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The Impact of Artificial Intelligence on Electrical Engineering: A Review of Current Applications and Future Prospects

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Abstract

This paper investigates previous research concerning the applications of artificial intelligence (AI) technology in electrical engineering (EE) systems. The EE is one of the fields where AI research gets a lot more attention. This paper examines the potential for AI transformation in EE due to advancements in modern technology and the urgent necessity for innovations in the sector. Recent research papers sourced from open literature constitute the survey dataset, facilitating a comprehensive overview of AI application across key domains of EE. The research focuses on the disciplines of renewable energy (RE), power systems, control systems, and power electronics. The research findings illustrate the benefits and challenges associated with the adoption of AI in these specific EE fields. A survey of the primary AI methodologies encompasses their successful applications and prospective research avenues for future endeavors. This research aims to offer academic guidance for scholars interested in the application of AI in EE by elucidating existing methodologies and fostering future innovation in this ever-evolving domain.

Keywords: Artificial Intelligence, Electrical Engineering, Applications

INTRODUCTION

Artificial intelligence has recently become a captivating instrument that is currently being effectively employed in the development of a diverse array of advanced technologies and systems [1]. In fact, AI has become a key driver of the innovation and has enabled many scientific fields to undergo the significant advancements [2]. This observation applies equally to the AI as an umbrella discipline and also to each of its constituent major branches, such as the machine learning, expert systems, robotics, artificial neural networks (ANNs), natural language processing (NLP), deep learning (DL), computer vision, reinforced learning, data science and data mining, and fuzzy logic (FL). One field that has particularly experienced revolutionary innovations due to AI is EE. These innovations are manifested in many aspects, such as greater efficiency and reliability, alternative versatile designs, and the development of novel systems such as new operating systems, as well as business and industrial automation. Our present review paper is aimed at providing a comprehensive overview of the impact of the use of AI in EE on these aspects [2]. The history of the utilization of AI in EE has evolved gradually over time. Initially, AI and EE developed independently, with AI focusing on the symbolic systems within the computer science departments [3]. However, with the rise of DL, a strong liaison between AI and EE was established, which led to greater overlap between their disciplines and paradigms and even culminated in the transformation of many electrical engineers into AI researchers [4]. Looking ahead, we can safely predict that the future of AI in EE seems bright. Embodied AI, which includes the biological systems intelligence analogy/mimicry and insect the intelligence analogy or mimicry. This is expected to play a vital role in the coming decades [5, 6].

Furthermore, the traditional methodology for designing AI systems, which presupposes a set goal, is predicted to grow increasingly unworkable. Russell [6] proposes a new paradigm in which the machine's confusion about the genuine aim would lead to the qualitatively new types of behavior that are the more robust and controllable. In general, the application of AI in the field of engineering is advancing rapidly, with the potential to significantly alter the fundamental nature and essence of the engineering profession [7]. Some of the new developments of AI in EE include the application of heuristic and optimization algorithms based on AI in power systems [8]. In the field of RE research, numerous AI techniques and algorithms are currently being employed to address a variety of engineering challenges [5]. Additionally, there is an urgent need to adapt the undergraduate electrical and computer engineering (ECE) curriculum to integrate the big data ML-AI courses and content [9].

The use of AI in EE can enhance the operations of the energy systems, particularly those significantly affecting the electricity market, with the introduction of a holistic view [10]. It is also important to develop intruder detection and prevention systems using AI techniques to counter cyber-attacks on electrical power systems [11]. Overall, the development of AI in EE is currently focused on improving power system operations, enhancing energy platforms, and integrating the big data ML-AI into the ECE curriculum. The present review paper plans to introduce the various applications of AI in EE systems, such as control systems, power systems, and RE systems. It strives to secure a complete insight into the role currently played (or can be played in the future) by AI in the broad EE field.

This review paper aims to explore the applications of the Artificial Intelligence (AI) within various domains of Electrical Engineering (EE), spanning power systems, control systems, renewable energy (RE) systems, and power electronics. The investigation explores the application of AI in these industries, emphasizing the benefits and obstacles that come with its implementation. It offers a thorough examination of the technological obstacles encountered during the integration of AI into these particular EE disciplines. Furthermore, the paper compares AI techniques used in electrical engineering with those applied in other domains, such as medical and pharmacological fields, economic systems, and agriculture. By doing so, it offers academic researchers a practical framework to optimize AI applications within their respective areas of study, ensuring a more efficient and targeted approach to future advancements. The methodology employed herein relies on systematically analyzing the existing literature about the use of AI in EE. Research papers from reputed ISI journals will be discussed, including those from publishers like the IEEE, Springer, and

ScienceDirect, among others. The selected research papers will be reviewed based on their relevance to AI utilization and on their scientific merits as well as adherence to agreed-upon scientific standards [12]. In short, this proposed paper intended to provide a very comprehensive, accurate and deep understanding of applications of AI in the field of EE and its effects, influences, and impact on this field. It is also designed to present an ample discussion on the benefits and challenges of using AI in EE. Hopefully, it will serve as a worthwhile addition to the open literature that increases the visibility and interest in the subject.

The Use of Artificial Intelligence in Renewable Energy Systems

In recent years, the utilization of AI in RE systems has experienced a surge in popularity. Researchers have investigated several AI applications to enhance the efficiency and reliability of the RE systems. These applications included demand response evaluation, energy forecasting and the energy storage optimization. This section reviews and summarizes various research papers that indicate the potential of AI in the RE sector. These papers span a wide range of various issues, including the use of AI in solar chimneys, solar collector optimization, and the evaluation of photovoltaic (PV) clean energy projects. They show how AI can be used to increase the energy storage and optimize RE systems. Overall, these studies emphasize the importance of AI in tackling the issues connected with RE systems and enabling the transition to a greener energy future [13].

Table 1.
Summary of AI applications in the Renewable Energy (RE) systems, including key findings, utilizations, and methods used in recent studies.

Paper	Results	Utilizations	Methods
Zulu et al. [14]	The overview of AI use in RE sector in Europe, focusing on smart cities. - AI techniques like machine learning (ML) and natural language processing (NLP) for energy storage optimization, forecasting, and demand response assessment. - Need for synergy to boost AI integration.	Energy storage optimization. - Energy forecasting. - Demand response assessment.	Machine learning - Natural language processing.
Ukoba et al. [15]	Overview of the AI applications in RE systems. - Opportunities for AI in demand response, energy forecasting, and energy storage optimization. - AI's potential in new business models.	Demand response assessment. - Energy forecasting. - Energy storage optimization. - New business models (energy market optimization and trading).	Machine learning (ML) - Deep learning (DL). - Neural networks.
Gupta et al. [16]	- Survey of AI's current state and future scope in RE. - Addressing challenges of intermittent and variable power production in RE systems. - AI's role in wind, solar, energy storage, and energy forecasting.	- Wind energy. - Solar energy. - Energy storage. - Energy forecasting. - Demand response assessment. - Energy management.	- Machine learning. - Fuzzy logic (FL). - Neural networks.
Al- Sayed et al[17]	- AI in NEOM, Saudi Arabia, to power a smart city entirely with RE. - Combined use of solar thermal, photovoltaic, wind tower, and battery energy storage. - AI-enabled RE systems producing dispatchable power	- Solar thermal. - Photovoltaic. - Wind. - Battery energy storage. - Molten salt energy storage.	- AI-enabled integration of RE technologies.

	at a cost of just above 7.5 cents/kWh.		
Abdessadak et al. [18]	- Shortcomings in solar chimney research, with a digital twin approach for global optimization. - MLP-ANN outperformed multivariate regression for solar chimney optimization.	- Solar chimney design optimization. - Building integration of solar chimneys.	- Multivariate regression. - MLP-ANN (multilayer perceptron artificial neural network). – Multi-objective optimization. – Non dominated sorting genetic algorithm II (NSGA-II).
Benammar et al. [19]	- AI techniques used for analysis, design, operation, optimization, control and maintenance of solar tower systems (CST).	- Solar tower system analysis and optimization.	- Various AI techniques for CST systems.
Mohaghegh et al. [20]	- AI in simulating, evaluating, and forecasting RE systems' operation and management. - Overview of AI techniques used in solar energy, such as neural networks and evolutionary algorithms.	- Modeling and forecasting of solar radiation. - Solar PV systems performance and control.	- Neural networks. - Fuzzy logic (FL). - Evolutionary algorithms.
Alawaji et al. [21]	- Evaluated solar power potential for PV projects in Saudi Arabia. - AI models for forecasting solar energy yield, with simple moving averages and naive models performing better.	- Solar energy yield forecasting. - PV project assessment.	- Simple moving average. - Naive models. - Other AI models.
Xia et al. [22]	- Investigated thermal properties of the evacuated tube solar collector with a parabolic concentrator. - Used AI techniques to forecast energy efficiency and temperature difference.	- Thermal performance optimization of evacuated tube solar collector.	- MARS (Multivariate Adaptive Regression Spline). - The Model tree (MT). - Gene-expression programming (GEP).

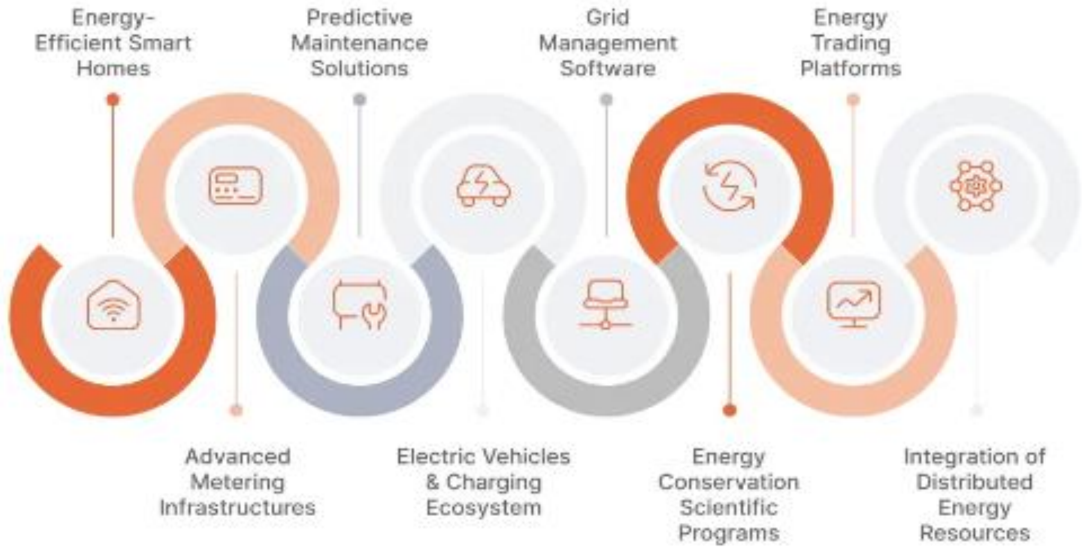

Figure 1.
The use cases of AI in Energy

Holistic approach and collaboration

In the study conducted by Şerban and Lytras [14], the authors stressed that multi stakeholder cooperation is crucial to enhance the contemporary AI application with the RE sector policy context enhancement. This approach is important for the improvement of the problems and optimization of benefits produced by the implications of AI into RE systems because it involves the creation of collective knowledge, sharing of best practices, and technology transfer, together with the building of creativity of fresh business models. Altogether, the table summarizes the state of knowledge on AI usage in the RE sector, the multiple applications, the findings made, and the approaches used in the recent studies. The results of this discussion outlined the potential of AI techniques based on the analyses of enhanced efficiency, reliability, and integration of RE systems while stressing a comprehensive and cross-disciplinary approach, thus advocating for the use of emerging technologies that could transform the systems [15].

Use of Artificial Intelligence in the Power Systems

Artificial intelligence has brought about many sudden, dramatic, and important discoveries or developments, which have enabled academics to investigate the potential uses of AI in a variety of disciplines, including that of power systems. This section serves as a literature review that discusses studies that used AI techniques such as FL, ANN, and metaheuristic approaches to address various issues in power systems such as harmonics and waveform distortion, battery management systems, PV systems, power system protection, hybrid AC-DC microgrids, wind turbines, and energy harvesting technologies. These studies provide vital insights into the potential of AI in optimizing power system performance, boosting efficiency, and lowering costs, as well as emphasizing the importance of ongoing studies in this field. The papers in Table 2 focus on the topics associated with the use of AI and other digital technologies in the power and energy industries.

These works are connected by the fact that all of them use such methods as machine learning, FL, and ANN to solve a number of issues arising from the power systems, energy storage, and RE sources (see Figure 2). Some of the key discussed topics include applying proper AI techniques in harmonic analysis and enhancement of power quality in electrical networks. Eslami et al. [23] illustrated that the use of methods such as the neural networks, support vector machines (SVMs) and decision trees is more beneficial than other traditional harmonic analysis methods, especially under fluctuating operating conditions. This proves that AI has the capability to improve the supervision and control of power quality disturbances. Another focus area is related to the usage of information technologies to solve problems in energy storage systems and batteries. Krishna et al. [24] also talked about how new tools like edge computing, cloud computing, the Internet of Things (IoT) and machine learning can be applied to manage battery modules' performance and energy storage systems.

There are also several papers focused on the methodology of AI and digitalization for increasing the efficiency of RE systems. Fara et al. [25] introduced a digital system that integrates AI, digital twins, and machine learning in off grid PV irrigation system improvement. Likewise, Alhamrouni et al. [26] put forward an advanced PV modeling technique with the help of FL control to facilitate power control. Some papers similarly discussed the protection and control of power systems with the assistance of AI. As demonstrated in a study about the use of ANN and FL in relaying, and some of its applications include fault classification and correction of CT/CVT transients [27]. Control parameters of an FL-based load the frequency control system for an island hybrid power system were optimized by using the artificial bee colony optimization method by Kumar et al. [31]. The earlier and broader papers by Zhao et al. [30] and

John et al. [32] offer other literature reviews encompassing the multidimensional role of AI, machine learning, expert systems, and WSN in penetration into power electronics, power system operation, and smart grid technologies. In conclusion, all of the papers in this table clearly indicate the trends of increasing usage of AI and digital technologies as well as more highly complex analytical methods in the environment and their application to address the multifaceted issues in today's power and energy systems. In the disclosed studies, the described approaches are shown to increase the effectiveness, reliability, and environmental friendliness in different energy spheres.

Use of Artificial Intelligence in the Control Systems

AI is increasingly being used in control systems in a variety of applications, including building control systems, industrial control systems, healthcare, energy management systems, and power grids. In complex and dynamic systems, the AI algorithms are being utilized to minimize energy usage, improve production processes, increase safety and resilience, and streamline decision-making. This section covers many studies that indicate the promise of AI in control systems, ranging from the use of AI in building the heating, ventilation, and air conditioning (HVAC) systems to wind energy conversion system (WECS) optimization and brain–computer interfaces. These studies highlight the importance of AI in tackling control system difficulties and enabling the development of efficient and sustainable technologies for the future [14]. Applying the concept of AI in control systems has become the leading revolution in industrial as well as engineering inventions.

The aim of this paper is to discuss the current developments and usages of AI-integrated control schemes and make clear how they help enhance productivity, environmental concern, and concern for safety in different fields. In Table 3, the advancements in AI-driven control systems: Optimizing industrial efficiency and sustainability is provided, and here is the discussion of AI techniques based on the used applications (see Figure 3). Renewable energy systems: Halhoul Merabet et al. [34] focused on the application and uses of artificial intelligence in WECS control using FL and neural networks. This proved the efficiency of AI-based strategies in increasing energy acquisition and embedding them in the grid. Likewise, Carpanzano and Knüttel [35] looked into the possibility of using AI-based control strategies for PV systems, where better performance as well as reliability was noted. AI operating in building automation and HVAC control: AI is especially to implied in building the automation and HVAC control systems, where it has received so much interest. Siskandar et al. [36] proposed an intelligent HVAC control strategy with systematic methodologies from ANN, which realizes the occupant comfort and energy requirement synchronously. Oborski and Wysocki extended their research on AI and IoT integration for improving building energy management in 2022. AI in healthcare systems: AI has also been applied in the healthcare domain regarding the integration of AI in healthcare systems and its safety.

Multiattribute value theory (MAVT) was applied by Davahli et al. [38] to prescribe the basic structure of a safety-controlling system that is aimed at preventing the dangers of AI-based healthcare applications. Li and Zhou examined the application of AI decision support in enhancing the patients' status and the overall quality of care. AI in industrial automation and energy management: For example, reinforcement learning is already employed in the improvement of the effectiveness of energy consumption and the use of resources within industries [40]. Together with IoT, AI is useful in the diagnosis of decline and faulty constructs of industrial tools. AI in transportation and logistics: Transportation and logistics in this growing era of technological advancements find a new paradigm in the integration of AI. Contemporary intelligent traffic systems have also aided in improving the speed at which traffic flows and reducing traffic congestion [42]. AI is applied in protective control in self-driving vehicles [43] and in the enhancement of an optimal supply chain [44]. Challenges and future directions: Since data collected from the real world are limited, the best ways have to be identified how to subdue this problem [45]. Dedicated scholars are of the opinion that sensing the ever-evolving inventive cumulative advancement in AI algorithms, sensor instruments, edge computing, and AI-facilitated control will only keep on scaling up.

Table 2.
The use of AI and other digital technologies in power and energy industries.

Paper	Results	Utilizations	Methods
Eslami et al. [23]	Analyzed harmonics in electrical power networks using AI techniques like SVM, decision trees, fuzzy systems, and neural networks. - Advantages of AI methods over conventional techniques under varying conditions. - Identified opportunities in ensemble learning and optimal training algorithms.	Harmonic analysis in power networks. - Improving conventional harmonic analysis methods.	Support vector machines (SVM). - Decision trees. - Fuzzy systems. - Artificial neural networks (ANN).
Krishna et al. [24]	Discussed the development of the energy storage systems (ESS) and challenges in monitoring and optimizing battery modules. - Digital technologies like cloud computing, AI, IoT, edge computing, and blockchain can help. - Suggested future research on hybrid AI models and digital twins.	Battery management systems. - Energy storage system optimization.	Cloud computing. – The wireless sensor networks (WSN). - AI. - Internet of Things (IoT). - Edge computing. - Blockchain. - Machine learning (ML).
Fara et al. [25]	Investigated off-grid photovoltaic (PV) irrigation systems using digitalization and numerical modeling. - Developed a digital platform using AI, digital twins, and ML for PV system performance improvement.	Photovoltaic irrigation pumping systems. - Performance improvement of PV systems.	Digitalization analysis. - Numerical modeling. - AI. - Digital twins. - Machine learning.
Chandramouli et al. [26]	Proposed an improved single-diode photovoltaic model using fuzzy logic control for maximum power extraction. - Calculated the voltage–current characteristics and deduced unknown parameters.	Photovoltaic system modeling. - Maximum power extraction.	Single-diode photovoltaic mathematical model. - Fuzzy logic (FL) control. - Resistance calculations.
Saha et al. [27]	Explored the use of AI for power system protection. - Proposed using ANN for CT and CVT transients, fuzzy logic signals, and multicriteria decision-making for digital relays.	Power system protection. - Resolving various relaying problems.	Artificial neural networks (ANN). - Fuzzy logic (FL).
Das et al. [28]	Proposed a harmonic compensation method for interlinking converters in hybrid AC-DC microgrids. - Developed modeling, stability analysis, and virtual impedance design for improving performance.	Improving performance and stability of hybrid AC-DC microgrids.	Modeling and stability analysis. - Virtual impedance design.

Haile et al. [29]	Optimized wind turbine power conversion by employing the Mamdani fuzzy inference system (MFIS) and blade pitch actuator control. - The energy harvesting of wind turbines was enhanced by 16.74% through optimization.	Wind turbine power-harvesting efficiency.	Fuzzy logic (FL). - Optimization techniques.
Zhao et al. [30]	Reviewed AI techniques used in control, design and maintenance of power electronic systems. - Suggested AI applications in data structure exploration, optimization and classification.	Power electronic systems design, control, and maintenance.	Expert systems. - Fuzzy logic (FL). - Metaheuristic approaches. - Machine learning.
Xu et al. [10]	Focused on energy harvesting technologies, introducing portable and wearable self-powered sensor systems. - Demonstrated AI's role in actuating and creating cognitive capabilities.	Portable and wearable self-powered systems.	Energy harvesting technologies. - Information processing. - AI technology.
Kumar et al. [31]	Optimized the load frequency control in an island hybrid power system model by using fuzzy logic (FL) and artificial bee colony (ABC) optimization. - Used SMES for optimizing power and frequency profiles.	Load frequency control in island hybrid power systems.	Fuzzy logic (FL). - Artificial bee colony (ABC) optimization.
John et al. [32]	Discussed intelligent system techniques and the wireless sensor networks in power systems. - Focused on the power optimization using AI and wireless sensor networks in control systems.	Power control management in current power systems.	Intelligent system techniques. - Wireless sensor networks.
Sahraoui et al. [33]	Used an intelligent maximum power point tracking (MPPT) technique that is based on ANN algorithms to optimize grid-connected photovoltaic system energy conversion. - Proposed algorithms improved performance under varying conditions.	Optimizing energy conversion in grid-connected PV systems.	The artificial neural networks (ANN). - MPPT (Maximum Power Point Tracking).

The Key Developments in the Field of AI in Electrical Engineering

Based on the existing literature studies, AI has been significantly used in aspects such as power systems, control systems, and RE. There are also different approaches examined by the authors, including deep reinforcement learning for the optimization of power systems and their connection with the energy systems [46], the application of ANN for practical usage in the energy processes and systems [47], and the use of AI approaches in RE systems for solving complex nonlinear problems without imposing assumptions [48]. Research works have addressed enhancing power generation systems using optimal power flow formulations by means of multi objective optimization techniques [49], presenting AI based reactive power dispatching schemes [50], and exploring machine learning-based approaches for diagnosing interferences in PV inverters.

This study also has disclosed the fate of the power system and RE integration depending on AI techniques to improve the stability, effectivenes and robustness of the power system. Table 4 highlights some of the basic applications of Artificial Intelligence (AI) in Electrical Engineering (EE). AI tools, such as neural networks and fuzzy logic (FL), have been utilized in load forecasting to improve upon traditional methodologies. In fault detection and diagnosis, AI has proven effective in detecting faults within record time and accurately classifying the fault type and severity (as shown in Figure 4). AI is also instrumental in the management of the variability and dispatch of Renewable Energy (RE) within the grid, as well as its integration. In the production, distribution, and scheduling of energy, techniques such as reinforcement learning and multi-agent systems have been implemented. These AI approaches allow for better alignment in generation, distribution, and pricing design, ultimately leading to cost reduction and improved efficiency. Real-time applications, such as Q-learning and genetic algorithms (GAs), have been successfully implemented to enhance these processes. Additionally, AI helps ensure control over power system stability, voltage regulation, and optimal power flow using neural networks, FL, and GAs.

The table demonstrates the potential of AI in addressing various key areas within EE. Cloud-based control systems and Industrial Internet of Things (IoT) are driving transformative applications across various fields. The increasing trend of smart industries, green energy, smart transport, smart buildings, and smart healthcare industries are rapidly adopting cloud-based solutions for system monitoring, management, integration, and optimization. These benefits include industrial process and asset management, distributed RE microgrid control, smart traffic control, and integration with smart buildings using Building Information Modeling (BIM) and IoT, as well as telemedicine and remote patient monitoring. Therefore, the expansion of these technologies enhance the concerns about security,

privacy, and regulatory challenges that must be addressed as these technologies evolve (as seen in Table 5 and Figure 5). In summary, the literature emphasizes the growing significance of cloud-based control solutions across diverse application areas, promoting enhanced efficiency, flexibility, and remote accessibility. Further research is needed to better understand the specific requirements and challenges for implementing such solutions across different sectors.

AI in Renewable Energy Systems

The applications of AI in Renewable Energy (RE) systems has shown substantial progress in several fields (refer to Table 6). The focus of this study is on hybrid RE system integration, where both techno-economic aspects and the optimization of sizing/configuration solutions are highlighted, facilitated by techno-economic analysis and multicriteria decision-making methodologies (illustrated in Figure 6). Hybrid RE system modeling investigates and analyzes the performance of hybrid RE systems and their parameters, with the goal of improving mathematical models, simulations, and operational parameter optimization. Optimizing both technical and economic factors in hybrid RE systems raises challenges related to competing goals, necessitating the consideration of metaheuristic algorithms and multiobjective optimization techniques.

AI applications in hybrid RE systems, including approaches such as the Artificial Neural Networks (ANN), reinforcement learning and FL have proven to perform better than conventional techniques in areas such as performance prediction, fault detection, and energy management of Hybrid Renewable Energy Systems (HRES). In conclusion, it is found that many research opportunities and possibilities exist for using AI to improve design and performance and for solving problems in RE systems in this promising field.

Table 3.

The summary of AI applications in control systems with the results, utilizations, and methods from the literature

Paper	Results	Utilizations	Methods
Halhoul Merabet et al. [34]	HVAC systems account for major energy consumption in buildings. - AI algorithms optimize energy use and maintain occupant comfort. - Energy savings and comfort improvements, though performance is limited by a lack of high-quality data.	Optimize building energy use. - Maintain thermal comfort for occupants.	Systematic evaluation of 20 AI techniques, including pattern detection, optimization, and predictive control. - Individualized comfort models.
Carpanzano and Knüttel [35]	AI-based solutions are relevant for industrial control systems to address sustainability and adaptability. - Overview of solutions for factory-wide optimization.	The sensor fusion. - Model predictive control (MPC). - Collaborative robots. - Self-optimizing machines. - Adaptive automation. - Production supervision and optimization.	Review of AI-based solutions for industrial control systems.
Siskandar et al. [36]	Developed a method using IoT, sensors, and AI (FL) to monitor and control greenhouse temperature and humidity. - Improved quality and quantity in greenhouse agriculture and fishery.	Greenhouse climate control. - Automated temperature and humidity regulation.	Temperature and humidity sensors. - Cooling fan. - Radio frequency identification (RFID) for access control. - FL control system.
Oborski and Wysocki [37]	Created an intelligent visual quality control system for Industry 4.0 manufacturing using CNNs. - Part of a holonic shop floor control system connecting operators, machines, and process monitoring.	Visual quality control. - Manufacturing process optimization.	Historical data collection for big data analysis. - Convolutional neural networks (CNNs) for image-based quality control. - Evaluation of multiple CNN algorithms.
Davahli et al. [38]	Addressed safety concerns of AI in healthcare. - Proposed a safety-controlling system (SCS) architecture using the MAVT approach.	Improve safety and reduce risks in AI-based healthcare systems. - Enhance human–AI interaction. - Implement emergency plans for AI-related incidents.	MAVT approach. - Checklist of safety features for healthcare AI systems.
Li and Zhou [39]	Explored an electrical detection and control system using AI for improved adaptability, efficiency, and safety compared to traditional systems.	Electrical detection and control systems.	Sensors, data acquisition devices, data processing units, and AI algorithms.
Sami [40]	Examined how AI can optimize electric automation control systems to address traditional system limitations.	Electric automation control systems.	AI algorithms.
Salime et al. [41]	Proposed a combined control method utilizing fuzzy field-oriented control (FFOC) and the direct power control (DPC) to optimize operation and ensure the quality of electrical energy in WECS.	WECS.	FFOC and DPC.

Gutierrez-Martinez et al. [42]	Reviewed noninvasive brain–computer interfaces (BCIs) based on P300 and SSVEP for motor rehabilitation. - DL and traditional AI techniques used for classification.	BCIs for motor rehabilitation.	Convolutional neural networks (CNNs), SVMs, and Latent Dirichlet Allocation (LDA).
Fukumoto et al. [43]	Created a remote experimental learning assistance system using ICT to help engineers learn about power systems.	Power systems education.	Remote experimental learning assistance system.
Lee et al. [44]	Established a universal methodology for AI to control energy consumption, creating a framework for energy-saving tools.	Energy consumption control.	AI-based learning, optimization, and control tools.
Guo et al. [45]	Evaluated AI applications in power grids, focusing on power control, generation, and transient stability assessment (TSA).	Power grid management.	AI-based power control, power generation, and transient stability assessment.

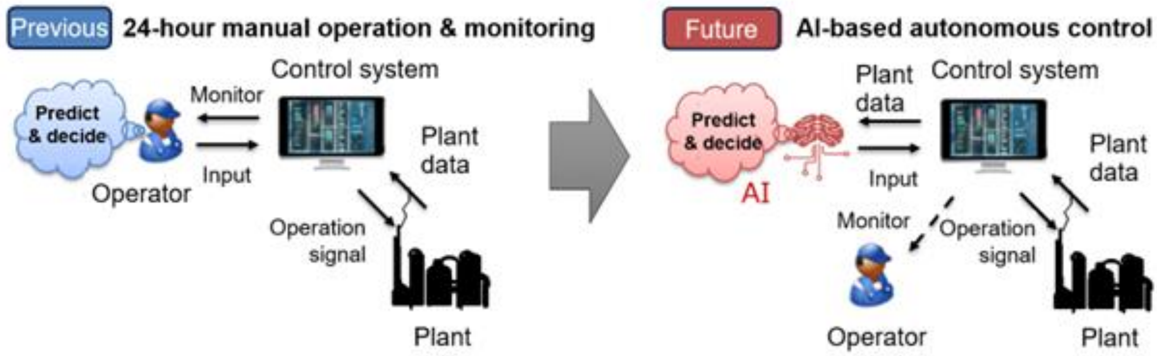

Figure 3.
AI applications in control systems. The diagram demonstrates AI system applications for different applications in control systems comparing manual and autonomous controlling.

Table 4.
The application of AI in the power systems: key points finding, methodology, and references.

Application Domain	Key Points Finding	Methodology	References
Load Forecasting	AI techniques can accurately predict short-term and long-term electricity demand. - Neural networks, FL, and hybrid approaches have outperformed traditional statistical methods.	Artificial Neural Networks (ANN) - Fuzzy Logic (FL) systems - Hybrid models (e.g., neuro-fuzzy and genetic algorithms)	Raza and Khosravi [51]
Fault Detection and Diagnosis	AI can quickly identify faults and their locations in power systems. - Machine learning algorithms can classify fault types and severity with high accuracy.	Support vector machines - Decision trees - Convolutional neural networks	Ali and Choi [52]
Renewable Energy Integration	AI techniques optimize the integration of RE sources into the grid. - Forecasting renewable generation, managing variability, and optimizing dispatch are key applications.	Reinforcement learning - Multiagent systems - Robust optimization	Shi et al. [53]
Energy Management and Scheduling	AI algorithms can optimize energy generation, distribution, and pricing to reduce costs and increase	Q-learning - Genetic algorithms - Multiobjective optimization	Shoaei et al. [54] and

	efficiency. - Techniques like Q-learning and genetic algorithms have been applied.		Brahmane et al. [55]
Power System Control and Optimization	AI helps maintain system stability, voltage regulation, and optimal power flow. - Neural networks, FL, and evolutionary algorithms are commonly used.	The Fuzzy Logic (FL) systems - Artificial Neural Networks (ANN) - Genetic algorithms and particle swarm optimization	Bano et al. [56] and Arya et al. [57]

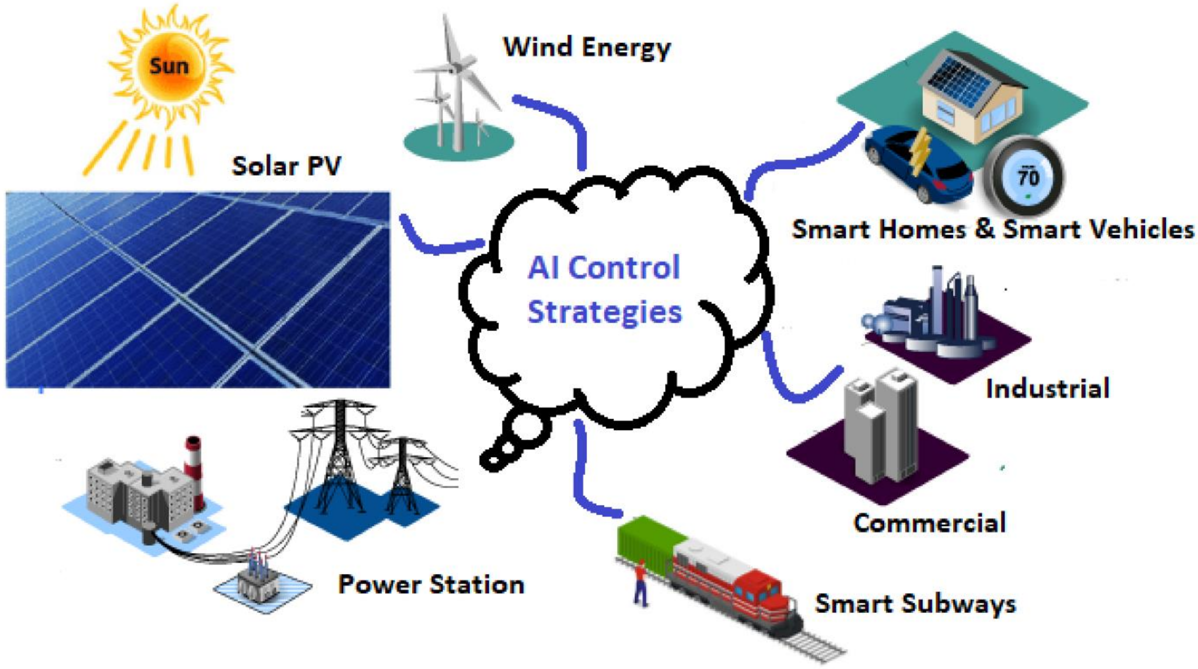

Figure 4.
The diagram in the figure shows the AI applications in power systems [14].

Figure 7 presents the evaluated results of the frequency of AI research publications during 2015–2020 in the form of a bar chart. This again is evident from this chart showing the high growth in the interest and research activity in the AI field within this period of 5 years. The positive trend in the year 2018 signifies that AI is a progressive field in research and is receiving maximum attention from researchers. What can be said about this bar chart is that it gives an exceptionally large general viewership of the exponential growth of publications based on AI subjects [82]. Over the same period between 2015 and 2020 [83], the concentration of AI patent activity by region can be observed from the line graph as shown in Figures 8 and 9. Using this graph of AI innovation and development, one can gain more information about how this area is distributed in geography.

Each shading represents how active the regions are in terms of patenting over the years. If we look at the graph, we can spot that China has had the highest growth in AI patenting compared to other territories like the United States, Europe, and Japan. This all points towards the idea that China is effectively leading in the world when it comes to commercializing AI research into patentable inventions. The use of the line graph provides the ability to compare AI patenting activity with other countries or regions in a streamlined manner. Figure 10 Pie chart of relative frequencies of application of the different AI techniques/methodologies in EE. The above bar chart helps in determining how many papers are related to a particular approach, such as machine learning, DL, and FL. The chosen chart type is as simple as it is effective, providing an instant all-encompassing view of where AI is taking the field of EE today and tomorrow, showcasing which of the AI paradigms reign supreme. It is useful in determining what types of techniques in AI are the most common and widely used concerning a given industry or area of research [84]. All around, these four figures offer a complete overview from an AI development perspective in terms of research publications, patent documents, and using techniques. Overall, with the help of the analysis of the articles, one can identify how technology has developed rapidly and is quickly being implemented in various fields, particularly EE. The integration of bar charts, line graphs, and pie charts helps to supplement and collectively represent comprehensive data insights on the major characteristics of AI innovation and application patterns.

Table 5.
The application of AI in control systems: key points finding, methodology, and references.

Application Domain	Key Points Finding	Methodology	References
Industrial Automation	Remote monitoring and control of industrial processes. - Integration of cloud-based control with industrial IoT.	Simulation-based evaluation. - Discussion of architecture and design principles.	Byeon et al. [59], Mourtzis et al. [60], Lu et al. [61], Wang et al. [62]
Renewable Energy Systems	Cloud-based control of distributed RE systems (e.g., solar and wind). - Optimization of energy generation and distribution.	Simulation-based evaluation. - Experimental validation on pilot setups.	Gao et al. [63] and Ling et al. [64]
Smart Transportation	Cloud-based control of traffic signals and intelligent transportation systems. - Vehicle-to-cloud communication for mobility management.	Simulation and modeling studies. - Discussion of system architecture.	Dong et al. [65], Li et al. [66], Lian et al. [67], Qiu et al. [68]
Building Automation	Cloud-based control of HVAC, lighting, and other building systems. - Integration with building information modeling (BIM) and the Internet of Things.	Simulation-based evaluation. - Proof-of-concept demonstrations.	Huang et al. [69], Wang et al. [70], Hu et al. [71]
Healthcare	Cloud-based control of medical devices and remote patient monitoring systems. - Telemedicine and remote healthcare delivery.	Case studies and feasibility analyses. - Discussion of security and privacy implications.	Hossain [58], Tan et al. [72], Li and Zhou [39], Shah et al. [73]

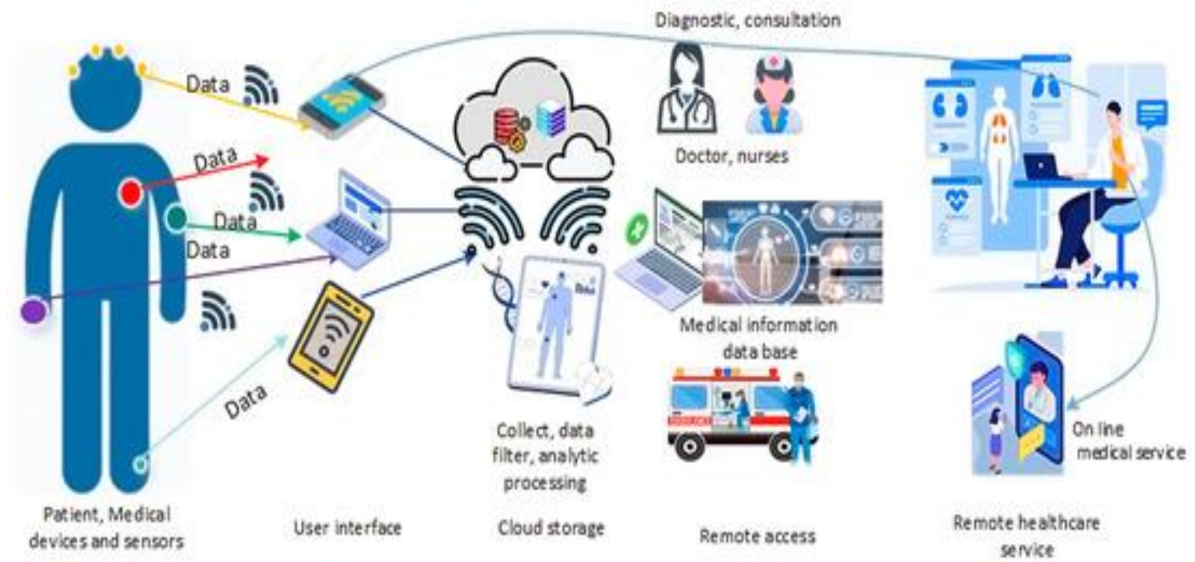

Figure 5.
The diagram of AI applications in control system as telemedicine and remote monitoring [13].

Table 6.
The application of AI in RE systems: key points finding, methodology, and references.

Application/Domain	Key Points Finding	Methodology	References
Hybrid Renewable Energy System Integration	Techno-economic factors for optimal hybrid system design. - Importance of optimal sizing and configuration.	Techno-economic analysis. - Multicriteria decision-making.	Maleki et al. [74] and Sinha and Chandel [75]
Hybrid Renewable Energy System Modeling	Accurate prediction of hybrid system performance under different conditions. - Optimization of system design and operation parameters.	Mathematical modeling. - Simulation and optimization.	Deng et al. [76] and Ma et al. [77]
Hybrid Renewable Energy System Optimization	Improvement of technoeconomic feasibility. - Trade-offs between conflicting objectives (e.g., cost, emissions, and reliability).	Metaheuristic algorithms. - Multiobjective optimization.	Upadhyay and Sharma [78] and Maleki et al. [79]
AI Applications in Smart Renewable Energy Systems for Detection and Prediction	Enhanced performance prediction, fault detection, and energy management. - AI-based approaches outperform traditional methods.	Artificial Neural Networks (ANN). - Fuzzy Logic (FL). - Reinforcement learning.	Bamisile et al. [80] and Maleki and Pourfayaz [81]

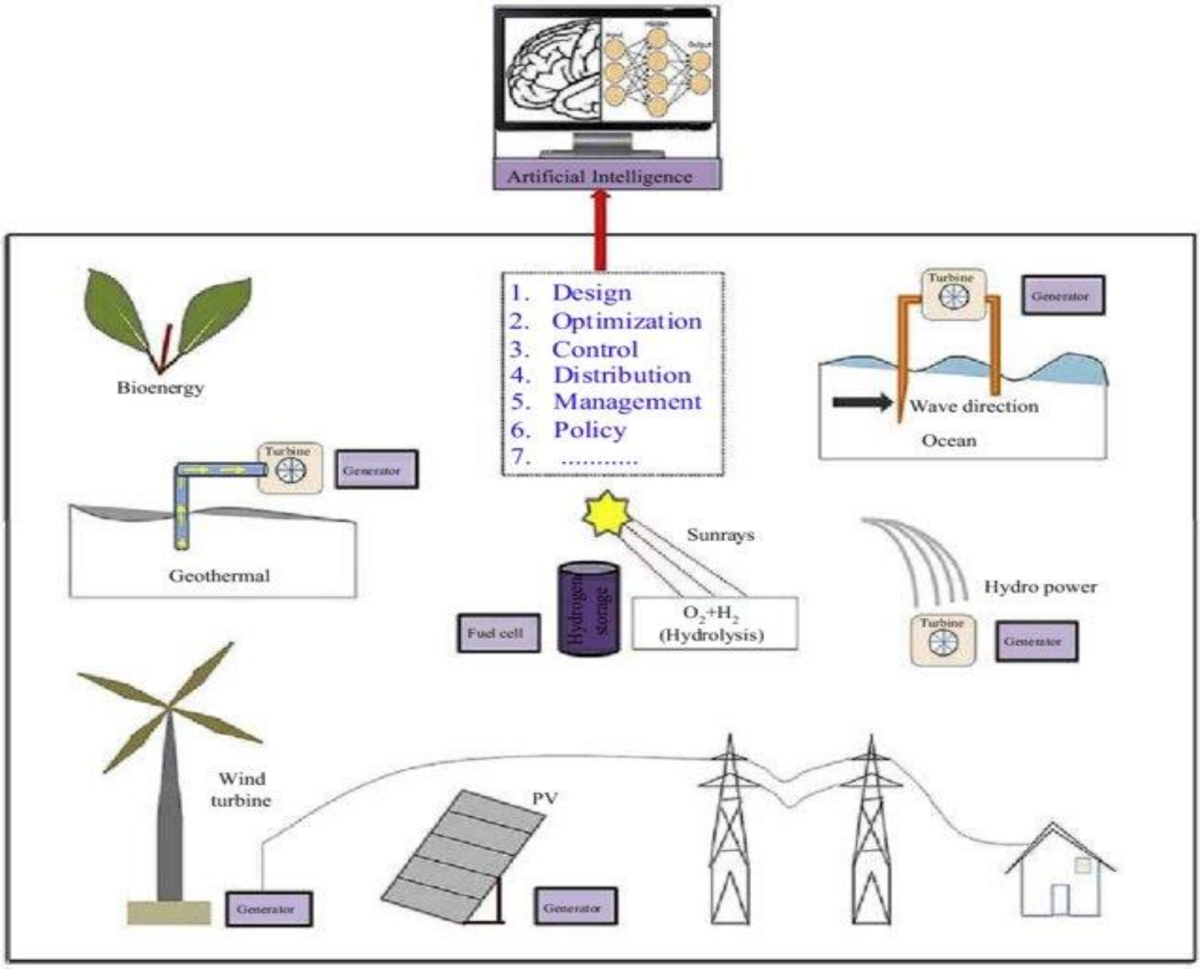

Figure 6:
The illustration of AI applications in the renewable energy [87].

This diagram focuses on system integration for efficiency, optimization to balance conflicting objectives, and smart renewable energy systems that predict, detect, and manage performance under varying conditions.

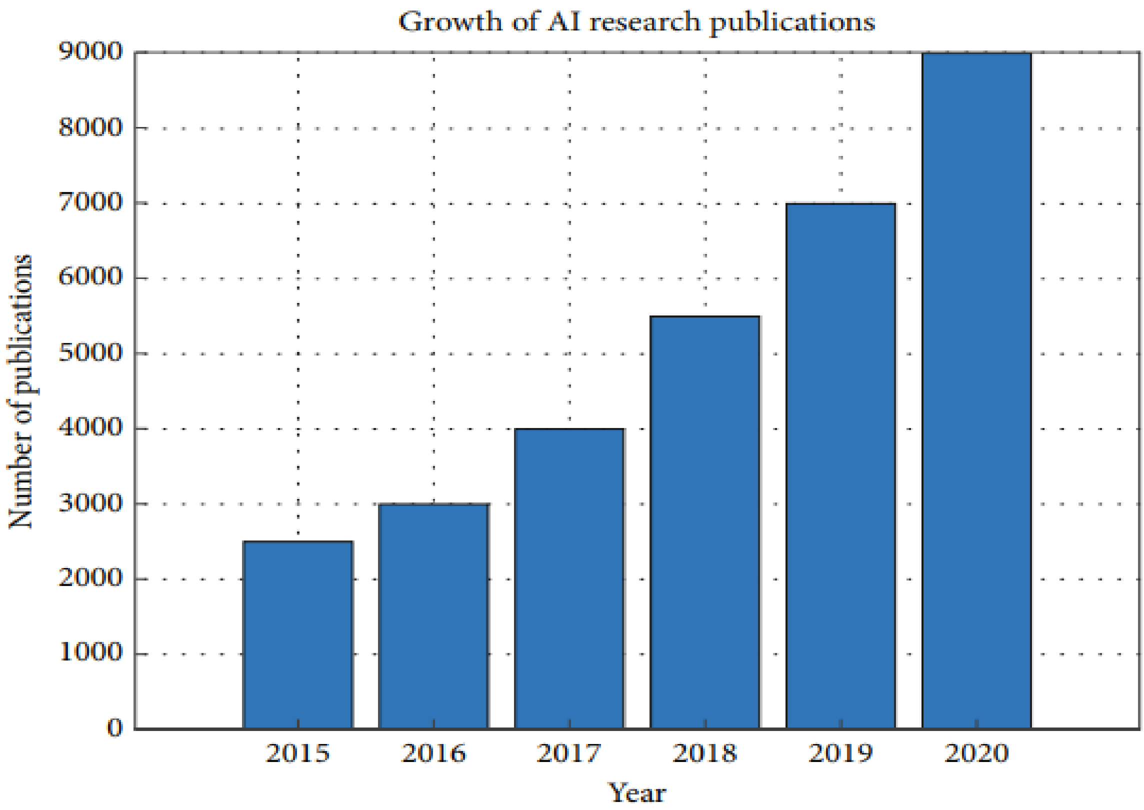

Figure 7.
This bar chart shows the growth in the number of AI research publications from 2015 to 2020.

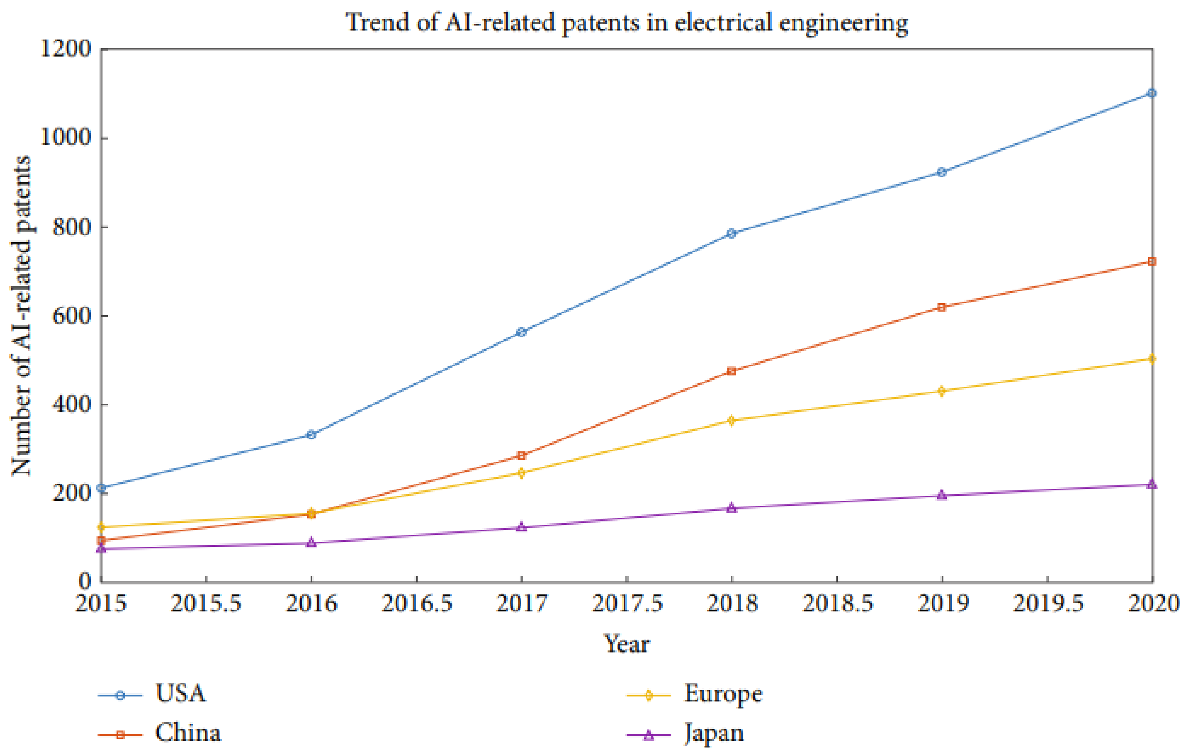

Figure 8.

Trends in AI patent activity by region from years 2015–2020.

Benefits and Challenges of AI in Electrical Engineering

Artificial Intelligence (AI) is transforming the electrical industries at a rapid pace, with the potential to considerably enhance safety, dependability and efficiency. AI-powered systems have the ability to automate processes, make data-driven decisions, and identify and diagnose problems more accurately and quickly than humans. This can lead to significant advantages for electrical systems, including enhanced grid resilience, increased utilization, and reduced costs. However, despite these advantages, there are some drawbacks to applying AI in electrical systems. The implementation of AI systems requires significant skill and resources, there are risks of cyber-attacks, and interpreting and explaining AI decisions remains a challenge. Therefore, it is critical to address these challenges thoroughly before deploying AI in electrical systems. Overall, AI has the potential to transform the electrical industry, but careful management of the associated risks and challenges is crucial for its safe and successful use.

Benefits

From Table 7, we can analyze the benefits of AI in the Electrical Engineering (EE). The integration of AI offers significant advantages in various aspects of electrical engineering. The AI contributes to energy savings by enhancing energy efficiency and reducing waste, leading to improvements in operational efficiency. Achievements in prediction, diagnosis, and preventive measures ensure the early identification of system issues, allowing for timely regulation. Automation of tasks through AI systems reduces the likelihood of errors, especially compared to manual operations performed by workers. Moreover, AI enhances the performance of renewable and smart grids and improves safety through effective failure analysis and regulation. Therefore, the use of AI at the strategic level holds great promise for advancing multiple aspects of EE, as it fosters improvements in energy efficiency, performance, and safety.

Challenges

Table 8 outlines various challenges associated with integrating AI into EE. One of the major issues is the volume and quality of data, including challenges related to large data sets and single-class fault labels. There is also the concern of increasing AI model complexity, which affects interpretability and creates a tradeoff between model complexity and usability. Many buildings have complex electrical systems that are difficult to integrate with AI due to the legacy technology involved, though integrating Information and Communication Technology (ICT) with consumer data presents some advantages. Additionally, AI systems pose security risks, particularly in the form of hacking attempts, necessitating robust security measures to protect these technologies. The development of ethical guidelines and principles to regulate AI in areas such as privacy, bias, and fairness is also essential. Finally, the emergence of super intelligence, or technological singularity, highlights the need for AI systems that are human-friendly and safe for widespread use.

Legal Implications about the Use of Artificial Intelligence

The growing role of AI in various fields, including EE, raises several ethical issues and challenges. Gaud [106] discusses key ethical considerations that should be observed when applying AI in EE. One primary concern is data privacy. The use of AI systems involves handling sensitive information such as customer data, design specifications, or research data, which must be protected through proper data governance policies and security investments. Algorithmic bias is another issue, where AI models may reflect biases present in the training data that leads to the unfair or discriminatory outcomes, especially in the areas like promotion, recruitment and resource allocation. This calls for effective testing for bias and the use of best practices in data collection. Transparency and explain ability are also very important for AI systems, as understanding the reasoning behind decisions fosters trust and accountability.

Safety and reliability are paramount for AI-based applications, such as self-driving systems or predictive maintenance, which must undergo rigorous safety testing and include human-in-the-loop mechanisms to prevent accidents. Ethics frameworks must be developed by organizations to ensure AI systems are used responsibly. These frameworks should address data ownership, fairness, human supervision, and responsibility. Finally, AI interaction is important to consider, as it’s essential to maintain the right balance of human control and comprehensibility, especially in sensitive moments. Addressing these ethical aspects proactively will help ensure that the use of AI in the electrical engineering is done in a responsible and socially acceptable manner.

Table 7.
Key benefits of AI in EE and supporting references.

Benefit	Description	Reference
Increased Efficiency	AI involves algorithms that improve energy consumption efficiency in power systems and reduce energy wastage. - Smart control algorithms in HVAC systems can achieve energy savings of up to 10% compared to standard control devices. - AI improves task scheduling response time, resource utilization, and makes cloud data center systems more energy efficient.	Yayla et al. [89] and Kang et al. [90]
Increased Accuracy	AI applications such as the machine learning and deep learning (DL) enhance the performance of predictive, diagnostic, and electrical maintenance tasks. - AI-based solar power forecasting models are more accurate than traditional models, improving the secure operation of power systems. – The Long Short-Term Memory (LSTM) improves electrical load forecasting, enhancing system reliability.	Wang et al. [91], and Angel et al. [92]
Improved Automation	Machine learning eliminates repetitive tasks and decision-making, reducing human work overload and mistakes. - AI is used in power system planning, design, control, simulation, prediction, estimation, diagnosis, and identification. - Reinforcement learning optimizes mixed autonomy systems that combine automated and human-operated subsystems.	Jiang et al. [93] and Wu [94]
Improved Energy Management	AI aids in controlling renewable energy (RE) systems, microgrids, and smart grids. - AI-based models enhance short-term load forecasts, which are vital in power management due to increasing dynamism in power systems. - Adaptive data-based and evolutionary DL methods have improved estimation accuracy and reduced errors in smart power systems with high RE shares.	Mijanur Rahman et al. [95]
Increased Safety	AI in electrical systems can prevent failures that may lead to accidents or injuries. - Example: NASA's NESTA agent–based monitor analyzes shuttle telemetry data and alerts engineers to potential issues, increasing safety and productivity. - Neural networks have been used to predict earthing resistor conditions in underground mines, improving electrical and explosion protection.	Semmel et al. [96] and Thanh and Bun [97]

COMPARISON BETWEEN DIFFERENT APPROACHES

Comparison between the Artificial Intelligence Techniques Used in Renewable Energy (RE) Systems

Several AI techniques are applied in Renewable Energy (RE) systems, particularly in solar power systems. A comparison of various AI algorithms is summarized below:

1. **Artificial Neural Networks (ANN):**

Faster processing time, higher accuracy, and greater generalizability compared to previous modeling techniques. Useful for various solar predictions and can be trained to forecast future solar energy production using historical data.

2. **Back propagation Neural Network (BPNN):**

A type of ANN commonly used for solar energy prediction. It can forecast future solar energy production using historical data and is applicable for various solar predictions.

3. **Adaptive Neuro-Fuzzy Inference System (ANFIS):**

This combines neural network learning with fuzzy logic reasoning. Useful for multiple types of solar predictions and can be trained for solar energy production forecasting.

4. **Genetic Algorithms (GA):**

An optimization algorithm used to improve solar energy system efficiency. It can optimize solar panel installation, sizing, and overall system control.

Comparison Between Artificial Intelligence Techniques Used In Power Systems

Khandelwal and Kumar [116] provide an detailed overview of AI techniques applied in power systems. These include:

1. **Fuzzy Logic (FL):**

Widely used in converters, controllers, AC/DC drives, and power electronics, FL is useful for harmonic detection, current source inverters, and photovoltaic (PV) systems.

2. **Artificial Neural Networks (ANN):**

Used for rectifier regulation, load forecasting, fault diagnosis and power system operation.

3. **Genetic Algorithms (GA):**

Applied in optimization tasks like optimal power flow, economic dispatch and the unit commitment.

4. **Expert Systems:**

Used to train algorithms for automation systems, diagnosing faults, forecasting load, and controlling power systems.

COMPARISON BETWEEN ARTIFICIAL INTELLIGENCE TECHNIQUES USED IN POWER ELECTRONICS

Zhao et al. [30] discuss various AI techniques used in the power electronics, highlighting the applications and limitations of each method:

1. **Expert Systems:**

Rule-based systems that make judgments based on expert knowledge, used for defect diagnosis and system design. They are limited by the availability of specialized knowledge and may struggle with complex situations.

2. **Fuzzy Logic (FL):**

Deals with uncertainty and imprecision in data. FL is used for control and fault diagnosis but can be difficult to design and tune.

3. **Metaheuristic Optimization Algorithms:**

This is used to find the near-optimal solutions for tasks like system design and control. These algorithms are computationally expensive and may not always find the global optimum.

4. **Machine Learning (ML):**

It uses the algorithms to discover patterns in the data and make predictions. ML is useful for fault diagnosis and control but requires large volumes of data and may struggle with complex systems.

Generally, each of the method has its own benefits and its own drawbacks, and the one chosen is determined by the specific task and the system under consideration. Ramachandran did not provide a direct comparison of AI approaches. He did, however, examine the use of AI in the power electronics for RE systems, while emphasizing how combining AI algorithms with power electrical devices can improve system efficiency and dependability.

Table 8.
AI techniques in EE applications

AI Technique	Advantages	Disadvantages
ANN [125]	Can manage copious amounts of data and nonlinear relationships.	Requires significant training and computational resources.
FL [126]	Can manage imprecise and uncertain data.	Can be difficult to design and optimize.
GA [127]	Can manage nonlinear and nonconvex problems.	Can be computationally expensive.
SVM [128]	Can manage high-dimensional data and nonlinear relationships.	Can be sensitive to kernel choice and parameter tuning.
DL [129]	Can manage complex and unstructured data.	Requires enormous amounts of data and computational resources.

FUTURE DIRECTIONS

However, implementing and applying AI techniques in EE applications have some pros and some cons; below are the following: One major difficulty is the electrical systems, which are often overly complicated and disrupted, which makes it hard to create efficient and stable AI models. Random variations in products, manufacturing, or production processes can be caused by external environments, parts wear and tear, or system failures, which makes it difficult for AI routines to model. Moreover, since several capacities inside the electrical systems are safety-critical, any AI deployment must be validated and evaluated thoroughly to maintain safety and reliability [133]. One of the issues I find interesting is the access/quality of data necessary to train good intelligent machine models. Design problems in EE primarily are dealt with circuits, systems, and equipment that have rare occurrences and may not be well documented. Developing complete teams for training may require time-consuming and exhaustively resourceful efforts. Moreover, due to the nature of data acquired electrically, there may be issues of data privacy and security that have to be well dealt with.

This stems from the fact that many of the AI techniques that have been developed in the recent past, especially the deeper forms of learning, require a lot of computational resources. The use of AI based applications in low-power electrical systems, including consumer devices, home appliances, IoT nodes, or various remote facilities, may necessitate special-purpose hardware platforms or specific algorithmic tuning for real-time implementations [88]. Still, one major concern that might hinder the adoption of AI in EE is the trust and interpretability problem that comes with the model. Some basic EE perspectives may also be problematic—although many EE systems may not mind using AI-based models, many of them may feel uncomfortable with the machine learning "black box" approaches. For this trust barrier to be overcome, it will be necessary for the AI systems to supply engineers with insights as to how they arrive at the decision-making they do in the process of sourcing the required answer.

The fourth key difficulty is related to the ways AI is incorporated into EE applications and workflows that are already in use. However, it illustrates that the integration of AI tools and techniques into traditional EE workflows is a complex process that may require a significant amount of time and effort to complete, particularly when the diverse needs of both the specialized AI and engineering groups are taken into account [88]. However, the following are some of the prospects and areas worthy of future research and augments on the application of AI in EE. One such opportunity to consider is the integration of AI with conventional engineering design methods, where the combined facets of both theories and approaches would be beneficial. This might include such approaches as integrating AI-based anomaly detectors or predictive maintenance schemes with rule-based experts' systems, for instance. Other research directions are federal learning and edge computing, where AI models will be placed closer to the information sources, which, in turn, minimizes the need for the aggregation of data.

They can enhance the AI architecture by ensuring scalability, increased privacy due to decentralization, and real-time functionality for EE solutions. Also, XAI has the prospect of boosting comprehension and interpretability of definite EE AI arrangements. Continuing engineering advancements and expanding the integration of AI models designing the end purposes can potentially enhance trust in the use of these solutions, as the AI models can provide more details on the decision-making process to engineers and end-users. Since the advancement of the various techniques under AI is progressive, we can predict that the integration of such techniques in EE applications will also be progressive, which will result in better electrical systems that are efficient, reliable, and intelligent. Nevertheless, reacting to the issues listed above as well as searching for new research directions will be critical to realizing AI's full potential in this industry.

CONCLUSIONS

The implementation of AI approaches in EE has been a major research focus in recent years. This is because AI has the potential to enable the construction of more efficient, dependable, and automated systems. Many AI approaches, such as heuristic and optimization algorithms, neural networks, machine learning, and DL, have been used to tackle diverse engineering problems in domains such as RE, power electronics, and power systems, according to the examined research publications. In fact, AI has been found to improve system performance, boost energy efficiency, and reduce costs in many domains. However, using AI in EE has considerable problems, such as computational complexity, the requirement for massive data to execute tasks, and the need to address ethical concerns, assure system security, and train technicians for system maintenance.

The articles that were examined herein also emphasized the need to tackle many difficulties in order to ensure the responsible and sustainable use of AI in EE. Based on published results, a comparison of AI methodologies revealed that there is no one-size-fits-all answer for all EE applications. The AI method chosen is determined by the specific application, the available data, and the desired outcome. As a result, it is critical to carefully assess which AI method is best suited for a certain application. Generally, the examined research papers demonstrated the potential of AI to positively alter or modify the discipline of EE, that is, to make this discipline different in details but not in substance, character, or identity, while ensuring that the ensuing change is for the better in some sense.

However, our survey indicates that more effort remains to be made to fully exploit the potential of AI and overcome the obstacles related to its usage. Future research should concentrate on developing the more efficient and effective AI algorithms for EE applications, addressing ethical and security concerns, and training people for system maintenance. Thus, even though there are some difficulties in applying those methods and techniques to EE applications, such as the complexity of the electrical system, data accessibility, trust in the model, and integration with the workflow, there are several potential areas for further research in the future. They consist of applying AI in the traditional engineering design methodologies, employing federated learning along with edge computing for better privacy and real-time performance, and combining AI with explainability for improved interpretability of the outcomes. In the future, AI is thus embedded in the enhancement of the efficiency, reliability, and intelligence of EE. That is why the further development of AI in this field would also necessitate discussing previous problems while determining new ones.

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