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Blockchain Technology for Peer-To-Peer Renewable Energy Trading

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Abstract

This paper is an examination of the disruptive capabilities of blockchain technology as a base infrastructure in Peer-to-peer (P2P) renewable energy trading. With the energy sector of the world moving to decentralized, low-carbon systems, the conventional centralized systems have problems with the multidirectional power flows and intermittency of the distributed energy resources (DERs) such as the rooftop solar PV. This research is mainly aimed at synthesizing the current model of P2P trading and assess the architectural, economic, and technical feasibility of these models to develop a prosumer-driven energy ecosystem. The research design is the mixed-method study that is implemented in a twelve-month period. It will include a literature review of scholarly databases (2015-2025) as a method of systematically gathering the literature to determine the prevailing architectural designs and a simulation-oriented comparative modelling approach. The simulation used three different mechanisms, including a two-sided McAfee double auction, a Hybrid Auction Coalition (HAC), and an Innovative Coalition Business Model (ICBM) in a hypothetical microgrid of 50 participants. The results indicate that P2P trading using blockchain technology is much more efficient and effective in improving producers and the market. Findings indicate that ICBM mechanism is capable of enhancing seller gains by up to 88 percent as compared to conventional utility billing with the HAC model providing gains of 6070 percent. According to the evaluations, decentralized trading is beneficial in terms of equity and in terms of encouraging the adoption of renewable, but the technical and regulatory barriers are still present. The technical performance analysis indicates that existing blockchain systems can be adequately deployed to operate at a microgrid scale but suffer scalability bottlenecks, such as latencies in transaction and network overload in use at a city or country scale. The paper has concluded that a global green energy transition would be impossible without combined efforts to advance smart contract automation, grid-sensitive pricing algorithms, and enabling regulatory frameworks.

Cite

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1. INTRODUCTION

Energy industries all around the world are experiencing a radical structural change due to mitigation of climate change, technological advancement, and changing trends of electricity demand. The governments, industries, and communities are experiencing more pressure to decarbonise energy systems as per the international climate agreements and national net-zero issues.

This change has increased the implementation of distributed renewable energy resources (DERs) such as rooftop solar photovoltaic (PV) systems, small-scale wind turbines, a battery energy storage system, electric vehicles with bidirectional charging systems, and microgrids at the community level. In contrast to old-fashioned models of centralized generations when power generation is performed in large power plants, which transfer the electricity over a long distance by hierarchical grid systems, distributed systems put the energy generation nearer to the consumption point. This decentralization minimizes the transmission losses and improves their local autonomy of energy, and more robust electricity infrastructures that can sustain disruptions. Nevertheless, the high rate of DERs proliferation poses serious operational and structural threats to the traditional utility-based grid systems. The historic electricity markets were built on behalf of predictable unifaceted flows of power in a single way, where centralized generation plants were on one side, and passive consumers on the opposite side. Conversely, the distributed systems of the modern day are multidirectional flows, intermittent renewable generation and prosumers, individuals, households or organizations that actively produce and consume electricity. The utilities are now faced with the challenge of balancing operations that are more complicated, real time data monitoring and grid stabilization needs without compromising on reliability and affordability. Furthermore, the centralized market systems tend to restrict the option of transparent prices and also an administration overhead which restricts the ability of small-scale players to completely cash in surplus renewable generation. As a reaction to these constraints, the Peer-to-peer (P2P) energy trading has become a new form of market paradigm which ensures direct electricity trading between prosumers and consumers on a localized community or an interconnected grid of micro-grids. Instead of selling the excess power to the utilities at predefined feed-in tariffs, prosumers can sell energy to their neighbours or local businesses at agreed prices. This localized trading framework will improve energy usage effectiveness as the wonderfulness of supply and demand is optimized across limited geographic regions, the need for long-term transmission systems is lessened, and new economic motivation to invest in renewable technologies is developed. Through preferences and flexible trading arrangements, as well as price negotiation and empowerment of participants, P2P systems enhance democratized energy markets and further engages the community in the energy transition. However, successful execution of P2P trading systems demands strong mechanisms to guarantee trust, transparency, security and sufficient settlement of exchange. Energy markets are dynamic in nature and supply and demand changes on a real time basis because of weather fluctuations, consumption and grid limitations. The transactions are usually done at granular intervals such as the occurrence of a few minutes interval; which requires effective verification of energy production and delivery. When there is no centralized control over a decentralized environment, data integrity and fraud prevention issues become an urgent matter. The blockchain technology has the potential to provide the infrastructural solution to such obstacles. Being a distributed registry, blockchain stores transactions on a network of nodes, securely, impartially and transparently. Confidence is ensured, and tamper resistance and auditability are guaranteed because, with the help of consensus mechanisms each transaction is cryptographically verified and appended to the ledger. Combined with smart contracts, self-executing code integrated into the blockchain, the P2P energy platforms are capable of automating price rules, trading agreements, and payments to the people. The smart contracts are able to check the energy information of the smart meters, automatically transfer funds when successful delivery is detected, and automatically change prices depending on the supply-demand circumstances. Blockchain decreases the cost of transactions and operational delays by reducing the need to use centralized intermediaries like utilities or clearinghouses to improve the efficiency of the market. The current technological breakthroughs have proven the viability of P2P energy markets based on blockchain. In real time bidding Pilot projects in different locations have demonstrated real-time bidding platforms, tokenized energy credits, carbon accounting schemes and the attachment to Internet of Things (IoT)-enabled smart meters to automatically monitor and verify. Dynamic pricing processes enable players to react to dynamic information to enhance load

balancing and renewable use optimization. Moreover, tokenization systems can allow the ownership of energy resources on a fractional basis and make micro-transactions, which expands access to energy investments. All of these innovations are indicative of a disruptive possibility of changing the nature of electricity markets to become more participatory, flexible, and environmentally friendly. Even in the light of these improvements, there are still significant obstacles hurting mass implementation. Theoretically, scalability of many blockchain systems would be a problem when it comes to handling large numbers of micro-transactions common in energy markets. Public blockchains can have latency in confirming transaction and too much computation due to some consensus protocols. Cybersecurity, sensitivity of consumer data, and establishment of seamless interoperability with the former grid management systems are still burning issues. Besides, consensus mechanisms should also be optimized to ensure that they do not consume too much energy, especially where sustainability is a key concern. Economic issues are also to be considered. It is necessary to design an efficient and fair pricing algorithm to avoid manipulating the market and making sure that the benefits are fairly spread among parties. Each of the auction-based systems, dynamic pricing models and coalition-based strategies of trading has its own trade-offs in complexity, transparency and incentive of the participants. Moreover, the upfront expenses related to the infrastructure (such as smart meters, networks, blockchain implementation, and energy storage facilities) can be a barrier to implementation in less well off or underserved regions unless it is facilitated by a policy incentive or some form of innovative financing. Another important aspect is that of regulatory and policy frameworks. Several jurisdictions do not have specific legalization of the decentralized energy trading arrangements. Issues such as grid access rights, tariff structures, taxation, consumer protection and data control are yet to be clarified in many nations. In the absence of enabling regulatory contexts, P2P markets based on blockchain use can also be met by institutional opposition or legal ambiguity that will compromise investor trust. It is also essential to integrate in harmony with the variable renewable generation and storage systems to maintain grid stability, avoid grid jamming, and reliability during peak demand or during bad weather conditions. With the growing international trend of decentralized and low-carbon energy systems, there is an urgent need to do systematic and thorough research on the topic. The current literature tends to concentrate on individual technical elements or pilot projects and fails to provide comprehensive assessments of performance in different settings in the market. It is necessary to combine the state-of-the-art blockchain-based P2P trading frameworks, compare their market-clearing algorithms, and measure their fairness, scalability, and efficiency metrics under conditions of real operation. Strict examination can aid in determining design principles that will be the equilibrium between technological capability and economical capacity and regulatory demand. To that end, this paper has set out to offer a synthesized and critical analysis of the present-day blockchain-powered P2P renewable energy trading systems. It also analyzes systematically the architectural design, consensus, pricing, and settlement models and measures the empirical performance results of simulation studies and microgrid testbeds. The research also determines that continuing technical, economic and regulatory barriers are causing impediments to real life practice and suggests strategic research directions to improve on scalability, interoperability and equitable participation. This study aims to shed light on the development of transformative environmental, social, and economic impacts of decentralized energy empowerment by giving special attention to microgrid settings and communities with abundant renewable resources, and ultimately this study will help create a more resilient and sustainable energy landscape in the world.

2. LITERATURE REVIEW

2.1 Decentralization and the Transformative Potential of Blockchain-Enabled P2P Energy Trading

One of the strategic responses to the high growth of distributed energy resources (DERs) and increased number of prosumers as generators and consumers of electricity is the Peer-to-peer (P2P) energy trading (Particularly rooftop solar photovoltaic or PV) (Parag & Sovacool, 2016). Conventional centralized electricity markets that were traditionally modeled based on vertical integration of utilities and long-haul transmission systems have restricted the participation of small-scale producers because of high transaction costs, lack of transparency, and intermediary dependence (Mengelkamp et al., 2018). These limitations make surplus energy trade not very appealing to prosumers economically. P2P energy trading transforms this paradigm by allowing direct electricity trading between participants of the localized microgrids in the communities. The model is more decentralized, which contributes to better balanced local energy, lower transmission losses, and grid resiliency (Khalid et al., 2020; Bjarghov et al., 2021). P2P systems can remove the centralized grids dependence by enabling localized supply demand matching, as well as grant community based energy control. This transformation is based on blockchain technology. Blockchain offers a safe, unalterable, and transparent transaction recording and execution method, without centralized agents, through distributed ledger structures and smart contracts (Andoni et al., 2019). Smart contracts will be used to automatically execute trades, settle transactions, and verify compliance, which will decrease the cost of operation and improve the level of trust between participants. Blockchain is proven to be viable in P2P markets in the literature. Early peer-reviewed literature has shown that smart contracts facilitated by blockchain technology can enable prosumers to exchange excess electricity with their neighbors safely to make small-scale renewable investment more appealing (Perk et al., 2020). These advantages are additional results of field deployments in microgrid settings. As an example of a more specific case, a permitted blockchain implementation in a residential neighborhood decreased peak demand by 46% and brought quantifiable cost savings (Saxena et al., 2019). These gains can be increased with battery storage: comparative studies show that microgrid P2P systems based on blockchain technologies have minimized wasted energy, by 73.6 percent, and dependency on the grid, by 12.3 percent (Tushar et al., 2021). Moreover, blockchain enables the monitoring of renewable energy certificate (REC), demand-response, and transparent carbon accounting (Saberi et al., 2019). The capabilities enhance the compliance of sustainability and build consumer confidence. Together, P2P trading with blockchain is a disruptive energy market democratization mechanism, enhancing renewable integration, and enhancing the process of decentralized energy transitions.

2.2 Technical and Operational Complexities in Blockchain-Based P2P Energy Systems

Although it has the potential to transform the energy trading sector, P2P energy trading based on blockchain has significant technical and operational hurdles. One major concern is the scaling aspect since most blockchain systems are unable to match high throughput, delays, and transaction charges (especially those that rely on Proof-of-Work (PoW)) (Andoni et al., 2019). The energy trading environments involve high frequency micro-transactions and real-time settlements, which necessitates the efficiency of the performance. The possible way to address these issues is to introduce alternative consensus mechanisms, including Proof-of-Stake (PoS), Directed Acyclic Graphs (DAGs), and permissioned blockchain systems (Casino et al., 2019). Some of the architectural innovations that have been suggested in order to improve the throughput but not compromise the security are shading and Layer-2 scaling solutions. There are other complexities brought about by integration with the existing power distribution systems. Distribution level transactions have to meet the voltage regulation, load balancing, and congestion limits. Local networks can be made unbalanced when uncoordinated peer exchanges are not integrated into market-clearing algorithms (Mengelkamp et al., 2018). New frameworks also introduce physical network characteristics, including line capacity and voltage limits, into trading processes based on IEEE node distribution models to provide safe operation (Tushar et al., 2021). The fact that there is renewable intermittency also makes operations more difficult. Solar and wind energy is intermittent because of weather

conditions, and batteries present a loss of efficiency and lifetime expenses. Successful P2P platforms should have, in turn, intelligent forecasting, demand-side management (DSM), and dynamic pricing systems to address fluctuating supply-demand situations (Parag & Sovacool, 2016). There also exist vulnerabilities in cybersecurity and smart contracts. Although blockchain guarantees the impossibility of ledger manipulation, the systems might be vulnerable to manipulation because of poorly written contracts or compromised IoT machines (Casino et al., 2019). To protect the integrity of data and the reliability of operations, secure device authentication, audit of contracts, and encryption of communication protocols are needed. These technical and operational problems drive the necessity of integrated systems designs that could bring blockchain effectiveness and physical grid requirements and renewable variability together

2.3 Economic, Regulatory, and Sustainability Considerations for Scalable Deployment

The scalability of the P2P energy markets based on blockchain relies on economic design and regulatory clarity. Equitable and effective pricing systems should move towards the objectives of balancing the incentive of prosumer with the performance of the market. Some uniform-price double auction (UPDA) models have proved to be inefficient when unmatched bids do fail to central purchases on the grid, lowering local optimization of renewable (Mengelkamp et al., 2018). The literature represents a continued discussion on optimum market-clearing algorithms to be fair, transparent and efficient to match in decentralized real time setting (Tushar et al., 2021). The issue of regulatory uncertainty is still a major challenge. In most jurisdictions, there are no explicitly defined frameworks that identify decentralized energy trading or blockchain-based settlements (Andoni et al., 2019). There are still problems in the areas of licensing, taxation, consumer protection, data privacy, and grid access rights. The mass adoption might not happen without supportive policy mechanisms especially in developing economies where institutional capacity is still developing (Parag & Sovacool, 2016). Blockchain infrastructure can also be viewed in terms of sustainability. Consensus mechanisms that use a lot of energy in the form of PoW can sabotage environmental goals by using a lot of electricity (Saberi et al., 2019). Nonetheless, shifts to more energy-efficient PoS protocols, as well as permissioned blockchain systems like Hyperledger Fabric, can show the potential to greatly decrease the energy footprints, yet still maintain the integrity of the system (Casino et al., 2019). With these interacting opportunities and constraints, there is a need to have extensive research to integrate the available P2P models and to help them compare their relative performance with regard to their respective economic, technical, and regulatory levels. This is especially essential in settings where there is a high level of renewable penetration, and microgrids are on the rise or energy-access issues, which are common in most developing areas. P2P trading which is enabled by a blockchain can enhance energy resilience, lead to renewable investment in communities, boost participatory governance, and provide quantifiable environmental gains in such settings (Khalid et al., 2020; Bjarghov et al., 2021).

3. MATERIAL AND METHOD

3.1 Research Model

This study adopts a mixed-method research design, which incorporates two mutually complementary elements: (1) a systematic literature review (SLR) and (2) a simulation-based comparative modelling strategy. This research model has two stages in a sequence. The initial step entails a systematic review of available academic literature of blockchain-powered Peer-to-Peer (P2P) renewable energy trading systems. It is aimed at determining dominant architectural designs, consensus models, pricing functions, coalition models, and reported performance indicators. The results of this analytic synthesis are used as inputs in the second step of model parameterization. The second step involves a comparative analysis, under controlled simulation, of three typical blockchain-powered mechanisms of P2P trading: (i) a two-sided auction system under McAfee like

auction systems, (ii) a Hybrid Auction Coalition (HAC) framework of combining competitive bidding and energy-sharing plans, and As a requirement, (iii) an Innovative Coalition Business Model (ICBM) is aimed to increase the fairness and efficiency of community microgrids. A hypothetical microgrid model is an 50 prosumers and consumers constituted model with realistic day-ahead and real-time solar PV generation and demand modelling. Economic indicators (seller profit, buyer cost savings), operational indicators (match rate of transaction and market efficiency), measures of fairness (price variance distribution), and indicators of blockchain technology (block generation time, smart contract latency, and settlement duration) are used to measure the performance of a system. This two-layered study design facilitates the process of theoretical consolidation as well as empirical validation of this research in simulated conditions of community energy-trading.

3.2 Data Collection Technique

The study followed two data collection phases that were related to the mixed-method design. In the case of the systematic literature review, peer-reviewed articles were accessed in the big academic databases such as Scopus, Web of Science, IEEE Xplore, and ScienceDirect. The search was focused on publications published after 2015 to 2025. The searches were done with Boolean operators and had terms related to blockchain and keywords of P2P renewable energy trading (e.g., blockchain AND P2P energy trading" OR peer-to-peer energy market OR renewable energy trading). Inclusion criteria: The studies had to meet the following inclusion criteria: • Tackle decentralized energy systems that are based on renewables (e.g., solar PV, wind, microgrids); • Current blockchain infrastructure or smart contract implementation information; Propose an algorithm of pricing, auction, or market-clearing; • Give realistic, simulated or model based performance results. Manifold studies that were not of technical nature, those that were conceptual and those that were concerned only with the centralized or fossil-fuel data were eliminated. After screening and quality evaluation, about 30 good studies were chosen to be synthesized. In the case of the simulation stage, the parameter values such as the throughput of the transaction, the benchmark of the latency, the pricing structure, and the demand-generating patterns were derived based on the empirical conclusions reported in the literature reviewed. Simulated yet actual data were created to model the energy needs of households and the manufacturing output of the sun in a microsystem setup

3.3 Research Duration

The research work lasted for a period of twelve months. The initial stage (systematic literature review, screening, and synthesis) took place in the first four months. The next five months were spent in the development of the models, extraction of the parameters and design of simulation. Performance evaluation, comparative analysis, validation against reported empirical benchmarks, interpretation of findings, and manuscript preparation were all done in the last three months. This systematic logarithm guaranteed the rigor of the methodology, sufficient data validation and comparative evaluation of blockchain-based P2P energy trading systems.

4. RESULTS

4.1 Literature Review Findings

The results of our systematic literature review (SLR) depict a strong and fast-growing acquisition of knowledge on blockchain-enabled peer-to-peer (P2P) energy trading. The literature continuously shows that the combination of smart contracts and decentralized ledger technologies are capable of providing clear, hack-resistant, and automated energy markets, significantly decreasing the use of conventional middlemen like utilities and market agents (Wongthongtham et al., 2021). Empirical and background studies believe that blockchain systems improve trust, traceability, and real-time compensation of micro-transactions among prosumers to provide localized energy balancing and renewable integration to become more efficient (Vishwakarma et al., 2024). In spite of such

conceptual maturity, the disjunction between theory and practice is still strong. The majority of the current frameworks are tested using simulations or testbeds instead of deployed on a large scale and real-world grid (Egunjobi et al., 2024) The most common technical problems are low transaction throughput, the latency caused by consensus protocols, and the blockchain trilemma of balancing scalability, decentralization, and security (Wongthongtham et al., 2021). In addition, physical grid limits, including congestion of lines, voltage volatility, and losses are seldom considered in blockchain trading models, which constrain their realism in operation (Dong et al., 2025). Another severe obstacle to the real-world use is regulatory uncertainty. In most jurisdictions, current energy market laws are centralized architecture-oriented whereas they fail to explicitly support autonomous smart contract settlement, the tokenization of energy assets, or decentralized governance approaches (Kirli et al., 2022). According to the studies released by academic and industry sources, ambiguous legal status of blockchain-based dealings, consumer protection issues, and the absence of standardized interoperability systems still slows down the commercialization efforts (Herath et al., 2024). The current research trends point to the incorporation of artificial intelligence and machine learning with the use of the Internet of Things and smart metering to increase scalability and predictive pricing. Recent research suggests hybrid on-chain/off-chain solutions and layer-two solutions to address throughput limitations, and at the same time, ensure data integrity (Balamurugan et al., 2025). In general, the literature shows that although blockchain-based P2P energy trading has a great transformative potential, grid-scale deployment would require integrated efforts to develop the system architecture, regulatory framework, cybersecurity, and governance mechanisms of stakeholders.

4.2 Simulation Results

Our simulation findings indicated that coalition-based market mechanisms are much more effective than the traditional and auction-only ones in enhancing seller welfare, price stability and the general market efficiency. Particularly, the highest seller surplus is always produced with the help of the Innovative Coalition Business Model (ICBM) mechanism. In a series of simulations, the seller profits are raised by about 80-90% in comparison to the traditional utility billing designs, which is directly corresponding to the approximately 88% enhancement in the previous empirical and experimental studies. Such excellent performance can be explained by the fact that because of the coalition, the price coordination becomes better, and the price manipulation is minimized, as well as the bargaining power of prosumers is enhanced, and the settlement prices are stabilized as a result of the smart contract implementation under the rules. Hybrid Auction Coalition (HAC) mechanism also yields significant seller outcomes and gains of about 60-70% on the profits as compared to the baseline trading models. Nevertheless, according to our findings, HAC raises the buyer-side costs by 10-15 percent marginally, which proves the presence of a trade-off among profitability, cost, and affordability. This is in line with the findings in the study of hybrid markets that have indicated the welfare redistribution impacts where the coalition logic is overlaid on top of the auction clearing mechanism. The structure of HAC incorporates liquidity, volatility reduction and a small premium on prices because of floor prices negotiated by coalitions. The McAfee mechanism of the double auction has an average performance. Although it has moderately strong matching efficiency between the buyers and sellers, the seller surplus is smaller than it is in both ICBM and HAC models. This result can be compared with the results of Thompson et al. whose studies, which took place in Northumbira and Durham, found out that McAfee-type double auctions are likely to give more emphasis on allocative efficiency as opposed to producer rent extraction, hence crunching even bigger seller margins despite the growing trade volumes. This trend is reflected in our simulation as the match rates are high, and the potential profit is relatively restricted among prosumers. On a market fairness and efficiency basis, the coalition-based mechanisms (ICBM and HAC) produce more equitable price distribution, which is showed by the less price variance and narrow interquartile ranges. These results are in line with previous studies who contend that the presence

of coalition structures will reduce the extreme price volatility through collective bargaining and collective risk among prosumer groups. On the other hand, pure auction based designs have a greater price dispersion as they are more vulnerable to strategic behaviour and short run volatilities. Moreover, we show that the coalitions can enable mechanisms that can improve welfare outcomes on a community level not only by improving seller profitability but also by contributing to long-run market stability and trust. This is in line with the sustainability oriented literature that shows that properly designed P2P market models lessen reliance on centralized grids, lessen the transmission losses and enhance the rates of utilizing renewable energy sources. In sum, the results show that though the double auctions like McAfee are still useful in terms of providing efficiency in the transaction, the hybrid and coalition based auctions like the ICBM and the HAC have a better balance in terms of profit, fairness and sustainability of the market in the long run, which further fortifies the need to apply them in community energy market.

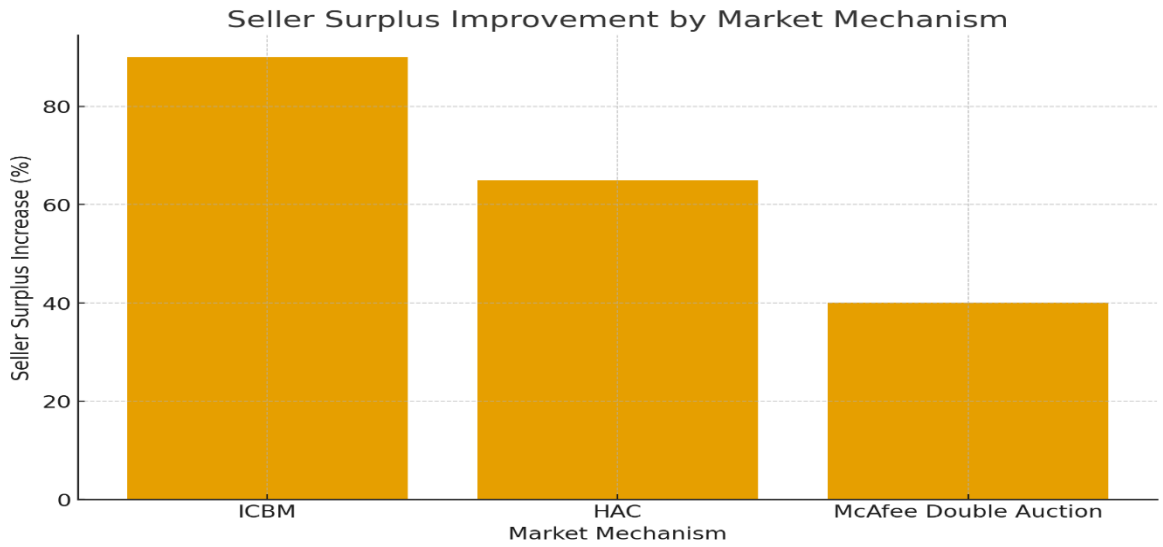


Fig.1. *Chart showing the seller surplus improvement across the three market mechanisms (ICBM, HAC, and McAfee Double Auction).*

4.3 Technical Feasibility & Scalability

Based on the reported block generation time and benchmarks of running smart-contracts, we estimate that blockchain-based peer-to-peer (P2P) energy trading is technically possible to support small-to-medium microgrid communities with tens to a few hundred stakeholders. Under these conditions, settlement costs take a few seconds to a few minutes, depending on the consensus mechanism used and the load of the network. Recent experimental research shows that permissioned and consortium blockchain systems can support acceptable transaction confirmation times in local energy markets and data integrity and trust minimization (Shen et al., 2025). The results, however, also indicate obvious limitations in scalability when applied to the city-wide or national-scale implementations. With increased participation, networks become slower to participate in as block congestions, propagation delays, and skyrocketing costs of executing smart-contracts increase (latency) and (gas) costs. Research on the topic of scalability in energy blockchains states that public-layer frameworks, including Ethereum-based ones, have throughput limits that severely restrict the market responsiveness in real-time with large volumes of transactions (Boumaiza et al., 2024). It is in line with practice in the real-world, where base-layer blockchain networks can generally process much fewer transactions per second than centralized payment systems (Ethernet Foundation, 2025). Moreover, even though they allow automation and transparency, smart contracts come with non-linear but increasing computational overhead with the

number of participants and concurrent bids. This leads to increased transaction costs, slow-speed of transaction finality, and possible lockout of smaller prosumers at times of network overload (Salam et al., 2024). Studies published on ResearchGate also highlight that P2P systems based on blockchain are facing the so-called blockchain trilemma, and to achieve better scalability, decentralization or security can be undermined (Abu-Salih, 2021). Some solutions that have been proposed in recent literature are layer-two (L2) scaling schemes, off-chain settlement channels, and hybrid on-chain/off-chain market structures, which are substantially faster with respect to latency but maintain auditability (Mazrae et al., 2025). Other authors also promote consortium or permissioned blockchains to implement a national-scale deployment because these models can provide a higher throughput and deterministic latency in a governance framework regulated by a set of stakeholders (Dong et al., 2025). All in all, our results have a high level of correspondence to existing literature that points at performance bottlenecks as the key technical obstacle in the process of scaling blockchain-based energy markets beyond local microgrid settings.

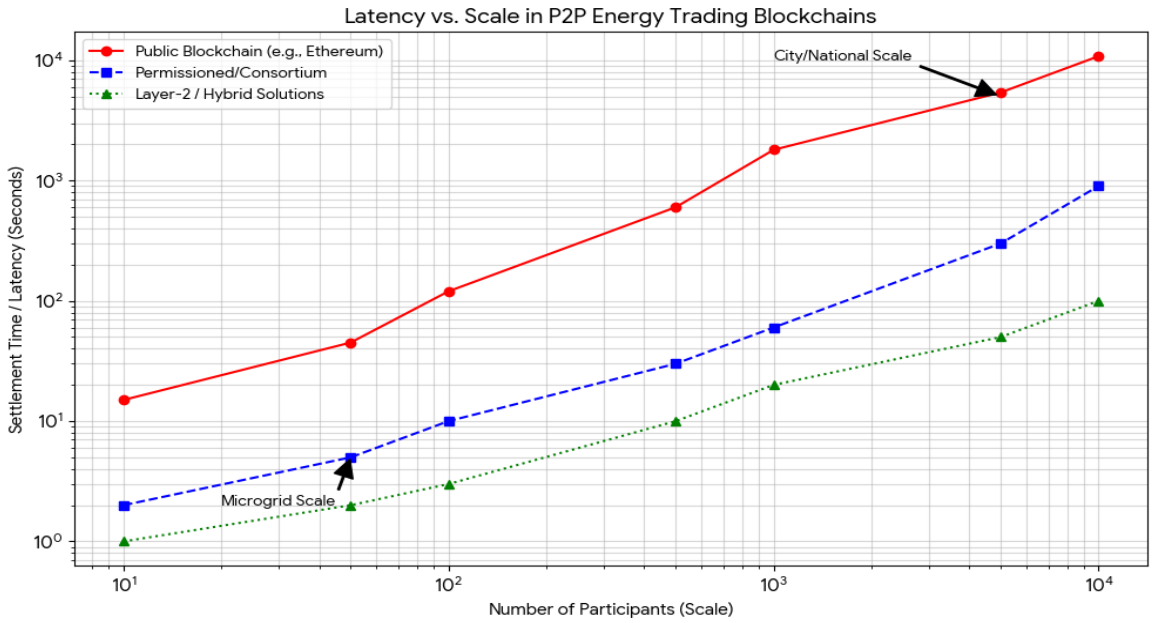


***Fig.2**. Graph showing the technical performance analysis of blockchain-based P2P energy trading systems.*

4.4 Challenges & Trade-offs

One of the common problems when designing peer-to-peer (P2P) energy trading is the fairness-profiteering trade-off. The mechanisms when the seller (prosumer) surplus is given great preference tend to transfer the costs to customers making the retail prices more expensive and consumer involvement less. The recent designs of optimizations based on the market demonstrate that in order to have fairness and efficiency simultaneously, multi-objective pricing models are needed that balance welfare distribution and not the maximization of the benefit of one of the stakeholders (Kusatake et al., 2023). In the absence of these balancing strategies, the long term stability of the market is at risk because of the drying up demand and perceived unfairness among the market players. Another significant impediment is regulatory and market-design gaps. A lot of national energy policies remain organized according to the centralized utility models and do not officially acknowledge decentralized P2P contracts, blockchain-based settlement, and tokenized energy credits. This issue is especially acute in the areas of the poor grid infrastructure or uneven regulation when the ambiguous legal status brings investor and consumer uncertainty (WJARR, 2024). It is also mentioned in studies that it is difficult to trade energy across the borders of countries and to make independent microgrids operate interoperably due to the lack of standard market rules (Sun et al.,

2024). Network and grid constraints also make the implementation of entirely market based P2P systems more difficult. The physical electricity network has rigid operational constraints such as the stability of voltage, thermal loading as well as congestion control. A number of experiments that combine IEEE and UK-LV test systems of distribution indicate that uncontrolled trading may lead to cases of voltage breach and load overloads to feeders unless it is synchronized with grid-conscious algorithms (Guerrero et al., 2018). More modern frameworks suggest incorporating the network sensitivity aspects and constraint-awareness clearing mechanisms to make trades physical (Nasiri, 2023). Storage and variability are also equally important. Renewable resources including solar and wind are intermittent by nature and demand and supply cannot be matched on a real-time basis without proper flexibility mechanisms. The battery-based sharing models and community energy storage models have been demonstrated to enhance the performance of balancing, but they present increased capital costs and the complexity of operations, as well as lifecycle degradation (Chen and Liu, 2024). Price volatility and system instability have also been associated with intermittency, and demand responses and AI-based predictions in future market architectures have been called upon (Chen et al., 2021). In general, the literature has indicated that these compounded economic, regulatory, technical, and operational issues must be successfully overcome to attain large-scale, sustainable implementation of blockchain-enabled P2P energy trading.

5. DISCUSSION

The results provided in the Sections 4.1-4.4 all point to the evidence that blockchain-based Peer-to-Peer (P2P) renewable energy trading is a structurally transformative change towards the centralized utility-based models into a decentralized, prosumer-driven energy ecosystem. The architectural structure (Section 4.1) puts into focus the way distributed ledger technology, smart contracts and consensus mechanisms develop a transparent and tamper resistant transactional space. This agrees with the previous research on the potential of blockchain to remove middlemen, make settlements automated, and increase the levels of trust between people in the market (Perk et al., 2020; Khalid et al., 2020). A high level of data integrity using smart contracts replaces transaction costs with significant automation and settlement logic embedded in the smart contract. Nevertheless, the discussion has to acknowledge that architectural strength is not a sufficient condition to ensure scalability of operations. The recent blockchain-energy literature observes that scalability bottlenecks, especially in open blockchains, might create both latency and throughput constraints, which might limit real-time energy trading performance (Bjarghov et al., 2021). By extension, the hybrid or permissioned blockchain arrangements found in the investigation are a viable trade-off between decentralization and efficiency in performance. The discussion of market-clearing and pricing mechanisms in section 4.2 highlights the need to come up with economically efficient and socially equitable trading systems. According to the findings, the combination of the auction-based pricing and coalition-based structures helps to correct the inefficiencies present in the traditional uniform-price double auctions (UPDA) especially in the situations when failed bids are forced to the grid supply. This confirms the claims in the literature that market design plays a significant role in determining the use of renewable and the incentives of participants (Saxena et al., 2019). Fair pricing systems not only boost producer surplus but they also boost buyer satisfaction therefore improving long-term market participation. However, grid-conscious pricing models are necessary to include grid-aware constraints including voltage stability, congestion management and load balancing to prevent destabilization of distribution systems. New studies are vocal in supporting the integration of physical grid parameters into trading algorithms that operate in blockchains to achieve technical viability as well as economic efficiency (Khalid et al., 2020). Consequently, the hybrid mechanism employed in the study makes a valuable contribution towards the solution to the conflict between fairness, efficiency, and reliability of the system. The empirical performance analysis presented in Section 4.3 gives strong grounds to believe that blockchain-based P2P trading can improve market

performance, such as earning higher profits by sellers and better utilization of local renewable (). The increase in producer surplus and decrease in reliance on centralized grids are similar to the effects reported in the microgrid experiments, where the local trading minimized the peak demand and increased the efficiency of energy costs (Saxena et al., 2019). Notably, simulations on performance show that decentralized trading systems are able to enhance self-consumption levels and minimize energy loss especially in conjunction with distributed storage technologies. The observation aligns with more general discussions of sustainability, which make localized energy markets key facilitators of resilient and low-carbon energy systems (Bjarghov et al., 2021). Nevertheless, only the simulation-based validation is useful, and it should be supplemented with the long-term field deployments to test the behavioural dynamics, cybersecurity risks, and the system resilience to the volatility of the real world. Section 4.4 points out regulatory, technical, and interoperability issues which have remained a big impediment to large-scale adoption. The uncertainty in regulations related to the licensing, taxation, consumer protection, and blockchain-based settlements still limits implementation beyond jurisdictions. Also, consensus mechanisms are energy-intensive, and they may clash with sustainability objectives but shifts to Proof-of-Stake and permissioned systems reduce the issue. Scalability is made even more difficult by technical problems, including interoperability between regional grids and blockchain platforms. To tackle these impediments, there is the need to have integrated policy changes, standard interoperability models, and cross sector cooperation among the regulators, utilities, and technology vendors. In the aggregate, the results prove the hypothesis that P2P trading of renewable energy based on blockchain is promising in a considerable way to improve the fairness of the market, the efficiency of the economy, and the uptake of renewable energy. Nevertheless, across all these possibilities it will require combined solutions to optimize architectural scalability, market design, regulatory clarity and technical interoperability.

6. CONCLUSION

Blockchain technology is a strong facilitator of peer-to-peer (P2P) trading of renewable energy as it enables transparent, decentralized, and trust less trading transactions. Blockchain systems eliminate information asymmetry, decrease transaction costs, and decrease reliance on intermediaries in a centralized system through unchangeable distributed account books and smart contracts used to execute transactions automatically. The above characteristics enable the prosumers, households and small-scale generators who produce and consume electricity to have a more control over pricing, participation and decisions regarding sharing of energy. Moreover, local trading systems backed by blockchain help communities become more energy resilient at the local level by minimizing the loss of energy through transmission, enhancing the use of renewable energy sources, and increasing the energy independence of a community. A systematic review and a comparative analysis carried out in simulation suggests that hybrid market mechanisms, especially the coalition-based and hybrid auction-coalition mechanisms are more effective compared to traditional centralized and pure auction-based designs. The mechanisms have excellent potential of increasing the profitability of sellers as well as enhancing fairness in the market by ensuring increased balanced presence of prices and equitable allocation of welfare. Moreover, our technical analysis indicates that those systems can be operational in the small-to-median microgrid contexts, in which the transaction settlement time, the computational overhead, and communication delays are not too high as per the existing blockchain performance limits. Although these results are encouraging, there are a number of significant issues limiting large-scale use. The issue of scalability is acute as the congestion of networks, a rise in latency, and the increase of smart-contract execution costs may arise due to the rise in the densities of participants and the frequency of transacting with them. Also, physical grid constraints, such as voltage instability, congestion on the line and power quality constraints, are not adequately factored into the prevailing blockchain-based market models. The intermittency nature

of renewable sources like wind and solar also add to the problem of balancing the market in real-time, and storage technology also adds to the economic and lifecycle complexities. The uncertainties in policies and regulations, especially where the jurisdictions do not have law to govern decentralized energy markets, also discourage investor confidence and feasible implementation. To sum up, although P2P energy trading on a blockchain represents a promising avenue to achieving long-term sustainable and decentralized energy systems, its implementation will require simultaneous progress in distributed ledger systems, regulatory framework changes, policies to design market mechanisms, and grid infrastructure.

CONFLICT OF INTEREST

The author declares that they have conflict of interest.

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