AI-Driven Decentralized Energy Systems: A Review of Peer-to-Peer Renewable Energy Networks

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Abstract

This work examines the transformational potential of AI-based decentralized energy systems: P2P renewable energy networks interconnect AI, blockchain technology, and multi-agent systems, thus circumventing the barriers of traditional centralized grids. This paper will trace how their latest trends in real-time energy optimization, secure smart contracts, and autonomous coordination of distributed resources can enhance grid resilience, minimize transmission losses, and democratize energy markets. However, it becomes evident that to enable mass adoption; significant challenges must be addressed regarding renewable energy intermittency, scalability limitations, regulatory loopholes, and cybersecurity threats. Through synthesizing current research and the analytical case of Brooklyn Microgrid, this paper discusses some of the barriers and potential future directions that must be emphasized, such as hybrid optimization models, standardized frameworks, and inclusive design for accelerating transitions towards sustainable and equitable energy systems.

Keywords: Decentralized energy systems; Peer-to-peer energy trading; Artificial Intelligence; Blockchain; Multi-agent systems; Renewable energy; Smart grids

1. Introduction

Decentralized energy trading is quickly receiving more attention as more people demand clean, efficient, and sustainable energy systems. The centralized generation and distribution that characterize the traditional energy system face energy losses, infrastructure costs, environmental concerns, etc. In this context, decentralized energy systems (DESs) are a viable alternative to generating and consuming energy locally. This allows individual "prosumers," those who produce and consume energy, to participate in energy markets actively. This paradigm shift has been enabled by recent advancements in renewable energy resources and information and communication technologies (ICT) [1].

Decentralized energy systems have deemed peer-to-peer (P2P) energy trading core in their operation. It pertains to the direct transaction of energy between prosumers without centralized intermediation. The P2P energy networks can help reduce the cost of transactions, improve energy access, and increase grid resilience. These networks operate through smart contracts, blockchain technologies, and secure digital platforms that autonomously execute transactions. Globally, P2P energy systems are gaining prominence, given their potential in energy democratization and sustainability, which encourages more participation of households and businesses in the energy economy [2].

Artificial Intelligence (AI) is an important technology to structure and balance P2P energy trading systems' performance, efficiency, and security. AI optimizes energy generation, storage, and consumption profiles

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through large sets of data analysis. Machine learning, predictive analytics, and multi-agent systems play a central role in enabling intelligent decision-making in decentralized energy networks. Furthermore, AI utilizes this intelligence to simultaneously predict demand and supply, optimize their operations, and stabilize P2P transactions from market volatility and grid imbalance [3].

On the one hand, integrating AI into decentralized energy systems improves operational efficiency, enhancing the security and transparency of energy transactions. These energy exchanges are recorded on a tamper-proof platform, with blockchain technology and AI as facilitators. Meanwhile, smart contracts handle transactions upon the existence of specific conditions, minimizing the likelihood of fraud and mistakes. Moreover, AI-supported cybersecurity mechanisms safeguard sensitive data and ensure the integrity of decentralized energy systems, thus creating trust among prosumers and other players [4].

However, several challenges stand in the way of realizing AI-driven P2P energy systems. They include technological limitations, regulatory uncertainties, and the quest for robust infrastructure. Data privacy, interoperability, and the absence of standards can hamper decentralized energy networks from going mainstream. Interfacing intermittent renewable sources like solar and wind into the mesh would require advanced forecasting and energy management strategies, which call for sophisticated AI solutions [5].

The present review will provide a detailed analysis of AI-augmented decentralized energy systems focusing on P2P renewable energy networks. It discusses technological drivers, benefits, and challenges related to these systems. Areas of AI-focused applications in energy trading published recently are presented as possible use cases in the study, with future research directions being laid out. The review acts as a stepping-stone to better understanding the AI pollutants in the cleanup of energy systems and facilitating a sustainable, resilient, and decentralized energy future.

2. Literature Review

The rapid evolution of decentralized energy systems and increasing penetration of renewable energy resources are causing fundamental changes in modern energy distribution systems. This has necessitated understanding intelligent and adaptive energy management solutions in research areas to ensure reliability, flexibility, and efficiency. Recent literature has highlighted AI, multi-agent systems, blockchain technology, and optimization algorithms that can serve as important instruments for addressing the complex problems of decentralized energy trading and management. In particular, peer-to-peer (P2P) energy trading frameworks, smart contracts, and distributed control mechanisms have emerged as key enablers for secure and transparent energy transactions. The section deals with comprehensive reviews of recent contributions. However, it is limited to advanced methodologies and emerging trends concerning energy management systems, decentralized energy trading models, and optimization techniques for interconnected microgrids.

With growing demand, aging infrastructure, and the global switch to cleaner energy generation, voltage stability has become integral to operating a power system. The research presented in [6] identified DG-renewable energy technologies such as solar photovoltaic (PV) systems, wind turbines, and small hydropower as one key remedy to enhance voltage stability in modern power systems. The technique employed by DG in voltage regulation consists of localized power generation to minimize transmission losses, combat voltage drops, and enhance the power network's total resilience. In addition, DG encourages reactive power compensation and lowers dependence on centralized generation, thus enhancing balanced power flows and the system's reliability. On the other hand, there are operational reverse effects from DG integration, such as voltage dips, reverse power flows, and harmonics. To this end, applying advanced control measures, grid modernization initiatives, and integrating efficient energy storage systems is seen to resolve these challenges and maximize the benefits of DG. Ultimately, the investigation highlights DG's technical, economic, and environmental plausibility in creating a sustained and resiliency-oriented power system adaptable to contemporary energy transition goals.

It has become imperative for efficient and sustainable energy management as businesses enter an environment of rising energy demands. The article labeled [7] describes the AI-powered smart grids as a transformational solution that uses machine learning, real-time analytics, and automation to optimize energy consumption, enhance grid reliability, and integrate renewable energy resources. Predictive analysis, internet-of-things (IoT) integration, and edge computing are core requirements of real-time energy optimization. Predictive analysis, internet-of-things, and edge computing are core requirements of real-time energy optimization. There are other advantages, such as cost reduction, improved energy efficiency, and

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reduced carbon emissions. However, such solutions also have specific challenges like cybersecurity threats, high infrastructure costs, and regulatory barriers. However, overcoming these requires policymakers, energy providers, and technology developers to work hand in hand. Some future innovations expected to enhance innovative grid technology and facilitate sustainable energy management include quantum computing, decentralized energy networks, and AI-enhanced energy storage systems.

This paper presents an innovative, completely decentralized, and intelligent energy management system (EMS) for smart microgrids based on a reinforcement learning (RL) strategy [8]. Since the authors developed an EMS for maximizing benefits not just to the microgrid but its components, including customers and distributed energy resources (DERs), as highlighted in the study quoted above, designing an EMS has been challenging due to the uncertainty associated with the renewable energy sources and the fluctuating demand from the customers. To address the aforementioned, he formulated the energy management problem as a finite Markov decision process, where each entity in the microgrid works as an intelligent agent. Thus, an efficient and model-free Q-learning algorithm derived the best policy applicable by these agents for optimizing the operations of renewable and non-renewable resources while minimizing battery degradation; hence, costs incurred from replacements are also minimized. In addition, it proposed two load-shifting schemes that could help customers lower their costs without sacrificing comfort. The system was evaluated under four operation scenarios: no learning, generator learning, customer learning, and whole learning. Simulation results from real power-grid datasets have demonstrated that this approach is superior to the traditional Monte Carlo method, proving it superior for innovative microgrid energy management.

In today's energy arena, microgrids are considered an enhanced element for system improvement, resilience, and sustainability. The research in [9] proposed influencing microgrid operations with a decentralized peer-to-peer energy trading system based on blockchain technology. Here, smart contracts over the Ethereum platform secure and allow transparency and efficiency for energy transactions in microgrids. Here, the Energy Token and Demand Response contracts allow dynamic energy trading facilitated through automation of transactions without charging an intermediary, thus optimizing surplus energy usage and reducing dependence on the primary grid. It was modeled in Simulink, passing energy credits as ERC-20 standard tokens while the demand-response contract modulated energy prices and rewards according to real-time energy production and consumption. Further, the Web3 library provides smooth connectivity from the blockchain network to microgrid components. Experimental results confirmed the system's efficacy, especially in establishing energy trading in solar peak generation hours, thus illustrating the potential of blockchain-based decentralized energy management in modern microgrids.

Microgrids are vital links in energy systems regarding resilience, sustainability, and operational performance enhancement. In the research discussed in [10], a novel decentralized peer-to-peer energy-trading framework was designed based on blockchain technology to enhance energy transactions in microgrids. The proposed system utilizes smart contracts deployed on the Ethereum blockchain, namely the Energy Token and Demand Response contracts, which ensure transparent, secure, and automated energy trading between distributed entities. The framework does away with intermediaries and enables a reduction in transaction costs, hence promoting the optimal use of excess energy to reduce dependence on the primary power grid. The architecture system model was then set up in Simulink, where standard ERC-20 tokens represented energy credits, while the Demand Response contract dynamically updated energy prices and rewards for market participants guided by real-time generation and consumption trends. The infrastructure of blockchain and microgrid components were seamlessly interconnected via the Web3 library. The results obtained during experiments showed that the successful execution of the smart contracts allowed the trading of energy during excess solar-generation hours in the noon sun, thus confirming the viability and feasibility of the proposed decentralized energy management solution.

The trading system in energy markets is evolving and showing promises of new or better innovations through changing regulatory policies and trends in market structures. In broad terms, the current energy landscape is addressed in a dichotomy of decentralized and centralized paradigms. The analysis in [11] focuses the reader's mind toward understanding the decentralized model as promising and becoming a reality in the East in the present-day energy markets through the feature of flexibility and quick adoption to technological changes or shuffles in consumer behavior. In contrast, traditional systems require extensive infrastructure renovation to connect new energy resources. The research explores how blockchain technology could bring the transformation necessary to enable decentralized energy trading. Living examples are used, including Brooklyn Microgrid, PowerLedger, WePower, and Sun Exchange, which sit well among the successful

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applications of blockchain-enabled energy trading platforms. As seen in these cases, important improvements include greater transparency, operational efficiency, and empowerment of consumers. The research also presents the broader impacts of decentralized energy trading on its major stakeholders, namely producers, consumers, regulators, and technology providers. It also makes predictions concerning the direction of advancements in blockchain technologies and their expected impacts on decentralized energy trading systems.

Decentralized energy trading concepts have become attractive next-generation alternatives to traditional energy management practices, particularly within the current transformation of modern energy systems. Based on the concept of a sharing economy, implementing such shared energy storage (SES) systems will go a long way in reducing the cost effects of storage investments by individuals while paving the way for decentralized energy trading situations. Within this respect, the paper under consideration in [12] designs a comprehensive energy-trading framework for an energy community composed of SES units, prosumers, and retail energy providers. The interaction between the prosumer and SES is modeled using a Stackelberg game that sees SES as the leader while the prosumer is the follower. Prosumers also interact in the market through either peer-to-peer energy sharing with other prosumers or energy transactions with SES units and the primary grid, maximizing social welfare. The existence and uniqueness of the Stackelberg equilibrium (SE) are mathematically proven. Further, a personalized pricing scheme that considers each participant's supply-demand ratio and market contribution is introduced to enhance market competitiveness. A fully decentralized solution algorithm concerning the fast alternating direction method of multiplier (ADMM)-based approach is also proposed to solve the prosumer optimization problem. The numerical simulations expose the validity of the designed transactive energy framework and its economic benefits to all involved stakeholders, including SES operators and consumers.

With recent developments in data science, artificial intelligence, and clean, sustainable energy sources, energy researchers now have many options to look for innovative solutions. AI and ML techniques have been recently used in a broad range of Renewable Energy Systems (RES) applications. While this application of AI and ML has seen steady use, interest in the topic has grown exponentially. The study in [8] thus attempts to discuss widely used and recognized AI techniques applied to electricity in the fields of renewable energy techniques. The paper discusses over ten AI modeling and optimization methods most commonly used in RES: Artificial Neural Networks (ANN), Long and Short-Term Memory (LSTM), Recurrent Neural Networks (RNN), CNNs, Genetic Algorithms (GA), and Particle Swarm Optimization (PSO). A survey of more than a hundred papers published between the years 2020 and 2022 is organized and presented in the results section, where these papers are classified according to the methods used and areas of application. In conclusion, the study outlines its findings, points out the limitations of the work done so far, and proposes ways for future research to improve the application of AI within RES optimization [13].

A comprehensive review paper on the effects of artificial intelligence (AI)-augmented enabling of distributed energy systems planning and operation within smart grids has been created, for instance, here. New technologies and techniques, such as machine learning, optimization, and cognitive computing in their rapid advancement, help bring new avenues toward introducing efficiency and reliability into electrical grids. AI promises many things regarding grid transformation- from demand and generation prediction to energy flow optimization and load management, management- everything in between. This paper gathers many aspects related to several recent advancements in AI applications within distributed energy systems, looking at topics like the coordination of distributed energy resources, the integration of intermittent renewable energy sources, and demand responses. Technical, economic, and regulatory challenges for introducing AI-based solutions would also be provided alongside the ethical dilemma surrounding automation and autonomous decision-making within the energy sector. Such analysis will also be fascinating as it tells how AI influences how smart grids are planned and operated. It also pinpoints some significant areas for future research development toward achieving an even more efficient, sustainable, and resilient electrical system [14].

Peer-to-peer (P2P) energy trading is a new paradigm for managing and efficiently utilizing energy. Energy Share AI is a rich P2P energy-trading platform that uses extensive machine learning for distributed energy sharing. The technology called Energy Share AI that connects consumers and prosumers via solar arrays, energy storage systems (ESS), and electric vehicles (EVs) is presented in this paper. This significantly improves energy management efficiency while cutting costs using deep reinforcement learning (DRL) algorithms, and thus will hold several advantages over traditional linear integer programming models, especially for optimizing bidirectional energy transfer with another aspect of the importance of ESS and

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photovoltaic (PV) systems for the efficient realization of P2P energy trading. Indeed, the results of this research prove that there can be a rich, cost-effective experience and sustainability brought by the translated peer-to-peer exchange of energy, resulting in flexible energy transfer among various profiles of households and different evolution stages of humanity [15].

This paper thoroughly reviews the various approaches in Deep Learning (DL) and Machine Learning (ML) for load forecasting in smart grids with special emphasis on linguistic precision and methodological depth with attempts to explore new contributions. The paper corresponds to the balanced language that makes a rigorous understanding of complex ideas possible, catering to specialists and a general audience. A presentation across DL models recently developed on different kinds of neural network systems and ensemble methods will evaluate its performance critically through an in-depth analysis of algorithms and computative frameworks. The method section provides a rigorous comparison of the DL and ML on the one hand versus conventional forecasting methods on the other, like Key performance metrics including Mean Absolute Percentage Error (MAPE), Root Mean Square Error (RMSE), as well as Mean Square Error (MSE), have been utilized for adequate evaluation of both accuracy and scalability. A remarkable contribution of the review is to assess real-world implementations and case studies demonstrating the application of DL and ML methods in solving energy management problems, like grid stability and demand prediction. Furthermore, new proposals in ensemble learning and probabilistic forecasting techniques will be exploited as functional methodologies to minimize uncertainties in energy demand. This work contributes to the discourse on existing research gaps and future research avenues to understanding the practical implementation of DL and ML in smart grids, ultimately laying a platform for further academic endeavors in this developing area [16].

A transition that is tipped towards renewable energy with an increase in demands for efficient and flexible energy management systems has necessitated these new solutions for the energy sharing of decentralized energy networks. This study describes optimization techniques for decentralized energy systems, especially network applications with improved distribution, flexibility, and operational reliability. We use a systematic review method to study recent developments in reinforcement learning (RL) algorithms, demand response (DR) strategies, and integration of battery energy storage systems (BESS)-all efforts designed to improve the flexibility and scalability of peer-to-peer (P2P) energy trading markets. Results indicate substantial advances in developing robust decision-making frameworks, efficient management of energy storage infrastructure, and real-time optimization techniques, aiding decentralized energy trading. Significant technical and regulatory challenges were outlined, comprising computational complexity, market uncertainties, and lack of a common legal framework. Ultimately, it recommends intelligent energy management systems and collaborative regulatory issues intending to solve these challenges. The novelty of this work rests in the structured and critical analysis of the emerging P2P energy trading models and paving the way for the future design of decentralized energy systems that prioritize efficiency, sustainability, and resilience [17].

Player-of-Interconnected-Microgrids considers modern innovative energy systems as essential entities that allow for localized energy generation, energy storage, and energy trading. Secure, efficient, and reliable energy trading among networked microgrids has become a critical challenge, especially when operational autonomy and complete economic optimization are of concern. The last few years have shown the feasibility of using blockchain technology in energy for self-governed, transparent, and secure energy transactions without any centralized trust. In this context, the existing two-layer, clever contracts-based energy trading mechanism aims to improve energy management with interconnected microgrids. The first layer presents a decentralized trading model to guarantee the demand-generation balance for islanded microgrids, thus boosting reliability and operational flexibility. The second layer enhances transaction security by utilizing the blockchain framework with a two-phase consensus mechanism, which combines Practical Byzantine Fault Tolerance (PBFT) and a modified Proof of Stake (PoS) algorithm for secure contract verification and storage. Simulation results in Python validate the proposed model's potential to enable transparent, secure and resilient energy trading in networked microgrids [18].

During the last decades, the rapid decentralization of global energy markets, spurred mainly by the growing integration of distributed generation resources, has initiated enhanced interest in energy trading between prosumers. However, implementing P2P trading presents various challenges, such as behavioral modeling, decision-making processes, and optimization complexities. In this context, Multi-Agent Systems (MAS), one of AI's most active research areas, have emerged as a suitable means to tackle these challenges due to their autonomous decision-making and decentralized coordination. This paper thus provides an extensive review of recent progress in MAS for P2P energy trading, highlighting their capability for effective distributed

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energy resources management. Some key challenges related to such implementations are agent learning, the privacy of data, and the computational burden arising from large-scale agent coordination. Overall, existing literature outlines several advantages of using MAS in P2P energy trading, such as higher renewable energy utilization, low transaction costs, better scalability of the system, and capabilities for adaptive decision-making. The review further describes contemporary research gaps and future research avenues to address the existing limitations and drive the development of intelligent, resilient, and privacy-preserving peer-to-peer energy trading systems [19].

A rapid shift into green technologies in today's power systems has been hastened by technological developments, fast urbanization, growing energy demand, and global compulsion to reduce carbon footprints. Integration of renewable energy resources with conventional grids provides immense benefits. However, it involves many challenges, precisely the power mismatch problem because of the intermittent nature of renewable energy generation and nonlinear energy consumption patterns. This may adversely affect the entire energy system's reliability, stability, and operational efficiency. Therefore, developing an efficient Energy Management System (EMS) to manage such uncertain conditions due to renewable energy generation and dynamic load demand while optimizing the operation of distributed energy resources becomes significant. This state-of-art review reflects the significant role that artificial intelligence (AI)-based techniques would play in such functions of the EMS concerning optimal scheduling of energy sources, forecasting renewable generation and load demand, and decentralized control via multi-agent systems. Advanced metaheuristic algorithms have proved their efficacy in scheduling and optimization tasks, capable of avoiding local optima and premature convergence. In addition, deep learning models, especially Long Short-Term Memory (LSTM) networks and Convolutional Neural Networks (CNN), have demonstrated superiority in spatiotemporal management of renewable and load datasets for exact prediction capability. Moreover, multi-agent-based systems show a potential decentralized control avenue that minimizes computation load and surpasses the performance of classical centralized approaches. Although advanced metaheuristic optimization algorithms and hybrid AI methods have been increasingly adopted in energy management applications, these techniques are still in their infancy phase, and there can be substantial performance improvements. This also discusses centralized and decentralized energy-sharing models through EMS among interconnected microgrids, stressing the combination of advanced forecasting models and metaheuristic algorithms to effectively combat the stochastic behavior of renewable energy generation and variable load demands [20].

The synopsis in Table 1 represents the vast array of recent works regarding AI-P2P renewable energy networks within the broader umbrella of decentralized energy systems. It includes information such as the function of distributed generation (DG) in voltage stability [6], blockchain-enabled P2P trading in microgrids [9, 10], and AI-powered optimization techniques for energy management [14, 20]. Additionally, in this table are some issues that continue to surface: regulatory uncertainties, computational complexity, and scalability. These and many other advanced technology features, such as reinforcement learning, smart contracts, and multi-agent systems, remain ripe with the possibilities of improving the energy-decentralized markets' efficiency, transparency, and resilience. However, data privacy concerns and the lack of standardization were significant barriers indicating a need for more research and the development of joint policies for widespread acceptance.

Table 1: Summary of Literature Review

Reference	***Focus Area***	***Key Findings/Contributions***	***Challenges/Limitations***
[6]	Role of Distributed Generation (DG) in voltage stability	DG enhances voltage stability, reduces transmission losses, and improves grid resilience.	Operational issues like voltage dips, reverse power flows, and harmonics.
[7]	AI-powered smart grids for enterprises	AI optimizes energy consumption, integrates renewables, and reduces costs.	Cybersecurity threats, high infrastructure costs, and regulatory barriers.
[8]	Decentralized energy management using reinforcement learning (RL)	RL-based EMS optimizes renewable and non-renewable resource operations, reducing costs.	Uncertainty in renewable generation and fluctuating demand.

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[9], [10]	Blockchain-based P2P energy trading in microgrids	Smart contracts enable secure, transparent, and automated energy trading.	Scalability and interoperability issues.
[11]	Blockchain for decentralized energy trading	Blockchain enhances transparency, efficiency, and consumer empowerment.	Regulatory uncertainties and infrastructure requirements.
[12]	Shared energy storage (SES) and P2P trading	Stackelberg game model optimizes energy sharing; personalized pricing improves competitiveness.	Computational complexity and market uncertainties.
[13]	AI/ML applications in renewable energy systems	Surveys ANN, LSTM, GA, and PSO for RES optimization.	Limited real-world implementation and data privacy concerns.
[14]	AI in distributed energy systems for smart grids	AI improves demand prediction, energy flow optimization, and load management.	Ethical dilemmas and regulatory challenges for autonomous decision-making.
[15]	EnergyShare AI for P2P trading with deep reinforcement learning (DRL)	DRL optimizes bidirectional energy transfer, reducing costs and improving efficiency.	High computational requirements and scalability issues.
[16]	DL/ML for intelligent grid load forecasting	DL models (e.g., LSTM, CNN) outperform traditional methods in accuracy and scalability.	Uncertainty in probabilistic forecasting and real-world deployment challenges.
[17]	RL and demand response for P2P optimization	RL enhances decision-making and energy storage management in decentralized markets.	Lack of standardized legal frameworks and computational burdens.
[18]	Blockchain for interconnected microgrids	Two-layer innovative contract system ensures secure, transparent energy trading.	Consensus mechanism efficiency and scalability.
[19]	Multi-agent systems (MAS) for P2P energy trading	MAS enables autonomous decision-making and improves renewable energy utilization.	Data privacy, agent coordination, and computational overhead.
[20]	AI for smart grid integration and optimization	Hybrid AI methods optimize scheduling, forecasting, and decentralized control.	Early-stage adoption; performance improvements needed.

In short, the literature reviewed has established that the unification of AI-based designs, blockchain technology, and multi-agent systems shows excellent hope for improved operation of decentralized energy systems. These methodologies offer enormous potential for optimizing energy trading, forecasting renewable generation, and uncertainty management in distributed energy networks. Nevertheless, some fundamental challenges exist, like computation complexity, privacy issues, and regulatory challenges obstructing wide-scale adoption. Future research is anticipated to develop hybrid optimization models, enhance scalability, and establish legally standardized frameworks for secure and efficient energy trading. This literature review provides important perspectives on current technologies and suggests possible future avenues for the development of intelligent energy management systems.

3. Discussion

These systems eliminate some of the significant inefficiencies of the existing centralized grids regarding energy losses and excessive infrastructural costs. A combination of artificial intelligence, blockchain

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technology, and multi-agent systems ensures that real-time decision-making is optimized by analyzing big data for energy generation, storage, and consumption. Consider examples in which machine-learning algorithms predict demand and supply patterns for flexible adjustment to improve grid stability, emphasizing reducing fossil fuel support. Nevertheless, the intermittency issues of solar and wind power sources must be addressed with improved forecasting models to discharge generation-load imbalance situations [21].

Blockchain ensures energy trading between peers with the highest level of transparency and security. Smart contracts are building blocks of blockchain technology that work automatically once their preset conditions are met. They allow for the sending of tokens in energy transactions, which reduces costs by eliminating intermediaries while keeping transaction records tamper-proof. Cases like the Brooklyn Microgrid and PowerLedger highlight how well a blockchain-enabled platform can allow prosumers to trade surplus energy among themselves easily. Despite steady developments, scalability remains an issue, as existing blockchain platforms cannot cope with high computational needs and latency. Moreover, regulatory frameworks have always lagged behind technological innovations, which brings uncertainties that inhibit widespread adoption. Policymakers should streamline their collaboration with technologists to set standardized protocols for establishing trust and interoperability [22].

Multi-agent systems (MAS) allow further decentralized energy networks to provide autonomous coordination for distributed energy resources (DERs). MAS allows adaptive decision-making such that microgrids can dynamically balance supply and demand. Such algorithms include reinforcement learning (RL)--based energy management systems (EMS) that optimize DER operations with a cost-minimizing objective, which has been shown in studies like [8] and [17]. However, MAS confronts challenges, such as threats to data privacy and computational overhead, especially during large-scale implementations. Further research should emphasize lightweight algorithms and privacy-preserving techniques to remedy the challenges while maintaining efficiency in the system [23].

The economic benefits, say, environmental from peer-to-peer networks within AI are immense. Localized energy production and consumption reduces transmission losses and carbon emissions. Those shared energy storage (SES) systems, as described in [12], tend to decrease individual investment costs while improving resilience at a community scale. However, economic efficiency is achieved through AI-assisted demand response strategies that induce load shifting from peak hours [24].

The prohibitive initial infrastructure costs and inequitable access to technology may further aggravate energy inequity, particularly in low-income areas. Therefore, policymakers must include such designs and subsidies to create opportunities for all to access benefits in the decentralized energy market.

There are also several other threats, such as interoperability in data, cyber security, etc., that need addressing. AI and blockchain will count on seamless data exchange, and systems heterogeneity often does not present standardized communication protocols between these heterogeneous systems. There is also significant hacking, data breaches, etc., when threats to decentralized networks come. Such systems matter a lot to have advanced encryption and intrusion detection systems embedded with AI-related abnormal behavior detection. Moreover, ethical issues of autonomous decision-making in the energy management system, such as accountability to algorithmic faults, require a robust governance framework to strike out the innovation-consumer protection balance [25].

Nonetheless, AI will decentralize energy systems in no time, making the renewable energy resource-endowed nations increasingly self-sufficient for sustainability, resilience, and democratization in energy markets. Advances in AI, blockchain, and multi-agent systems have resolved flocks of issues related to the operation of decentralization. However, barriers like regulatory uncertainty, scalability, and equity remain. Their collaboration will thus be necessary for surmounting such hurdles over the growth of future research avenues such as hybrid optimization models, interoperable standards, and community-centric designs in speeding up a decentralized future energy transition. Such a discussion stipulates the holistic solutions towards ensuring that technological innovation is integrated into socio-economic and regulatory frameworks.

4. Conclusion

This is a critical analysis of AI-assisted decentralized energy systems and P2P renewable energy networks, noting their revolutionary nature in eliminating the impediments caused by the efficiency of conventional

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centralized grids. AI integration with blockchain and multi-agent systems enables localized energy generation, transmission loss reduction, and grid resilience. AI assists in the optimization of real-time energy distribution, predicting demand-supply mismatch situations, and enhancing operational efficiencies. Renewable energy resources' intermittency and reliance upon advanced forecasting models remain significant challenges that continuously demand innovation and research.

Blockchain technology has become foundational for secure trading in P2Ps, with smart contracts enabling automated transaction processing without intermediaries. Initiatives like Brooklyn Microgrid and PowerLedger provide a proof of concept for decentralized energy markets, allowing for efficient trading of surplus energy from prosumers. Nonetheless, scaling challenges, high computation requirements and regulatory uncertainties impede widespread adoption. Therefore, policymakers and technologists must harmonize and customize standardized frameworks that address interoperability, security, and fair participation in market operations-most important to build trust among stakeholders.

MAS contributes further to such decentralized energy networks with their ability to allow autonomous coordination among distributed energy resources (DER). Essentially, reinforcement learning (RL)--based energy management systems (EMS), as demonstrated in [8] and [17], are optimizing DER operations under minimal costs and improving grid resilience. Some of the challenges are still posed by data privacy risk, computational overhead, and coordination at a large scale. Therefore, future studies should focus on lightweight algorithms, edge computing, and privacy-preserving mechanisms to respond to these challenges while assuring efficiency and scalability in the system.

AI-assisted development of P2P networks has enormous economic and environmental benefits. First, these systems lessen transmission losses, carbon emissions, and dependence on fossil fuels by localizing power generation and consumption. Community structures of shared electricity storage reduce investment for the individual, creating energy resilience on a community basis. AI-enhanced demand-response strategies further encourage load diversion from peak to off-peak times. High infrastructure initial costs and unequal access to technology make energy inequity a reality for these underserved locations. Inclusive design, grants, and regulatory support must reach the top of policymakers' priority list to ensure equitable participation in decentralized energy markets.

Technical barriers to the widespread uptake of decentralized energy systems include data interoperability, cybersecurity threats, and ethical concerns. AI and blockchains depend on seamless data integration; however, heterogeneous systems often lack standard communication protocols. Cyber-attacks such as hacking and data breaches threaten the viability of decentralized networks. Advanced encryption, AI-based anomaly detection, and intrusion prevention must be ensured to protect these systems. The ethical implications of autonomous decision-making in energy management, about algorithmic error liability, need regulatory frameworks assuring that innovation and consumer protection are equal partners.

In conclusion, AI-enabled decentralized energy systems hold valuable promise for establishing sustainability, resilience, and democratization in energy markets worldwide. While AI, blockchain, and MAS have resolved mainly the technological issues, numerous barriers remain, including regulatory uncertainty, scalability, and equity. Future research must further hybrid optimization models, interoperable standards, and community-focused designs to facilitate adoption. Researchers, industry stakeholders, and policymakers must collaborate to overcome these barriers. This review highlights the need for holistic solutions that fuse state-of-the-art technology with socio-economic and regulatory factors into the pathway toward a sustainable and decentralized energy future.

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