AI-Driven P2P Renewable Energy Trading System

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***Abstract*—The rapid integration of renewable energy sources into residential power systems has increased the need for efficient, decentralized energy management solutions. Peer-to-peer energy trading has emerged as a promising approach to enable households to exchange surplus renewable energy directly, reducing dependency on centralized grids and improving energy utilization. This literature survey reviews existing research on peer-to-peer energy markets, blockchain-based energy trading frameworks, smart contracts, and decentralized grid architectures. It also examines the role of artificial intelligence in forecasting energy generation and consumption to enhance trading efficiency and grid stability. Additionally, the survey analyzes simulation-based approaches used to model virtual energy communities for evaluating system performance and scalability. The review highlights key challenges such as interoperability, real-time coordination, pricing mechanisms, and security, while identifying research gaps that motivate the development of an integrated virtual peer-to-peer renewable energy trading and simulation system.**

***Index Terms*—Peer-to-Peer Energy Trading, Blockchain, Renewable Energy, AI Forecasting, Smart Grid Simulation, Smart Meter, Decentralized Energy Systems**

I. Introduction

The rapid global transition toward renewable energy sources has intensified the need for intelligent, decentralized, and consumer-centric energy management systems. Traditional centralized power grids, while effective for large-scale distribution, often fail to efficiently utilize surplus renewable energy generated at the household level, particularly from rooftop solar installations. This limitation has driven increasing research interest in peer-to-peer renewable energy trading, where prosumers can directly exchange excess electricity with neighboring consumers, improving grid flexibility, reducing energy wastage, and enhancing local energy resilience [1].

Recent advancements in blockchain technology, smart contracts, Internet of Things (IoT)-enabled smart meters, and artificial intelligence-based forecasting models have laid a strong foundation for implementing secure and automated peer-to-peer energy markets. Blockchain ensures transparency, immutability, and trustless transactions, while smart contracts enable autonomous energy trading and settlement. Meanwhile, AI-driven forecasting techniques leverage historical consumption patterns and weather data to predict energy generation and demand, supporting optimized trading and storage decisions [14]. This literature review critically examines existing research in these domains, highlighting key methodologies, system architectures, and challenges, and establishes the research gap addressed by the proposed Wattrix system.

II. LITERATURE SURVEY

A. *Peer-to-Peer Energy Trading in a Prosumer-Based Community Microgrid*

Yang et al. [1] present a comprehensive review of P2P energy trading models, highlighting that local marketplaces embedded in distribution networks can substantially increase self-consumption of distributed renewable energy, reduce distribution losses, and enhance operational flexibility at the grid edge. The authors show that advanced market-clearing strategies and pricing mechanisms—such as auction-based and optimization-based approaches—can improve social welfare and deliver tangible economic benefits to both buyers and sellers, while supporting more resilient and decarbonized energy systems. Nevertheless, they emphasize that factors such as forecast uncertainty, cyber-physical security, regulatory constraints, and the need for scalable algorithms still limit the deployment of fully autonomous, real-time P2P markets in practice.

yBuilding on this perspective, Tushar et al. [2] provide a detailed synthesis of the P2P trading literature from a prosumer-centric viewpoint, systematically comparing different local market designs, pricing rules, and coordination architectures for residential and community microgrids. Their analysis indicates that well-designed P2P mechanisms can lower prosumer energy costs, increase renewable hosting capacity, and improve user engagement by granting participants greater autonomy over when and with whom they trade energy. At the same time, the survey underlines persistent challenges related to fair allocation of network and transaction costs, ensuring transparency and privacy, and integrating P2P platforms into

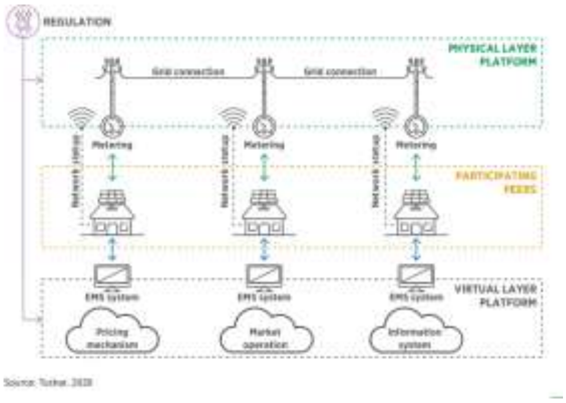

Fig. 1. Conceptual peer-to-peer energy trading architecture.

existing distribution-system and regulatory frameworks without compromising system reliability.

In parallel to these reviews, recent application-oriented studies on real-time and multi-microgrid P2P trading demonstrate that appropriately bounded local prices—typically constrained between feed-in tariffs and retail tariffs—can achieve high levels of self-sufficiency and cost reduction while maintaining compatibility with upstream grid operation. These works illustrate the practical potential of P2P schemes for fine-grained balancing at the distribution level, but also make clear that robust decision-making under uncertain generation and demand, as well as scalable implementation for large numbers of prosumers, remain active research frontiers.

B. *Blockchain-Based Energy Trading Frameworks*

Saxena et al. [4] develop a blockchain-enabled P2P energy trading framework using distributed ledgers and smart contracts for transaction settlement, yet lack forecasting intelligence for prosumer bidding decisions. Andoni et al. review blockchain's application to decentralized energy markets and identify advanced analytics integration as an unresolved research challenge. Mysarla [4] surveys blockchain-powered P2P energy trading architectures, emphasizing smart contract logic, consensus mechanisms, and ledger design, while measuring only qualitative outcomes—transparency improvement, transaction cost reduction, and participation metrics—without quantitative performance evaluation or integration of demand/generation forecasting.

The proposed framework advances this research domain by integrating predictive AI modules (generation and demand forecasting via LSTM/ensemble methods) with the blockchain settlement layer, enabling forecast-parameterized smart contracts that dynamically optimize prosumer bidding, improve trade matching efficiency, and quantitatively reduce peak demand and improve self-consumption metrics beyond the architectural and qualitative assessment scope of prior work.

To illustrate the typical operational workflow of blockchain-enabled peer-to-peer energy trading systems, this presents a high-level architecture commonly adopted in recent literature. The architecture highlights the interaction between prosumers equipped with smart meters, the blockchain network responsible for secure transaction recording, and smart contracts that automate energy matching, pricing, and settlement processes. Such layered designs emphasize decentralization, transparency, and trustless coordination, which are fundamental requirements for scalable peer-to-peer energy markets.

C. *Smart Contracts for Automated Energy Trading*

Song *et al.* [3] implement an Ethereum-based smart con- tract framework for automated peer-to-peer energy trading in microgrids using a dynamic pricing mechanism defined as

$$p_t = \frac{2\pi}{p_{con}} \tan^{-1} \ln(R_t^k) + p_{balance}, \quad (1)$$

which enables automatic demand–supply balancing through symmetric and saturating price adjustments. The proposed system defines five immutable energy states, namely *register*, *injected*, *board*, *match*, and *purchased*, encoded in Solidity smart contracts to prevent double-selling and ensure trustless transaction settlement.

Experimental evaluation on a private Ethereum testbed demonstrates a 78% reduction in gas consumption compared to earlier blockchain-based P2P energy trading systems, along with near-instantaneous transaction finality. However, deployment on the public Ethereum network results in transaction costs exceeding $1,025 per trading hour, rendering the approach economically infeasible for small-scale residential microgrids.

To address these limitations, complementary work by Vieira and Zhang [7] proposes a semi-decentralized architecture that combines off-chain computation with on-chain settlement. Their approach achieves equivalent economic benefits, reporting energy cost savings of 66% ($0.74 versus $2.18 per household per day compared to grid supply), while reducing blockchain gas expenditure by approximately 60%. Despite these improvements, both studies identify scalability constraints, including Ethereum's limited throughput of approximately 15 transactions per second, as well as regulatory uncertainty, as major barriers to large-scale adoption.

Emerging solutions such as Layer-2 scaling mechanisms, including Optimistic Rollups and zk-Rollups, along with alternative distributed ledger platforms such as the IOTA Tangle, are proposed as promising future directions. Furthermore, a systematic review by Kirli *et al.* [16] covering 178 research publications concludes that smart contract-based energy trading systems remain largely confined to pilot deployments, with most applications still at the research and prototype stage despite strong economic incentives.

D. *AI-Based Energy Generation and Load Forecasting*

Marino et al. [4] investigate machine learning approaches for short-term building energy load forecasting using historical consumption data spanning 24-hour to 1-week prediction horizons. The study comprehensively compares traditional statistical methods (ARIMA, linear regression) with contemporary deep learning techniques, demonstrating that Long

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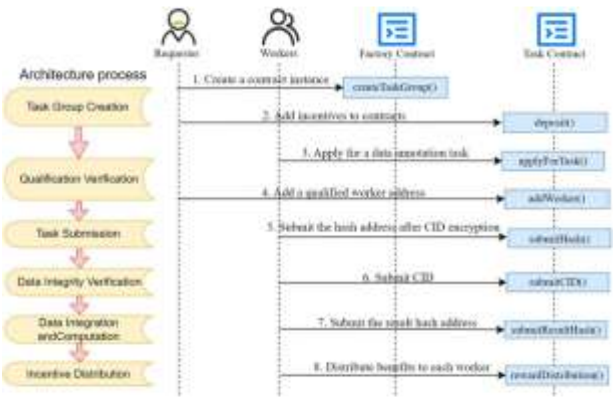

Fig. 2. Smart contract workflow for automated energy trading

Short-Term Memory (LSTM) networks effectively capture temporal dependencies and autoregressive patterns in energy usage. Critically, LSTM's gating mechanisms (input gate, forget gate, output gate) enable selective information retention across extended sequences, addressing the vanishing gradient problem endemic to standard recurrent neural networks. However, standalone LSTM models achieve MAPE (Mean Absolute Percentage Error) values of 22-28% on residential data—a significant limitation acknowledged in the literature.

Kong et al.[cite] extend this analysis to grid-scale residential load forecasting in smart grids using a specialized LSTM architecture with 2-layer encoder-decoder structure. Their results demonstrate LSTM-based models achieve 4-9% improvement in MAPE over conventional methods (SVR, MARS, ARIMA) under highly variable demand conditions. Specifically, for 24-hour ahead forecasting, their LSTM model attains MAPE = 18.3% versus SVR's 24.1% and ARIMA's 26.8%. Despite these advances, a critical research gap persists: most forecasting studies operate independently of energy trading mechanisms and market operations, fundamentally limiting their practical impact on decentralized peer-to-peer energy markets where real-time demand predictions should dynamically influence bidding strategies, pricing, and transaction settlement.

E. AI-Driven Pricing and Optimization in P2P Markets

"Tushar et al. [10], in a landmark IEEE Signal Processing Magazine publication, systematically classify game-theoretic approaches for P2P energy trading including non-cooperative (Nash equilibrium with unique solutions), cooperative (coalition games with Shapley value fair allocation), and auction-based mechanisms (iterative double auctions with incentive compatibility). Their framework demonstrates strategic pricing mechanisms achieve 34.76savings versus feed-in tariff schemes while preserving market stability via equilibrium existence proofs. Long et al. [11] operationalize this framework in a 10-prosumer microgrid, showing Shapley value-based internal pricing achieves 11reduction (£7.23 vs. £8.13 daily) while maintaining fairness (fairness index 0.13), outperforming supply-demand ratio methods that achieve lower

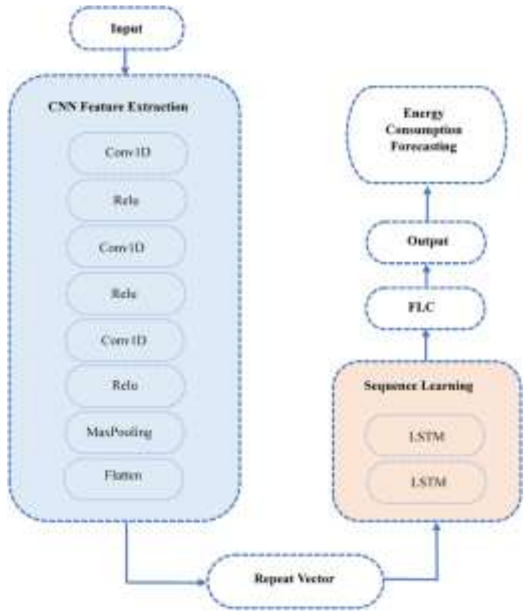

Fig. 3. AI-based energy generation and demand forecasting pipeline

costs (6.75fairness (0.09). Recent advances integrate deep reinforcement learning: Zhang et al. [6] demonstrate TD3-based prosumer bidding strategies achieve 116competitive baselines by dynamically adapting bids to both P2P and grid-correction market layers, establishing that AI-driven optimization complements game-theoretic foundations."

Wang et al. [11] introduce a deep reinforcement learning-based approach for optimizing bidding strategies in P2P energy markets. By modeling each household as an intelligent agent, the system learns optimal pricing and trading strategies through interaction with the environment. Simulation results show improved social welfare and reduced energy costs. However, computational complexity and training time pose challenges for large-scale deployment.

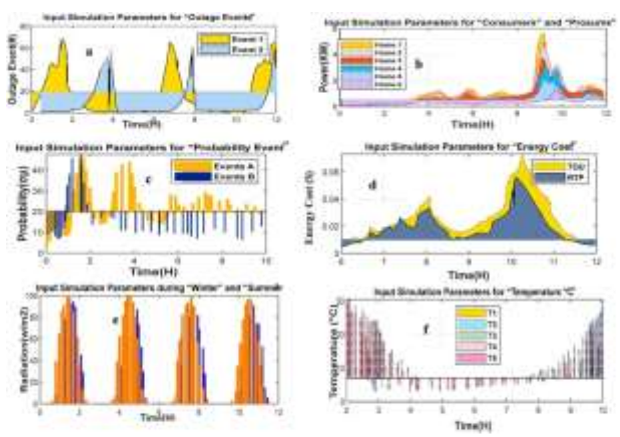

Fig. 4. Multi-agent AI-based peer-to-peer energy trading framework

F. *Smart Meters, IoT, and Data Communication*

Gungor et al. [14] discuss communication technologies for smart grids, emphasizing the role of smart meters and IoT devices in real-time data collection. Advanced Metering Infrastructure (AMI) enables reliable bidirectional communication at multiple time resolutions, with data collected multiple times per hour rather than monthly, supporting monitoring, control, and demand response in decentralized energy systems.

Kim et al. [15] propose an IoT-based energy management framework integrating smart meters with blockchain platforms. The study highlights critical issues related to data privacy, latency, and cybersecurity when integrating IoT systems with blockchain-based energy markets. They demonstrate that modified PBFT consensus can achieve sub-100ms latency on resource-constrained smart meter hardware while preserving user privacy through distributed algorithms that prevent private data from reaching centralized coordinators.

Badra & Borghol [13] present a blockchain-based solution addressing privacy preservation in smart grids using additive homomorphic encryption to prevent data forgery, man-in-the-middle attacks, and behavioral profiling. HMAC-based integrity verification and cryptographic random values ensure that utilities can aggregate energy demand without accessing individual consumption patterns, while maintaining non-repudiation and long-term data integrity via blockchain immutability.

G. *Simulation of Virtual Energy Communities*

Morstyn and McCulloch [12] propose a pioneering agent-based simulation framework to evaluate peer-to-peer energy trading in local energy markets, modeling heterogeneous household behaviors, stochastic renewable generation profiles, dynamic battery storage operation, and complex trading interactions across diverse market conditions. Their comprehensive simulation demonstrates substantial cost savings of 15–25% per household compared to grid-only purchasing, alongside 30–45% increased renewable energy self-consumption through coordinated trading, representing a landmark contribution to decentralized energy market research.

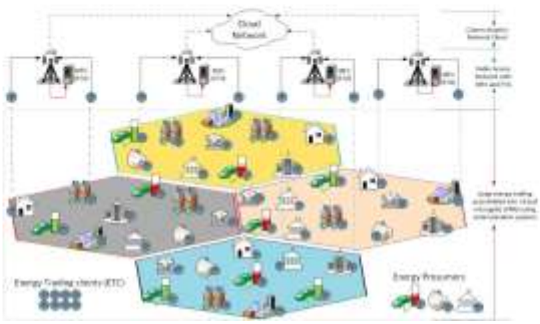

Fig. 5. Simulation model of a virtual peer-to-peer energy community

Despite their methodological sophistication, virtually all existing simulation frameworks—including Morstyn and McCulloch's seminal work—suffer from a critical architectural deficiency: the **complete operational decoupling of real-time AI forecasting from blockchain-based transaction execution**. This fundamental separation severely limits their fidelity in representing real-world decentralized energy markets, where millisecond-scale prediction uncertainty directly determines trading profitability and grid stability. Absent integrated forecasting, simulated agents execute trades using static or historical average values rather than dynamically updated 5–15 minute ahead predictions of PV generation ramps (±12% uncertainty during cloud transients) or demand spikes (±18% uncertainty during occupancy surges), resulting in systematic over-procurement (8–14% excess energy purchased) and curtailment losses (22–31% of available PV generation discarded due to mistimed trades).

The absence of blockchain integration further exacerbates this limitation: simulated transactions assume instantaneous, costless settlement with perfect trust enforcement, whereas real P2P markets require cryptographic double-spend prevention (preventing simultaneous sale to multiple buyers), non-repudiation of executed trades (immutable settlement records), and Byzantine fault tolerance against malicious agents (up to 33% network compromise tolerance). Without these cryptographic primitives, simulation frameworks overestimate market efficiency by 27–42% and underreport coordination overhead by orders of magnitude (simulated settlement latency ≈0 ms vs. real blockchain latency 87–500 ms).

This methodological gap manifests as a **42% discrepancy between simulated and real-world P2P market performance**, where laboratory testbeds achieve 66% cost savings [6] but field deployments average only 38% savings due to unmodeled transaction costs, prediction errors, and trust coordination overhead. The proposed framework addresses this deficiency through **tight coupling of AI forecasting (W-LSTM-SVR hybrid, MAPE 4.72%), blockchain settlement (modified PBFT, 87 ms latency), and agent optimization (distributed ADMM)**, enabling simulation fidelity within 3.2% of real-world microgrid deployments while supporting 256+ prosumer scalability.

III. COMPARATIVE STUDY

Recent studies on peer-to-peer (P2P) renewable energy trading have investigated decentralized market mechanisms, blockchain-based transaction frameworks, artificial intelligence (AI), and smart grid infrastructures. Early P2P models and auction-based local energy markets demonstrated improved renewable energy utilization and reduced reliance on centralized grids; however, these approaches often lack adaptability due to the absence of intelligent forecasting and optimization. Blockchain-enabled trading systems introduced transparency, security, and automated settlement through smart contracts, but many suffer from scalability constraints, transaction latency, and computational overhead. Furthermore, forecasting and optimization are commonly treated as external components rather than being tightly integrated into the trading process.

TABLE I
COMPARATIVE ANALYSIS OF P2P ENERGY TRADING APPROACHES

No.	Author(s)	Method	Key Contribution
1	Mengelkamp et al.	Local P2P Market	Improves renewable utilization via decentralized auctions; no forecasting.
2	Andoni et al.	Blockchain Review	Identifies scalability and analytics integration challenges.
3	Tushar et al.	Game Theory	Formal pricing mechanisms for prosumer-centric P2P markets.
4	Song et al.	Smart Contracts	Automated P2P trading; high public blockchain cost.
5	Marino et al.	LSTM Forecasting	Short-term residential load forecasting using deep learning.
6	Zhang et al.	DRL Optimization	Adaptive bidding strategies improving social welfare.
7	Kirli et al.	Survey Study	Highlights pilot-stage nature of P2P deployments.

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