International Journal of Scientific Research & Engineering Trends
Volume 11, Issue 2, Mar-Apr-2025, ISSN (Online): 2395-566X

Artificial Intelligence in Energy Management: A Comprehensive Literature Review on Methods, Applications, and Challenges

Jayendra Jadhav, Aashirwad Mehare, Aditya Wandhekar, Sanyukta Pawar, Pranjal Chavan, Vedant Nigade
Dept. Artificial Intelligence Vishwakarma University Pune, India

Abstract- The mounting pressure for efficient and sustainable energy solutions has driven the adoption of Artificial Intelligence (AI) in contemporary energy systems. This literature review consolidates evidence from more than 20 recent studies on AI-based approaches for renewable energy and smart grid management. It discusses AI methods like machine learning, deep learning, reinforcement learning, and optimization techniques applied in energy forecasting, load management, fault detection, and demand response. The review emphasizes AI's application in improving energy efficiency, lowering costs, and facilitating decentralized energy systems. It also touches on the most important hardware devices involved, e.g., photovoltaic panels, smart meters, IoT devices, and battery storage systems. Although it has the potential to transform, the use of AI in energy systems is confronted with various challenges such as high infrastructure expenditure, data needs, system integration problems, and regulatory issues. This paper concludes by establishing research gaps and outlining future directions for the complete utilization of AI to achieve a sustainable and intelligent energy ecosystem.

Index Terms- Artificial Intelligence (AI), Renewable Energy, Smart Grid, Energy Management Systems, Machine Learning, Deep Learning, Load Forecasting, Demand Response, IoT, Energy Optimization.

I. INTRODUCTION

The world movement towards sustainable energy systems is motivated by growing environmental issues, expanding energy requirements, and carbon-emission reduction needs. Renewable energy alternatives like solar, wind, and hydro are potential substitutes for fossil fuels, but their intrinsically intermittent and variable nature poses great challenges to energy stability and efficiency [1], [2]. To solve these challenges, the use of Artificial Intelligence (AI) has proved to be a probable solution for energy system optimization in different industries [3], [4].

AI facilitates intelligent forecasting, real-time monitoring, anomaly detection, and adaptive control in smart grids, smart homes, and industrial settings. Machine learning (ML), deep learning (DL), reinforcement learning (RL), and genetic algorithms are extensively used to improve decision-making and operating efficiency in energy management systems [5], [6]. These technologies help not only in energy saving and operation resilience but also enable decentralized paradigms such as peer-to-peer (P2P) energy trading and demand-side management [7], [8].

This paper provides an exhaustive literature review of more than 20 studies on the applications of AI in renewable energy management and smart grid optimization. It covers methodologies, applications, hardware constituents, advantages, and disadvantages of AI-based energy solutions. The aim is to bring together a coherent perception of existing developments and pinpoint future directions to meet the existing challenges in implementing AI in energy systems

Ai Techniques in Energy Management

Artificial Intelligence methods are playing a revolutionary role in energy systems by making predictive analytics, real-time control, and autonomous decision-making possible. Different AI methods are used based on the application area, from time-series forecasting to optimization, fault detection, and demand-side management [9][10].

Machine Learning (ML) and Deep Learning (DL)

Supervised machine learning models such as Support Vector Machines (SVM), Decision Trees (DT), and Artificial Neural Networks (ANN) are popular applications in load forecasting and anomaly detection [11], [12]. Deep learning algorithms such as Convolutional Neural Networks (CNN) and Long Short-Term Memory (LSTM) networks are better suited for dealing with large volumes of sequential energy data, providing better forecasting accuracy for solar and wind energy production [13][14].

Reinforcement Learning (RL)
Reinforcement Learning is increasingly being adopted for its capacity to learn in changing environments and make optimal choices in the long run. It performs best in demand response, energy trading, and real-time HVAC control systems [15]. Multi-agent RL systems have been successfully implemented in decentralized smart grid systems to manage energy consumption and storage [16], [17].

Optimization and Metaheuristic Algorithms
Genetic Algorithms (GA), Particle Swarm Optimization (PSO), and Ant Colony Optimization (ACO) are widely used for system-level optimization issues, like energy distribution scheduling and microgrid load balancing [18], [19]. These techniques enable cost-effective and energy-efficient configurations without exhaustive computation.

Hybrid Models
Current literature has witnessed a surge in hybrid models that integrate ML/DL with metaheuristics, statistical models, or fuzzy logic for building more accurate and robust models [20]. For example, CNN-LSTM or ANN-GA hybrids are utilized for energy forecasting as well as fault prediction in photovoltaic systems [21].

These AI methods not just enhance forecasting accuracy and grid responsiveness but also lower operating expenditures and encourage sustainable energy habits across all areas.

Application Areas
AI technologies are increasingly being implemented in different areas of energy to meet challenges related to forecasting, load management, optimization, and system control. The following is a description of prominent application areas where AI has been making major contributions.

Smart Homes and Buildings
AI has a revolutionary function in managing energy consumption in urban buildings and smart homes. Intelligent systems are able to manage lighting, heating, and cooling automatically by adapting to environmental patterns and learning users' habits. For instance, Sharma et al. [25][33] proposed an AI-based energy management system with a photovoltaic and storage system for urban buildings that minimizes energy wastage and maximizes sustainability. Likewise, Jha et al. [45] developed an IoT-based AI-integrated Home Energy Management System that facilitates demand-side management as well as distributed generation (DG) support so that homes can be made smart and energy efficient.

Smart Grids and Grid Optimization
In smart grid scenarios, AI makes energy distribution real-time, load prediction, and fault detection possible. AI models improve grid reliability by balancing supply and demand in real-time as well as merging renewable sources dynamically. Khan et al. [23][44] presented a comprehensive review of AI-based approaches to load prediction and anomaly identification in smart grids, which illustrated enhanced grid dependability. Javaid et al. [27] highlighted the role of AI in optimizing power consumption across the grid, emphasizing demand response strategies and predictive maintenance. Zhang et al. [24] and Gupta et al. [22] also emphasized the importance of AI in enhancing grid sustainability and fault detection mechanisms.

Renewable Energy Forecasting
Solar and wind renewable energy systems are significantly weather-dependent, so forecasting is critical for integrating them into the grid. Forecasting of energy output is accurate with AI models like LSTM and hybrid deep learning techniques. Ahmad et al. [26] and Verma et al. [34] explained how AI optimizes renewable integration through prediction of solar radiation and wind speeds. Chen et al. [36] put forth a deep learning-based solar energy forecasting framework that enhances smart grid planning as well as load management and ultimately maximizes energy availability and stability of the grid.

Industrial Energy Management
Industrial facilities have sophisticated energy systems with high consumption levels. AI has the potential to significantly lower operating costs and energy losses by identifying anomalies, optimizing machine performance, and forecasting energy needs. Malhotra et al. [42] investigated AI-based industrial energy management approaches that are consistent with Green Deal goals and found a significant potential to minimize carbon footprints. Nair et al. [43] proved the efficacy of machine learning in industrial equipment monitoring and dynamically changing operation strategies to optimize efficiency.

Agriculture and Smart Irrigation
AI is improving agricultural productivity while minimizing energy and water consumption in the form of smart irrigation. By combining AI with IoT sensors, farmers can take informed decisions with regard to soil moisture, weather, and crop analytics. Verma et al. [30] introduced a model based on AI and IoT for optimal control of irrigation, keeping wastage at a minimum. Das et al. [38] further demonstrated a hybrid reinforcement learning and machine learning model for campus-scale energy systems, including agricultural zones, highlighting AI's adaptability in diverse use cases.

Hardware and Infrastructure

The success of AI in energy management depends greatly on the physical and digital infrastructure that supports data acquisition, control, and optimization. From the literature reviewed, the following types of hardware are most commonly applied in AI-based energy systems:

Photovoltaic (PV) Panels and Wind Turbines

PV panels constitute the core of AI-based renewable energy systems. These are most prominently applied to solar forecasting, instantaneous energy optimization, and MPPT with deep and reinforcement learning techniques [22] [25]. Likewise, wind turbines leverage AI for prognostic maintenance, blade optimization angles, and forecasted power production [24] [26]. AI-assisted drones coupled with image detection technology are used as well to monitor PV facilities from the air as well as on turbine blades [24], [26].

Battery Energy Storage Systems (BESS)

Lithium-ion-based BESS systems are central to the storage of excess energy and smoothing out fluctuations. AI algorithms maximize battery usage patterns, forecast load demand, and enhance energy self-consumption in grid-connected and off-grid systems [25], [29], [34]. Their installation is essential in smart homes, EV-charging stations, and microgrids [26], [40].

Start Meters and IoT Sensors

Smart meters and extensive IoT sensor networks collect up-to-date telemetry data such as voltage, current, power consumption, temperature, and occupancy. These streams feed load forecasting, anomaly detection, and predictive maintenance into AI-based models [23], [31], [33]. Edge computing and fog devices like Raspberry Pi modules and microcontrollers provide the localized AI-driven decision-making and low latency necessary [38], [39].

HVAC Systems and Smart Appliances

HVAC systems integrated with AI (such as fuzzy logic controllers and Q-learning agents) lower energy consumption by as much as 58.5% in residential and commercial buildings through adaptive control mechanisms [30], [32]. Smart thermostats, occupancy-based controls, and networked lighting systems are commonly mentioned in smart campus and building case studies [35], [38].

EVs, Smart Grids, and Microgrids

AI is key to making V2G (Vehicle-to-Grid) systems possible, wherein Electric Vehicles become mobile storage devices. Smart inverters, AMI (Advanced Metering Infrastructure), and SCADA systems make two-way flows of energy and real-time control possible in AI-enhanced smart grids [26], [34], [42]. AI-based microgrids optimize dispatch of energy, enhance reliability during power outages, and integrate distributed generation systems efficiently [29], [43].

Agriculture-Specific Hardware

Precision agriculture systems combine AI with other hardware components like soil moisture sensors, DHT11 humidity modules, water flow meters, pumps, and relays. These are managed by microprocessors (e.g., Raspberry Pi or Arduino) for intelligent irrigation scheduling and minimized resource utilization [30], [37]. AI models allow prediction-based irrigation and dynamic resource allocation in energy-water nexus systems [37], [45].

Benefits of Ai in Energy Management

Artificial Intelligence is transforming energy management through increased efficiency, real-time response, and green practices. According to the reviewed literature, following are the recurring key advantages constantly reported:

Improved Forecasting Accuracy

Machine learning models like LSTM, CNN, GRU, and hybrid deep learning architectures have been demonstrated to greatly outperform conventional statistical models in solar and wind power generation forecasting as well as electricity demand forecasting [22], [24], [25]. Better forecasts enhance grid scheduling, curtailment minimization, and decrease dependency on fossil-fuel-based backup systems [26], [27].

Cost Reduction and Energy Savings

AI-optimized systems lower electricity bills by timing power consumption in off-peak hours, enhancing HVAC efficiency, and minimizing energy wastage. For example, research has shown up to 55% reductions in household electricity bills and 80% savings in power usage in AI-driven 5G network energy management systems [24], [30], [33].

Enhanced Grid Stability and Reliability

Real-time monitoring of the grid, fault prediction, and dynamic load management are enabled by AI, which leads to improved grid resilience. Proactive scheduling of maintenance and self-healing measures minimize the risk of blackouts and increase equipment lifetime [25], [32], [34].

Sustainable and Decentralized Energy Systems

AI supports decentralized energy generation via peer-to-peer trading platforms, smart contracts, and blockchain technology. These technologies empower prosumers and communities to manage and share renewable energy efficiently, particularly in microgrids and rural installations [26], [29], [42].

Smarter Consumer Engagement and Demand Response

AI algorithms facilitate individualized demand-side management based on real-time consumption behavior, which allows consumers to shift loads smartly. AI-driven dynamic pricing models encourage off-peak usage, which enhances energy efficiency and reduces peak demand charges [30], [38], [39].

Multi-Sector Applicability

Applications of AI range across various industries, such as agriculture (intelligent irrigation), commercial buildings (efficient HVAC), and industrial automation (fault-tolerant manufacturing systems). Case studies have shown significant increases in resource utilization, yield, and productivity [30], [37], [40].

Challenges and Limitations

Notwithstanding the revolutionary possibilities of AI in energy systems, various challenges stand in the way of its large-scale implementation. These challenges cut across technical, economic, infrastructural, and policy-related aspects, as the reviewed literature testifies.

High Data Requirements

Deep learning, LSTM, and reinforcement learning AI methods need huge amounts of clean, labeled, and continuous data to function effectively. Yet, numerous areas, especially in developing nations, are confronted with challenges in data availability, sensor coverage, and real-time transmission [24], [26], [35].

High Infrastructure and Deployment Costs

The deployment of AI-based energy management systems requires substantial capital expenditure on IoT infrastructure, battery energy storage systems (BESS), smart meters, and computing hardware. For instance, a study demonstrated a breakeven time of more than 13 years for AI-controlled PV+BESS configurations, rendering short-term adoption economically unfeasible [30], [31], [40].

Integration with Legacy Systems

Existing power grids, production facilities, and building control systems are generally not built with AI in mind. The implementation of AI on such legacy systems creates interoperability issues and even necessitates a total system replacement, driving costs and implementation times up [29], [34], [36].

6.4 Cybersecurity and Privacy Risks

Real-time monitoring and control-based AI systems that are dependent on cloud or edge networks are susceptible to data breaches, cyberattacks, and tampering. Maintaining data integrity and secure communication in IoT-based smart energy systems is an ongoing issue in the literature [23], [32], [38].

Lack of Transparency in AI Models

Deep learning models, though strong, tend to be "black boxes"—generating outputs without explanations. This lack of interpretability impedes trust and accountability, especially in high-stakes applications such as grid stability and predictive maintenance [27], [37], [39].

Regulatory and Workforce Gaps

A lack of international uniformity in policies and standards governing the ethical and safe application of AI in energy systems exists. In addition, there is a severe shortage of experts who possess both energy domain expertise and proficiency in AI technologies that stands in the way of implementing this technology [25], [33], [41].

Future Research Directions

To maximize the transformative power of AI in energy systems, however, future research needs to tackle crucial technical, infrastructural, and ethical challenges. Collective efforts must be put into making AI-powered energy solutions scalable, transparent, and secure.

Explainable and Transparent AI (XAI)

To promote trust and safe deployment in mission-critical infrastructure, research needs to give top priority to the development of explainable AI (XAI). Enhancing model interpretability will be important for use cases such as load forecasting, anomaly detection, and fault detection, where transparency and regulatory compliance are of the utmost importance [24], [25], [27].

Data Interoperability and Standardization

One of the major gaps in AI integration in energy systems is the absence of open data formats and communication protocols. There should be research aimed at developing open datasets, interoperability standards, and open formats to facilitate simpler model deployment and integration with legacy infrastructure [28], [32], [35].

Lightweight and Transfer Learning Models

AI solutions need to be flexible to low-resource settings, including rural or microgrid-based installations. Transfer learning methodologies and lightweight AI algorithms should be researched in the future to lower computational expenses without compromising performance [23], [29], [34]. These technologies would improve the implementation of AI in resource-limited environments [23], [29], [34].

Secure and Resilient AI Frameworks

The increasing dependence on real-time data in smart grids and IoT-based systems necessitates sound cybersecurity. Future work should focus on creating fault-tolerant and secure AI architectures. These encompass secure edge computing, adversarial learning defense, and anomaly-aware models capable of identifying and countering cyber-physical attacks in energy networks [26], [30], [38].

AI Integration with Emerging Technologies

There is great potential for AI to complement new technologies such as blockchain for decentralized energy trading, quantum computing for optimization, and 5G for low-latency grid control. Studies investigating these intersections

International Journal of Scientific Research & Engineering Trends
Volume 11, Issue 2, Mar-Apr-2025, ISSN (Online): 2395-566X

could unlock new opportunities for AI in the energy sector, allowing for more efficient and resilient systems [27], [33], [36].

Policy and Workforce Development
With the pace of development in AI technologies, there is an immediate need for regulatory guidelines controlling their safe and ethical application to energy systems. In addition, interdisciplinary education courses need to be established to develop a workforce educated in both AI and energy management to provide a pipeline of expert professionals [31], [37], [39].

II. CONCLUSION

This review of literature underscores the revolutionary potential of Artificial Intelligence to make energy systems more efficient, reliable, and sustainable. Through the integration of findings from more than 20 studies, the review brings out how AI methods, like machine learning, deep learning, reinforcement learning, and optimization techniques, have been used with considerable success in key areas, such as load forecasting, renewable energy forecasting, demand-side management, and fault detection.

The merging of AI with intelligent grids, renewable energy resources, and IoT infrastructure has yielded great dividends—enhanced predictive accuracy, lower operating expenses, increased grid stability, and support for decentralized energy systems. Nevertheless, there are some monumental challenges like high data demand and infrastructure, the issue of cybersecurity threats, complexity in merging AI with old systems, and the black box nature of complex AI models that still hinder broad-scale adoption.

To address these weaknesses, research in the future has to centre on enhancing explainable AI, crafting light and safe models, ensuring interoperability between data, and building policy infrastructure that enables ethical and scalable implementation of AI for energy. With continued progress of AI, integration with cutting-edge technologies like blockchain, 5G, and quantum computing is poised to dominate the evolution of the next intelligent and sustainable energy network.

In summary, AI is leading the world's energy shift, providing potent solutions to drive the transition to cleaner, smarter, and more secure energy systems.

REFERENCES

1. M. A. Khan et al., "AI-Empowered Methods for Smart Energy Consumption," Int. J. of Energy Research, 2022.
2. F. Ahmad et al., "Comprehensive Study of AI in Renewable Energy," Renew. Sustain. Energy Rev., 2021.
3. P. Kumar et al., "Present and Future of AI in Renewable Energy," Renew. Sustain. Energy Rev., 2022.
4. Z. Chen et al., "AI-Based Forecasting for Optimized Solar Energy Management," MIT Thesis, 2023.
5. A. Das et al., "Smart Green Energy Management for Campus," Smart Cities, 2023.
6. A. Gupta et al., "AI-Powered Energy Community Management," IEEE Access, 2021.
7. R. Zhang et al., "AI-Powered Smart Grids," Energies, vol. 14, 2021.
8. N. Javaid et al., "AI-Driven Approaches for Optimizing Power Consumption," Sust. Energy Technol. Assess., 2023.
9. P. Kumar et al., "Present and Future of AI in Renewable Energy: A Comprehensive Survey," Renewable and Sustainable Energy Reviews, vol. 165, 2022.
10. F. Ahmad et al., "Comprehensive Study of AI in Renewable Energy," Renewable and Sustainable Energy Reviews, 2021.
11. R. Singh et al., "Leveraging AI in Energy Management: Evaluating Machine Learning-Based Solutions for Efficiency," SpringerLink, 2023.
12. M. A. Khan et al., "AI-Empowered Methods for Smart Energy Consumption," Int. J. of Energy Research, 2022.
13. Z. Chen et al., "AI-Based Forecasting for Optimised Solar Energy Management," MIT DSpace, 2023.
14. A. Verma et al., "Optimizing Renewable Energy Systems Through AI," SpringerLink, 2023.
15. A. Das et al., "Smart Green Energy Management for Campus," Smart Cities, 2023.
16. R. Zhang et al., "AI-Powered Smart Grids for Energy Optimization," Energies, vol. 14, 2021.
17. A. Gupta et al., "Artificial Intelligence-Powered Energy Community Management," IEEE Access, 2021.
18. S. Singh et al., "Energy Management in Renewable Energy Systems Using AI," ResearchGate, 2023.
19. M. Sharma and R. Bhardwaj, "AI in Energy Transition," Energy Reports, 2022.
20. S. Joshi et al., "AI-Driven Energy Management in Industry," ResearchGate, 2023.
21. T. Verma et al., "AI-Powered Autonomous Energy Management System for Hybrid Heat Pump," ResearchGate, 2023.
22. A. Gupta et al., "Artificial Intelligence-Powered Energy Community Management for Developing Renewable Energy Systems in Smart Homes," IEEE Access, vol. 9, pp. 1394-1407, 2021.
23. M. A. Khan et al., "AI-Empowered Methods for Smart Energy Consumption: A Review of Load Forecasting, Anomaly Detection, and Demand Response," International Journal of Energy Research, 2022.

24. R. Zhang et al., "AI-Powered Smart Grids for Energy Optimization and Sustainability," Energies, vol. 14, no. 5, 2021.
25. M. Sharma et al., "An Efficient Artificial Intelligence Energy Management System for Urban Building Integrating Photovoltaic and Storage," Energies, vol. 15, no. 7, 2022.
26. F. Ahmad et al., "Comprehensive Study of the Artificial Intelligence Applied in Renewable Energy," Renewable and Sustainable Energy Reviews, vol. 152, 2021.
27. N. Javaid et al., "AI-Driven Approaches for Optimizing Power Consumption: A Comprehensive Survey," Sustainable Energy Technologies and Assessments, 2023.
28. S. Joshi et al., "Utilization of Artificial Intelligence in the Optimization of Renewable Energy Systems and Grid Management," ResearchGate, 2023.
29. M. Sharma and R. Bhardwaj, "Integrating Artificial Intelligence in Energy Transition: A Comprehensive Review," Energy Reports, vol. 8, 2022.
30. T. Verma et al., "Harnessing AI and IoT for Optimized Smart Irrigation: Integration and Resource Conservation," ScienceDirect, 2022.
31. N. Javaid et al., "AI-Driven Approaches for Optimizing Power Consumption: A Comprehensive Survey," Springer, 2023.
32. R. Singh et al., "AI-Driven Approaches for Optimizing Power Consumption: A Comprehensive Survey," Springer, 2024.
33. Sharma et al., "An Efficient Artificial Intelligence Energy Management System for Urban Building Integrating Photovoltaic and Storage," Energies, vol. 15, no. 7, 2022.
34. A. Verma et al., "Optimizing Renewable Energy Systems Through Artificial Intelligence: Review and Future Prospects," SpringerLink, 2023.
35. S. Singh et al., "Energy Management in Renewable Energy Systems Using AI," ResearchGate, 2023.
36. Z. Chen et al., "AI-Based Forecasting for Optimised Solar Energy Management and Smart Grid Efficiency," MIT DSpace, 2023.
37. T. Verma et al., "AI-Powered Autonomous Energy Management System for Hybrid Heat Pump and Solar Thermal Integration in Residential Building," ResearchGate, 2023.
38. A. Das et al., "Smart Green Energy Management for Campus: An Integrated Machine Learning and Reinforcement Learning Model," MDPI Smart Cities, vol. 8, no. 1, 2023.
39. S. Kumar et al., "AI-Driven Energy Optimization Enhancing Efficiency in Urban Environments with Hybrid Machine Learning Models," SSRN, 2024.
40. [40] S. Joshi et al., "Energy Management in Renewable Energy Systems Using AI," ResearchGate, 2023. [Repeated in other sections].
41. N. Patel et al., "AI-Driven Approaches for Optimizing Power Consumption," SpringerLink, 2024.
42. R. Malhotra et al., "AI-Driven Energy Management: Innovative Solutions for Achieving Green Deal Targets in Industry," ResearchGate, 2023.
43. A. Nair et al., "Leveraging AI in Energy Management: Evaluating Machine Learning-Based Solutions for Efficiency," ResearchGate, 2024.
44. S. Khan et al., "AI-Empowered Methods for Smart Energy Consumption: A Review of Load Forecasting, Anomaly Detection, and Demand Response," SpringerLink, 2023
45. A. Jha et al., "AI Powered IoT-based Home Energy Management System towards DG Integration," ScienceDirect, 2022. [Online].