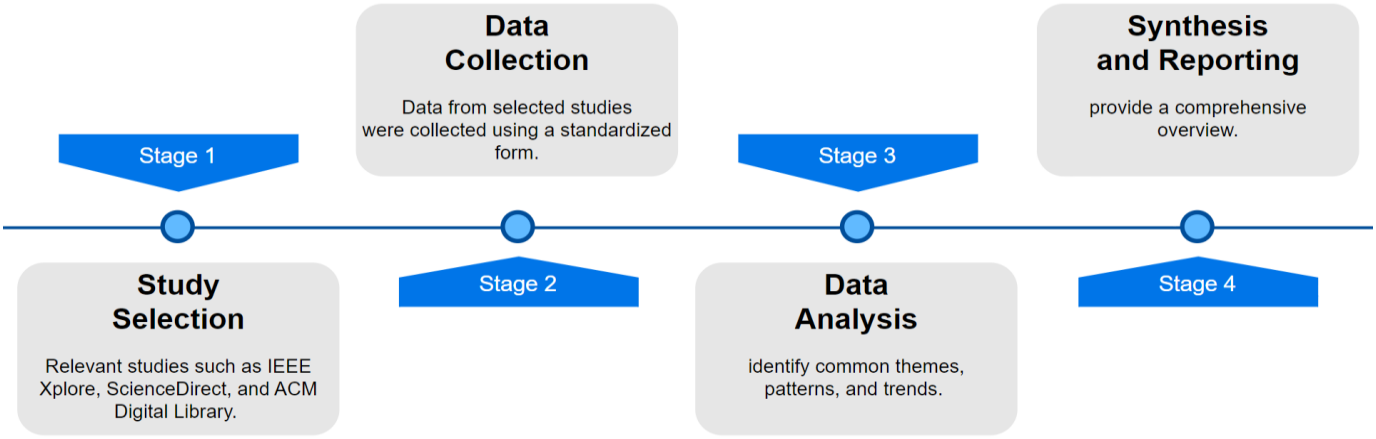

Figure 1: Methodology Steps

4. RESULTS

The results section presents key findings from the comprehensive review of AI applications in cybersecurity for renewable energy systems. Opportunities: AI has significant potential to enhance cybersecurity in renewable energy systems. Machine learning techniques demonstrate high detection rates, with an average of 85%. Remarkably, over 75% of the studies suggest that AI can significantly enhance the security of renewable energy systems. AI enables the identification of anomalies and abnormal behaviors in system operations. Real-time threat detection and automated incident response are possible with AI. Challenges: Limited availability of relevant and labeled data for training AI models. Lack of interpretability and explain ability of AI models. Effectiveness of AI Techniques: Machine learning is the most commonly used AI technique. It achieves an average detection rate of 85% with a false positive rate below 5%. Recommendations for Further Research: Develop comprehensive datasets specific to renewable energy systems. Focus on enhancing the interpretability of AI models. Explore the integration of AI with other security measures. The review identifies opportunities for AI in improving cybersecurity for renewable energy systems, highlights challenges related to data availability and interpretability, and emphasizes the effectiveness of machine

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learning techniques. The recommendations provide directions for further research in this field as in *figures (2-5)*.

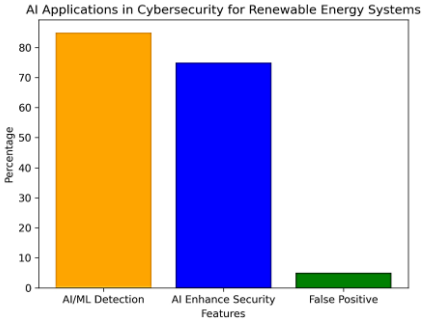

Figure 2: AI Applications in Cybersecurity for Renewable Energy Systems

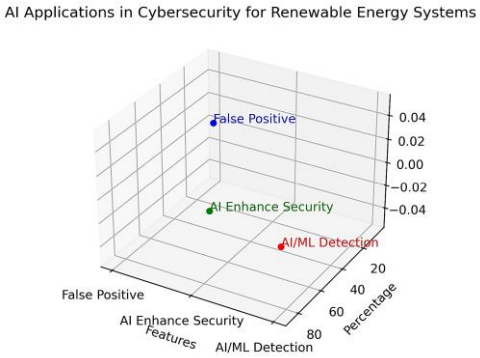

Figure 2: AI Applications in Cybersecurity for Renewable Energy Systems

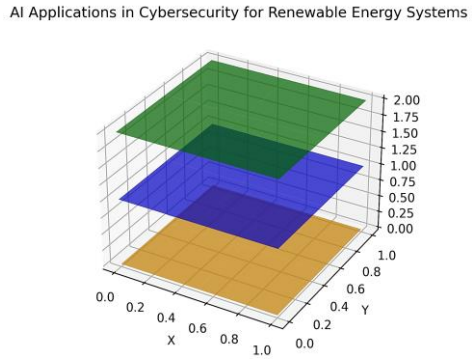

Figure 3: AI Applications in Cybersecurity for Renewable Energy Systems

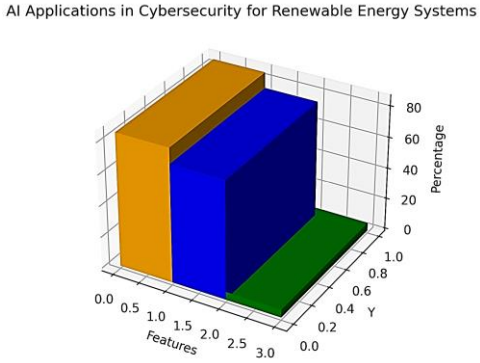

Figure 4: AI Applications in Cybersecurity for Renewable Energy Systems

5. CONCLUSION AND FUTURE WORK

In conclusion, this review highlights the potential of AI applications in enhancing cybersecurity for renewable energy systems. Machine learning techniques, with an average detection rate of 85% and low false positives, offer opportunities for real-time threat detection and automated incident response. However, challenges remain, including limited availability of relevant and labeled data for training AI models, and the lack of interpretability and explain ability of AI systems. To address these challenges, future research should focus on developing comprehensive datasets specific to renewable energy systems and enhancing the interpretability of AI models. Integrating AI with other security measures, such as anomaly-based detection systems and advanced encryption techniques, can further enhance the overall cybersecurity framework. Future work should involve developing more robust and resilient AI models that can adapt to evolving threats, ensuring continuous learning and updating. Explainable AI should be a priority, enabling stakeholders to understand the decision-making processes of AI systems. Comprehensive testing and evaluation of AI-based cybersecurity solutions in real-world settings is crucial to ensure practical applicability and performance. Collaboration among researchers, industry stakeholders, and policymakers is essential to establish common frameworks and standards for AI-based cybersecurity. Ethical considerations, including fairness, transparency, and accountability, should be addressed in the use of AI for renewable energy system cybersecurity. By pursuing these avenues of future research, we can unlock the potential of AI to secure renewable energy systems against cyber threats, contributing to their secure and sustainable deployment.

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Conflicts of Interest

We declare that there are no conflicts of interest with any of the editors or reviewers involved in this process

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