



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: peer-to-peer (P2P) renewable energy networks interconnect AI, blockchain technology, and multi-agent systems, thus circumventing the barriers of traditional centralized grids. This paper traces how recent 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, 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 barriers and future directions such as hybrid optimization models, standardized frameworks, and inclusive design for accelerating transitions toward 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 demand grows for clean, efficient, and sustainable energy systems. The centralized generation and distribution that characterize traditional energy systems face energy losses, infrastructure costs, and environmental concerns. In this context, decentralized energy systems (DESS) are a viable alternative for generating and consuming energy locally. This allows individual “prosumers,” those who produce and consume energy, to participate actively in energy markets. This paradigm shift has been enabled by recent advancements in renewable energy resources and information and communication technologies (ICT) [1].

Decentralized energy systems have made peer-to-peer (P2P) energy trading central to their operation. P2P trading involves

direct energy transactions between prosumers without centralized intermediation. Such networks can reduce transaction costs, improve energy access, and increase grid resilience. They operate through smart contracts, blockchain technologies, and secure digital platforms that autonomously execute transactions. Globally, P2P systems are gaining prominence because of their potential for energy democratization and sustainability, encouraging households and businesses to participate in the energy economy [2].

Artificial Intelligence (AI) is an important technology for structuring and balancing the performance, efficiency, and security of P2P energy trading systems. AI optimizes energy generation, storage, and consumption profiles through large data analysis. Machine learning, predictive analytics, and multi-agent systems enable intelligent decision-making in decentralized energy networks. AI can predict demand and

supply, optimize operations, and stabilize P2P transactions against market volatility and grid imbalance [3].

Integrating AI into decentralized energy systems improves operational efficiency while enhancing transaction security and transparency. Blockchain provides a tamper-proof platform for recording energy exchanges, while smart contracts execute transactions when predefined conditions are met, reducing fraud and mistakes. AI-supported cybersecurity mechanisms also protect sensitive data and ensure the integrity of decentralized energy systems, thereby building trust among prosumers and other stakeholders [4].

Several challenges still hinder AI-driven P2P energy systems, including technological limitations, regulatory uncertainties, and the need for robust infrastructure. Data privacy, interoperability, and the absence of standards can prevent decentralized energy networks from going mainstream. Integrating intermittent renewable sources such as solar and wind requires advanced forecasting and energy-management strategies, which call for sophisticated AI solutions [5].

This review analyzes AI-augmented decentralized energy systems with emphasis on P2P renewable energy networks. It discusses technological drivers, benefits, challenges, recent AI-focused applications in energy trading, and future research directions for a sustainable, resilient, and decentralized energy future.

2. LITERATURE REVIEW

The rapid evolution of decentralized energy systems and the increasing penetration of renewable energy resources have encouraged extensive research on AI, blockchain, reinforcement learning, multi-agent coordination, and energy-sharing platforms. Distributed generation improves voltage stability, reduces transmission losses, and strengthens grid resilience, but it can also introduce voltage dips, reverse power flows, harmonics, and operational complexity [6].

AI-powered smart grids optimize enterprise energy consumption, integrate renewable sources, and reduce operational costs. These approaches support demand forecasting, energy-flow optimization, and load management. However, high infrastructure costs, cybersecurity threats, and regulatory barriers remain important concerns [7, 8].

Reinforcement learning has been proposed for decentralized energy management in smart microgrids. In such systems, each entity can operate as an intelligent agent that learns policies for optimizing renewable and non-renewable resources, minimizing battery degradation, and supporting load shifting. Q-learning and robust reinforcement-learning approaches demonstrate advantages over traditional methods, but uncertainty in renewable generation and fluctuating demand remain central challenges [9, 10].

Blockchain-enabled P2P energy trading has attracted considerable attention because smart contracts support secure, transparent, and automated transactions. Decentralized platforms can eliminate intermediaries, reduce costs, and empower consumers. Nevertheless, scalability, interoperability, consensus efficiency, infrastructure needs, and regulatory uncertainty continue to limit large-scale deployment [11, 12, 13, 14].

Shared energy storage (SES) and personalized pricing frameworks have also been investigated. Stackelberg-game models

can optimize community energy sharing and improve market competitiveness, but computational complexity and market uncertainty must be addressed [15]. AI and machine-learning techniques such as artificial neural networks, LSTM, recurrent neural networks, convolutional neural networks, genetic algorithms, and particle swarm optimization have been widely applied to renewable energy systems, especially forecasting and optimization [16, 17, 18].

Multi-agent systems (MAS) provide autonomous coordination for distributed energy resources and support adaptive decision-making in P2P energy trading. They improve renewable energy utilization, reduce transaction costs, and enhance scalability, yet they also raise privacy, coordination, and computational-overhead concerns [19].

The synopsis in Table 1 represents recent works regarding AI-P2P renewable energy networks under the broader umbrella of decentralized energy systems.

In short, the literature establishes that unifying AI-based designs, blockchain technology, and multi-agent systems offers strong potential for improving decentralized energy systems. These methods can optimize energy trading, forecast renewable generation, and manage uncertainty in distributed networks. Nevertheless, computational complexity, privacy issues, and regulatory challenges obstruct wide-scale adoption. Future research is expected to develop hybrid optimization models, enhance scalability, and establish standardized legal frameworks for secure and efficient energy trading.

3. DISCUSSION

AI-driven decentralized energy systems eliminate several inefficiencies of existing centralized grids, including energy losses and excessive infrastructure costs. Combining artificial intelligence, blockchain technology, and multi-agent systems enables real-time decision-making by analyzing large data streams for generation, storage, and consumption. Machine-learning algorithms can predict demand and supply patterns, support flexible adjustment, improve grid stability, and reduce reliance on fossil fuels. However, intermittency in solar and wind power must be addressed with improved forecasting models to prevent generation-load imbalances [21].

Blockchain ensures transparent and secure peer-to-peer energy trading. Smart contracts execute automatically when preset conditions are met, allowing energy transactions while reducing costs by eliminating intermediaries and preserving tamper-proof records. Cases such as Brooklyn Microgrid and PowerLedger highlight how blockchain-enabled platforms can allow prosumers to trade surplus energy among themselves. Despite progress, scalability remains an issue because many blockchain platforms struggle with high computational needs and latency. Regulatory frameworks also lag behind technological innovation, creating uncertainty that inhibits adoption [22].

Multi-agent systems allow decentralized energy networks to coordinate distributed energy resources autonomously. MAS enables adaptive decision-making so that microgrids can dynamically balance supply and demand. Reinforcement-learning-based energy management systems optimize DER operation with cost-minimizing objectives, as shown in prior studies [9, 10, 23]. Yet MAS faces challenges such as data-

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 such as 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.
[9]	Decentralized energy management using reinforcement learning	RL-based EMS optimizes renewable and non-renewable resources, reducing costs.	Uncertainty in renewable generation and fluctuating demand.
[11, 12]	Blockchain-based P2P trading in micro-grids	Smart contracts enable secure, transparent, and automated energy trading.	Scalability and interoperability issues.
[13]	Blockchain for decentralized energy trading	Blockchain enhances transparency, efficiency, and consumer empowerment.	Regulatory uncertainties and infrastructure requirements.
[15]	Shared energy storage and P2P trading	Stackelberg-game pricing optimizes sharing and improves competitiveness.	Computational complexity and market uncertainties.
[16]	AI/ML in renewable energy systems	Surveys ANN, LSTM, GA, and PSO for RES optimization.	Limited real-world implementation and data-privacy concerns.
[8]	AI in distributed smart-grid systems	AI improves demand prediction, energy-flow optimization, and load management.	Ethical dilemmas and regulatory challenges for autonomous decisions.
[20]	EnergyShare AI with deep reinforcement learning	DRL optimizes bidirectional energy transfer, reducing costs and improving efficiency.	High computational requirements and scalability issues.
[17]	DL/ML for grid load forecasting	LSTM and CNN models outperform traditional forecasting methods.	Probabilistic uncertainty and real-world deployment challenges.
[10]	RL and demand response for P2P optimization	RL enhances decision-making and storage management in decentralized markets.	Lack of legal standards and computational burdens.
[14]	Blockchain for interconnected micro-grids	A two-layer smart-contract system ensures secure transparent trading.	Consensus-mechanism efficiency and scalability.
[19]	Multi-agent systems for P2P trading	MAS enables autonomous decision-making and improves renewable utilization.	Data privacy, agent coordination, and computational overhead.
[18]	AI for smart-grid integration and optimization	Hybrid AI optimizes scheduling, forecasting, and decentralized control.	Early-stage adoption and need for performance improvements.

privacy threats and computational overhead, especially in large-scale implementations. Future work should emphasize lightweight algorithms and privacy-preserving techniques.

The economic and environmental benefits of AI-assisted P2P networks are substantial. Localized energy production and consumption reduce transmission losses and carbon emissions. Shared energy storage decreases individual investment costs while improving community-level resilience. AI-assisted demand-response strategies also encourage load shifting away from peak hours [24]. However, high initial infrastructure costs and inequitable access to technology may intensify energy inequality, particularly in low-income areas. Policymakers should support inclusive designs and subsidies so that decentralized energy markets remain broadly accessible.

Other threats, including data interoperability and cybersecurity, require careful attention. AI and blockchain rely on seamless data exchange, yet heterogeneous systems often lack standardized communication protocols. Decentralized networks also face hacking and data-breach risks. Advanced encryption, intrusion detection, and AI-based anomaly detection are necessary. Ethical issues in autonomous energy-management decisions, such as accountability for algorithmic faults, require robust governance frameworks that balance innovation and consumer protection [25].

4. CONCLUSION

This review critically analyzes AI-assisted decentralized energy systems and P2P renewable energy networks, emphasizing their potential to overcome limitations of conventional centralized grids. Integrating AI with blockchain and multi-agent systems enables localized energy generation, reduces transmission losses, and improves grid resilience. AI supports real-time energy distribution, demand-supply prediction, and operational efficiency. Renewable-resource intermittency and dependence on advanced forecasting models remain significant

challenges requiring continuous innovation.

Blockchain technology is foundational for secure P2P trading, with smart contracts enabling automated transactions without intermediaries. Initiatives such as Brooklyn Microgrid and PowerLedger demonstrate the feasibility of decentralized energy markets. Nevertheless, scaling challenges, high computational requirements, and regulatory uncertainty impede wider adoption. Policymakers and technologists must harmonize standardized frameworks addressing interoperability, security, and fair market participation.

MAS further strengthens decentralized energy networks by enabling autonomous coordination among distributed energy resources. Reinforcement-learning-based EMS approaches optimize DER operations at minimal cost and improve grid resilience. Future studies should focus on lightweight algorithms, edge computing, and privacy-preserving mechanisms to improve scalability and efficiency.

AI-assisted P2P networks offer large economic and environmental benefits by reducing transmission losses, carbon emissions, and fossil-fuel dependence. Shared storage and demand-response strategies can improve resilience and reduce costs. However, unequal access and high infrastructure costs require inclusive design, grants, and regulatory support. Overall, AI-enabled decentralized energy systems hold valuable promise for sustainability, resilience, and democratization in global energy markets. Researchers, industry stakeholders, and policymakers must collaborate to develop hybrid optimization models, interoperable standards, and community-focused designs for a sustainable decentralized energy future.

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