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TOPICAL REVIEW

Peer-to-Peer Trade and the Sharing Economy at Distribution Level: A Review of the Literature

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ABSTRACT Peer-to-peer (P2P) energy trading has gained significant importance in recent years due to the growing energy needs worldwide. To ensure the effective and efficient implementation of P2P energy trading, it is necessary to analyze the concept from multiple dimensions. This study aims to investigate the challenges that may hinder the smooth flow of P2P energy trading and identify strategies to overcome them. Technical, cybersecurity, renewable energy integration, economic, pricing mechanisms, and regulatory challenges are among the key obstacles that may curtail the full potential of P2P energy trading. In addition, the full achievement of the P2P energy trading potential requires a global response from stakeholders to ensure widespread acceptance and adoption. Game theory and agent-based modeling can effectively address these challenges and facilitate the successful implementation of P2P energy trading.

INDEX TERMS Agent-based modeling, game theory, peer-to-peer energy trading, pricing mechanisms, renewable energy integration, regulatory frameworks.

I. INTRODUCTION

The emergence of P2P trade can be traced back to 1971, giving rise to the first inter-chat service in 1988, which facilitated the sending of the inaugural email [1]. Far from being a mere technological novelty, this development acted as a catalyst, stimulating advancements in various domains. One notable milestone was the launch of Napster in 1999, a P2P sharing service that revolutionized the way users exchanged digital music files, particularly MP3s, over the internet [2]. Thus, it facilitated an unprecedented level of accessibility to free online music. By 2003, the landscape had evolved to include social networking and bookmarking sites, extending the impact of P2P systems beyond mere file sharing. Platforms like Facebook, YouTube, Snapchat, Instagram, and LinkedIn have since become integral parts of daily life [3], [4].

Transformative changes are occurring in energy markets. These changes can be attributed to the decentralized nature of renewable energy sources and are further fueled by the adoption of sharing economy principles, allowing consumers to directly trade electricity within their communities [5]. In this context, P2P energy exchange serves as a decentralized paradigm that enables both producers and consumers to participate in electricity transactions. With the integration of emerging technologies like blockchain [6], P2P has become a reliable mechanism for secure energy exchanges. In fact, blockchain has the potential to redefine operational dynamics and value creation in P2P energy trading. This technological integration expands access to local markets and enhances the overall economic viability of energy trading [7].

Among the key enablers of P2P energy trading are so-called prosumers, smart meters, and decentralized marketplaces. These elements collectively facilitate the transactional flow of electricity in a non-centralized fashion. Given the inherent physical constraints of power systems, the synergistic combination of blockchain technology and P2P trading platforms can offer significant economic advantages. For instance, smart meters serve as crucial technological assets, delivering granular data on both energy consumption

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and production, and thus form the backbone of P2P energy trading ecosystems. These elements not only influence the exchange and acquisition of information but also redefine the dynamics within the sharing economy. Today's P2P trading ecosystem extends across a myriad of sectors, offering services that economically empower users by streamlining both transactions and resource allocation. In the realm of energy, P2P trading serves as a conduit for electricity exchange between distributed energy resources (DERs) and end-users. This system enables users to diversify their electricity supply options through the use of digital platforms, intelligent metering technologies [8].

Recent trends in power trading, as noted by [9], mark a radical shift from its traditionally centralized frameworks. This transformation can be traced back to the deregulation of energy markets, thereby paving the way for private enterprises to offer customized electricity services to a wider customer base. P2P energy trading operates in the absence of intermediaries and leverages smart electric grids, which are endowed with sophisticated automation, information technology (IT), and communication systems to monitor power flows from generation to consumption [10].

Smart grids play a pivotal role, as they not only monitor but also dynamically adjust power inflows and outflows to meet real-time or near-real-time energy demands. Further research corroborates the growing significance of modern P2P trading systems, which have been meticulously designed to cater to both customers and prosumers who prefer to avoid third-party involvement [9] Given this consumer preference, community-oriented P2P trading has gained substantial traction. In this model, local distribution system operators act as facilitators, fostering advanced interactions between stakeholders, such as prosumers and consumers. They also wield the capability to orchestrate a unique blend of suppliers and end-users, thereby optimizing the social welfare of the local community in an effective and efficient manner.

As elucidated by Tushar et al., P2P trading has evolved into a contemporary energy management strategy with mutual economic advantages for both consumers and producers [11], Not only does it facilitate the trading of electricity as a commoditized good or service, but it also contributes to grid stability reduced peak demand, minimized network losses, and lower reserve requirements. While these benefits accrue to utilities and consumers alike, the system is not without its challenges. These challenges are multi-faceted, affecting transactional integrity across both virtual and physical network layers and having far-reaching implications on the operational efficiency and reliability of P2P trading within the sharing economy context. Further research by Paudel et al. [2020], underlines that energy transfers in this model are subject to power losses and associated costs, underscoring the need for ongoing development and refinement of P2P trading systems [12] P2P trading serves as a versatile platform for market participants, enabling them to reap substantial benefits via optimized electricity resource allocation. This optimization not only alleviates demand pressures but also curtails maintenance and operational expenditures within the sector [12].

Moreover, it holds the promise of enhancing the reliability of electrical systems. Given the burgeoning literature emphasizing the significance and multi-stakeholder advantages of P2P trading, it stands as a progressive model in addressing the ever-increasing global energy demands. This, however, also brings to light various challenges and opportunities that necessitate a thorough literature analysis for comprehensive understanding and effective implementation.

A. RESEARCH OBJECTIVES AND QUESTIONS

Following are the research questions that the current study aims to heed:

- Assess and mitigate the technical challenges inherent to P2P energy trading.
- Investigate the mechanisms for application and pricing that could foster cooperation and efficiency in P2P energy trading, examining both the merits and limitations of these strategies.
- Identify the economic and regulatory obstacles impeding the widespread adoption of P2P energy trading and propose potential solutions for overcoming them.
- Evaluate the ramifications of P2P trading and the sharing economy on various stakeholders, including consumers, governmental bodies, and power producers.

II. THEORETICAL FRAMEWORK

The theoretical framework utilized in this study serves as a robust, versatile analytical tool, designed to be adaptable across diverse contexts and scenarios. This framework offers utility in a wide range of disciplines, delivering the kind of nuanced theoretical insight that is crucial for a holistic understanding of the problem at hand [13]. A theoretical framework can also be conceived as a structural scaffold that accommodates or underpins one or multiple theories. Their importance in scholarly research is paramount as they articulate and contextualize distinct concepts, thereby highlighting why the issue under investigation warrants thorough analysis. For this study, we have devised a theoretical framework aimed at furnishing an abstract yet precise depiction of the problem in question. The framework is visually represented in Figure1 below:

A. GAME THEORY

Game Theory serves as a robust mechanism for simulating strategic interactions among multiple players within a defined set of rules and outcomes. This theory has pervasive applications, extending its relevance to fields such as business, finance, economics, political science, and psychology [14].

The scenarios modeled as "games" can range from competitive market dynamics, such as reactions to price cuts between competitors, to decision-making frameworks in mergers and acquisitions, and even behaviors in stock market trading. Conceived in the 1940s by John von Neumann, a renowned mathematician, and Oskar Morgenstern,

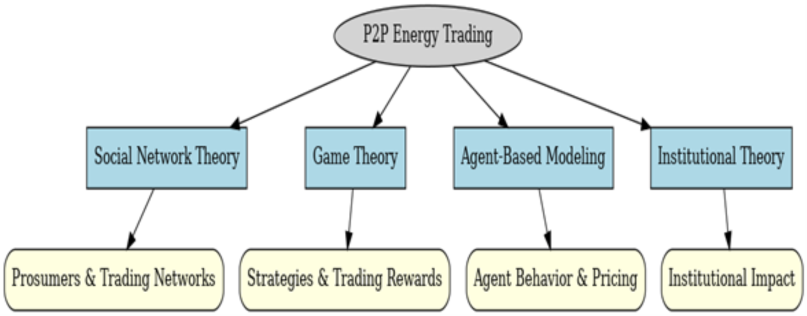

FIGURE 1. The framework of the current study.

an economist, Game Theory serves as a comprehensive, interdisciplinary lens for analyzing the interconnected decisions of agents in competitive situations [14].

According to Colman, the essential elements of games are as follows (See Figure2):

- Players: Who plays? Strategic decision maker within the context of the game.
- Strategy: A comprehensive plan of action a player will follow, contingent upon the varying circumstances that may arise during the game.
- Payoff: The rewards, which can be quantified in various forms, received by a player for reaching a specific outcome.
- Equilibrium: The state where all players have made their decisions, culminating in the final outcome.

Game Theory is invaluable for equipping stakeholders with analytical tools for situations where interdependent decision-making is crucial [15]. This interdependency compels players to consider the possible decisions or strategies that competitors might employ meticulously and critically. In the realm of this research, Game Theory assumes a pivotal role in modeling energy trades and formulating pricing mechanisms. Specifically, in P2P trading scenarios, it can be leveraged to predict how price alterations on one side could influence the other. As pointed out by Rahman [2020], the adoption of new trading strategies at various levels may present a host of technical challenges [16].

P2P trading is conceptualized as a trustless ecosystem in which prosumers exchange energy with various consumers, eliminating the need for intermediary involvement [17].Game Theory stands as a highly versatile framework, facilitating the effective design and analysis of energy trading mechanisms for more intelligent, adaptive grid systems. It finds extensive application in contemporary energy trading research and is poised to play an increasingly vital role in the development of future smart grids [18].

Key manifestations of Game Theory in the energy market include the utilization of auction mechanisms and the exploration of non-cooperative games. The auction mechanism serves to optimize the alignment between supply and demand dynamics, providing a transparent and efficient trading platform. In contrast, non-cooperative Game Theory

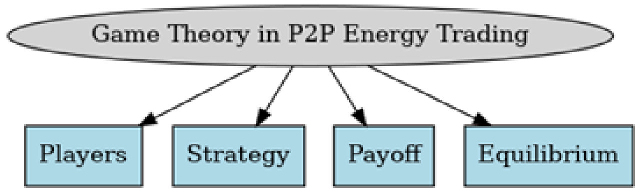

FIGURE 2. Game theory in P2P energy trading.

offers a lens to scrutinize the complex decision-making processes engaged in by competing entities. This approach is particularly insightful for uncovering conflicting interests and gauging the consequential impacts of these decisions on the trading ecosystem. Therefore, Game Theory emerges as an indispensable theoretical construct for the scope of this research.

B. AGENT-BASED MODELLING

An agent-based model is conceived as a computational framework aimed at scrutinizing the actions and interactions among multiple, autonomous agents [19]. These agents can range from individuals to institutional entities such as corporations or organized groups. By dissecting the behavior of these varied agents, agent-based modeling yields insights into the governing dynamics of their outcomes. Importantly, this modeling approach integrates various underlying theories, including but not limited to Game Theory and Complex Systems Theory [20].

According to Wilensky and Rand, the agent-based framework finds wide-ranging applications across multiple disciplines, from biological sciences to sociology, ecology, and other realms of social sciences [21].Its relevance to this study is underscored by its potential for modeling intricate stakeholder interactions in the energy trading ecosystem, which may encompass producers, consumers, and grid operators.

In the realm of agent-based modeling, the roles and types of agents are context-specific. These agents, whether individual, multiple, or cognitive in nature, are configured to make informed decisions aligned with the prevailing trading strategies [22]. In P2P trading scenarios, agents assume context-dependent roles and responsibilities, operating within a decentralized framework devoid of a governing central authority [23].

Agent-based modeling, therefore, offers a viable approach for managing the complexities inherent in the architecture of energy trading [24]. Furthermore, it provides a fertile ground for examining the feasibility and impact of consumer participation in trading [25]. Agent-based models hold significant promise for navigating future challenges related to sustainability and environmental effectiveness in energy trading operations. They offer a dynamic platform conducive to rapid P2P energy exchanges. The work of Macal, elucidates the intricacies of agent-based modeling within specific settings, describing a system as a conglomeration of distinct decision-making entities, collectively referred to as agents [22].

In the realm of agent-based modeling, each agent engages in a comprehensive assessment of the situational context before making informed decisions [22] These agents can manifest a wide array of behaviors, each tailored to fit the specific system roles they represent, whether that be in production, consumption, or managerial capacities. Such iterative interactions among agents are pivotal to the efficacy of the agent-based modeling process. This modeling technique utilizes advancements in information technology to delve into the intricate dynamics of systems through a rigorous mathematical approach. The justification for employing agent-based modeling in the current research lies in its ability to capture diverse behavioral patterns among agents, thereby offering invaluable insights into real-world systems. These interactions can be systematically evaluated and dissected to understand underlying dynamics. Furthermore, the method enables the holistic modeling of agent behaviors throughout various processes [26].

The research conducted by Heedeniya exemplifies the application of agent-based modeling in energy-sharing scenarios [27], Their study scrutinizes the interactions between agents in both communal and individual settings to discern strategies for optimizing renewable energy consumption. The findings indicate that when applied judiciously, agent-based modeling can serve as a powerful tool for behavioral analysis. Consequently, this study also aspires to harness the capabilities of the agent-based modeling framework for its investigative purposes.

C. SOCIAL NETWORK THEORY

The researcher Nimmon et al., define Social Network Theory as a comprehensive theoretical framework that amalgamates various theories aimed at dissecting human behavior across multiple social units–ranging from individuals and teams to organizations [28] This theory is particularly geared towards understanding the intricate web of interpersonal relationships that shape human actions within social contexts (See Figure3).

In Social Network Theory, a myriad of analytical methodologies is employed. Contemporary approaches, for example, incorporate elements of rational sociology to elucidate the nexus between network relationships and socio-cultural constructs like identity and culture [29]. The epicenter of these methodologies often revolves around the themes of culture and communication, thereby illuminating societal power structures.

As articulated by Liu et al., Social Network Theory places a paramount emphasis on the instrumental role that social relationships play in facilitating information flow and catalyzing behavioral shifts [30]. The theory's applicability has evolved substantially, finding utility as an analytical lens across diverse empirical landscapes [31].

The theory holds pertinent relevance to the present study by offering insights into the formation and dynamics of social networks within specific social settings. It elucidates how individual behavior can be modeled, making it a valuable asset in predicting the diffusion rates of emerging energy technologies. Moreover, the theory can aid in identifying key stakeholders whose influence could either accelerate or impede the technology adoption process. Specifically, Social Network Theory allows for strategic contemplation of variables that could impact P2P trading [32].

The application of this theory in the current research is twofold. The first aspect involves a comprehensive analysis of changes in social networks to glean insights into stakeholder behavior within social settings. This foundational understanding enables the subsequent modeling of strategies aimed at catering to stakeholder interests. The second aspect focuses on the formulation of strategies to optimize stakeholder engagement. As such, the theory offers critical insights with direct implications for P2P trade, substantiating its inclusion in this study.

D. INSTITUTIONAL THEORY

In today's complex socio-economic landscape, a multitude of stakeholders–ranging from individuals and consumers to governments, NGOs, and formal institutions–collectively exert a profound impact on both the broader economy and the specific niche of P2P trade. As outlined in the Encyclopedia of Law and Economics [33], institutional economics delves into the intricate interplay between economic systems and institutional frameworks. This interaction is crucial for deciphering the mechanisms that drive economic functions, development, and performance. Furthermore, the impact of these institutions on economic dynamics is a central concern.

The core focus of Institutional Theory lies in understanding the evolution of institutions, identifying avenues for their improvement, and ascertaining the subsequent implications for economic systems (Figure4). In the context of the present study, Institutional Theory is of paramount importance because it elucidates the shaping of institutions and their capacity to modulate individual behavior [34]. For instance, government regulations serve as a salient

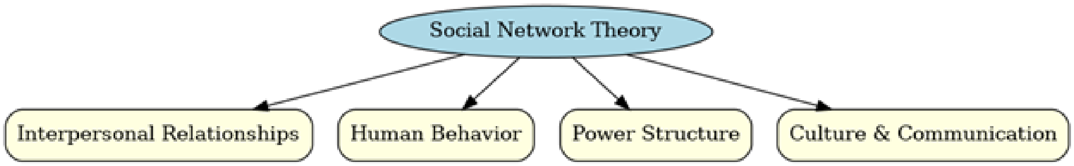

FIGURE 3. Social network theory.

example of institutional mechanisms that can significantly shape individual experiences and choices. If new legislation emerges concerning energy consumption or sharing, it is almost certain to exert a considerable influence on both producers and consumers. Likewise, tax policies on direct sales can also alter stakeholder behavior in meaningful ways.

Given this backdrop, the rationale for incorporating Institutional Theory into this research is to explore the ways institutions are constructed and how they influence individual and collective behaviors. The application of Institutional Theory in the present study is twofold: The first stage involves an in-depth analysis of the institutions impacting the P2P trading landscape. The second stage shifts the focus toward strategic decision-making aimed at mitigating any adverse institutional impacts on P2P trade [35].

E. THE INTERPLAY AMONG THE FOUR SELECTED THEORETICAL FRAMEWORKS

This study's theoretical framework integrates Social Network Theory, Game Theory, and Agent-Based Modeling to illuminate the multidimensional aspects of P2P energy trading(Figure5).

In the context of Social Network Theory, P2P energy trading can be conceptualized as a complex system characterized by sustainable supply and demand dynamics [36]. This theory employs the metaphor of 'connections' and 'nodes,' which in the realm of P2P trading, symbolize prosumers and trading networks respectively. It is imperative to quantify various attributes of these networks, such as their size, density, and the quality of energy being transacted.

Game Theory, on the other hand, offers a framework grounded in the principles of distributed patterns, capturing elements like micro-grid ownership and the multifaceted nature of energy resources [37].It provides an analytical lens for examining strategies related to trading rewards and volumes. In a P2P trading environment, Game Theory becomes crucial when consumers' behaviors are responsive to fluctuations in price metrics.

Agent-Based Modeling serves as another cornerstone theoretical construct that enables the simulation of various variables and interactions inherent in P2P energy trading systems. This computational paradigm quantifies agents' behavior in shaping the energy trading pricing structure. Furthermore, the integration of blockchain technology within an Agent-Based Modeling framework holds the potential to significantly amplify the economic viability of P2P trading [38].

F. THE INTERPLAY BETWEEN P2P ENERGY TRADING AND THE SHARING ECONOMY

P2P energy trading and the sharing economy are intrinsically intertwined, both representing decentralized models that redefine traditional economic interactions. The sharing economy serves as a well-structured economic paradigm, elucidating the mechanisms behind resource sharing and utilization. Moreover, the sharing economy's principles of competitive value generation align closely with strategic elements in P2P models, enhancing the dynamics of energy trading [39]. Cuenca et al. argue that P2P-oriented energy communities have the potential to disrupt traditional models of local energy exchange. Such communities focus on optimizing both base and peak load management to meet consumers' energy demands more efficiently [41]. In the evolving landscape of energy economics, P2P trading is not merely an alternative but a transformative approach that augments the supply chain services in the energy sector. The synergistic relationship between P2P energy trading and the sharing economy extends beyond mere resource allocation. It influences the very fabric of energy demand, blending economic considerations with socio-cultural perspectives [40].

This fusion fosters a more efficient resource management strategy for energy providers, facilitating localized transactions and fostering robust connections within energy systems. Plewni further supports this notion, stating that the organizational structures following P2P trading paradigms are particularly efficacious within a sharing economy framework. Such structures enhance the sustainability of energy demands in an increasingly competitive environment [41]. It is effective for the promotion of sustainable energy demands regulated in the competitive era.

Due to the ever-increasing complexity and reach of energy distribution networks, a flexible and efficient energy grid has become imperative. In this context, data-driven approaches serve as crucial tools for meeting fluctuating energy demands [41]. One fundamental aspect shaping the symbiosis between the sharing economy and P2P systems is resource sharing. For instance, companies utilizing renewable energy sources like solar panels and wind turbines benefit from a sharing economy model, which serves as a cornerstone for their operational benefits, customer needs, and pricing

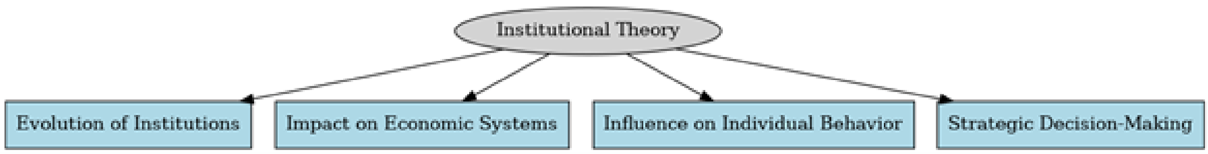

FIGURE 4. Institutional theory.

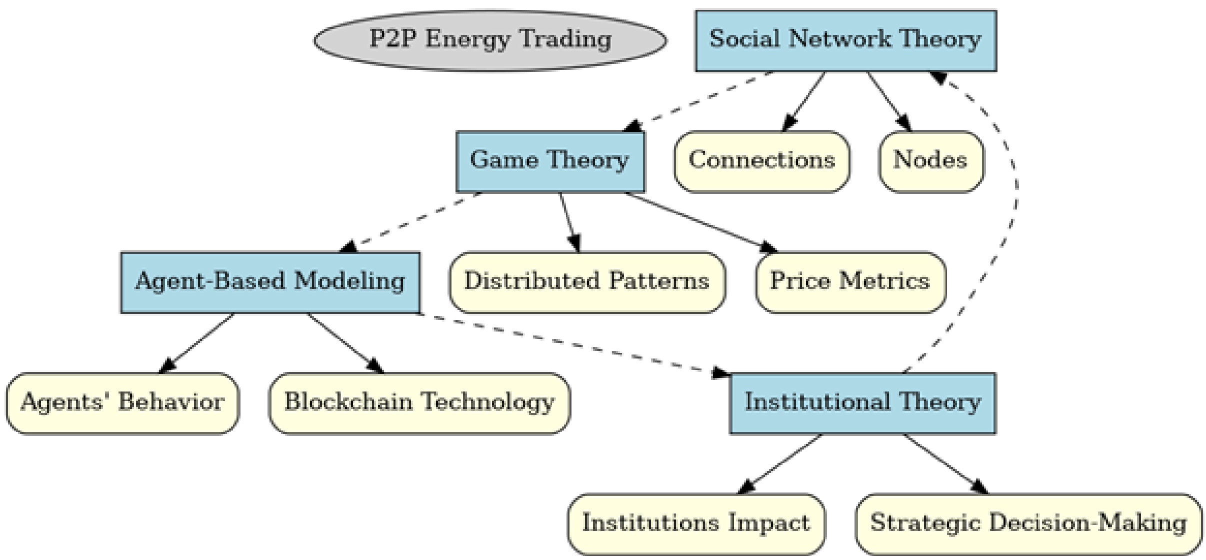

FIGURE 5. The interplay among selected theoretical frameworks in P2P energy trading.

strategies [42]. In the digital age, the sharing economy is poised to be the future landscape of P2P electricity trading. Uniquely, this model obviates the need for direct links between users and brokers, thereby enhancing the security and privacy of P2P trading operations [43].

Such a framework also accommodates the efficient management of surplus energy, thereby fostering sustainability. In a sharing economy, decentralized approaches are not just optional but essential, especially for enabling online transactions in energy trading systems and for catering to diverse cultural perspectives [42]. The role of energy trading in a decentralized setting is not only to facilitate direct trade options among consumers but also to contribute to the larger goals of sustainability and energy transition. These factors are pivotal for optimizing energy resource utilization in a competitive environment filled with dynamic energy demands.

P2P models serve as catalysts in energy distribution, potentially realigning strategic systems to better fulfill energy-related demands. The sharing economy, in this context, becomes a critical lens through which to examine sustainability metrics [44].

It provides insights into strategies for sustainable energy distribution, making it indispensable in the current era of shared economies. In essence, P2P energy systems enable more effective trading within a sharing economy framework, tailoring to competitive industrial demands and end-user needs [39]. Consequently, the synergy between P2P energy trading systems and the sharing economy is not only significant but also instrumental in forging connections between potential users in energy trading.

P2P systems hold a distinguished place in the realm of sharing economy paradigms. Such systems serve as critical conduits for enhancing accommodation strategies and for the effective management of energy resources. For instance, implementing a sharing economy model is pivotal for fostering synergistic interactions among various energy communities [45]. Through platforms dedicated to P2P energy trading, we can not only facilitate resource management but also advance the broader objectives of sustainable energy transition. This is particularly crucial for tailoring solutions that are aligned with individual consumer demands. In a world increasingly reliant on sustainable energy, P2P trading serves as an enabler to harmonize the energy objectives of disparate communities. It offers a framework that allows consumers to adapt and regulate their energy needs, thereby fulfilling overarching strategic goals [46].

P2P is not merely a mechanism for transaction; it is a data-driven approach that enhances the efficacy of business models in the energy sector. It provides a structured pathway for direct electricity trading within the confines of a sharing economy, offering a sustainable edge to energy trading practices. To summarize, the symbiosis between P2P energy systems and the sharing economy is unmistakable. The sharing economy serves as a fertile ground upon which P2P energy trading thrives. It provides a robust platform that enhances resource allocation efficiencies, thereby driving sustainable energy distribution in a highly effective manner.

III. REVIEW OF P2P ENERGY TRADING

P2P energy trading constitutes a disruptive innovation in the energy sector, serving as a platform for the bilateral exchange of electricity between consumers and suppliers. Utilizing cutting-edge blockchain technology, this trading paradigm not only democratizes energy distribution but also adds a layer of transparency and security to transactions [47].

Over the past decade, the landscape of energy resources has undergone a seismic shift, particularly with the rise of distributed energy resources, as indicated by [48], This surge in the number of prosumers–entities that both produce and consume energy–has laid the groundwork for the emergence of decentralized energy markets. In this new ecosystem, P2P trading is not merely an alternative; it's rapidly becoming a mainstream model for energy exchange, fortified by digital technologies like blockchain and the Internet of Things (IoT) [49].

The allure of P2P energy trading is manifold. For consumers and prosumers alike, the model promises autonomy and flexibility, reducing dependency on centralized energy providers and intermediary agents [50]. Its decentralized nature is especially conducive for the integration of renewable energy sources, thereby aligning with contemporary needs for sustainable energy consumption while minimizing the role of third-party entities [51]. However, the path to widespread adoption of P2P energy trading is fraught with challenges, many of which are political in nature. Studies by Junlakarn et al.; Soto et al., illuminate the institutional barriers that stand in the way of seamless implementation [38], [52]. These challenges are not merely technical but are deeply entangled with regulatory frameworks that vary across nations. For instance, in countries like Germany and the Netherlands, the absence of a conducive regulatory environment impedes the legal sale of energy by consumers, thereby stymieing the growth of P2P trading platforms.

A. ECONOMIC AND INFRASTRUCTURAL ASPECTS OF P2P ENERGY TRADING

The findings of Paudel et al. state that P2P energy trading is a venture that requires a substantial economic investment [53] The financial commitment extends beyond simple transactional costs, encompassing the development of a robust digital trading ecosystem complete with smart devices, meters, and broadband communication networks. The study further divides this investment into two different types. The first type of investment is categorized as foundational, needed to establish a monitoring system, communication network, workstation, and broadband-based system to run the server. This foundational investment also accounts for the maintenance and operational services required in P2P energy trading, a pivotal element for the successful deployment of P2P microgrids for electrification [54].

The other type of investment targets platform-centric costs, including infrastructure, smart devices, communication networks, market research, and forecasting systems. Additionally, there are often hidden costs in the form of transaction fees that can be triggered by compliance with legal and regulatory frameworks. Given the high capital requirements, the adoption of P2P energy trading becomes economically challenging for less affluent nations.

B. GLOBAL ACCEPTANCE AND MARKET DYNAMICS

Studies by Zhang et al.; Wilkinson et al., indicate that P2P models are globally implemented to alleviate the challenges faced by customers [54], [55] Therefore, there tends to be a high demand because it addresses customer intervention problems. Moreover, the model creates lucrative opportunities for participants, which is why P2P energy trading has gained wide acceptance globally.

Research further confirms that P2P energy trading is implemented across the globe to tackle problems faced by customers [56]The model commands a high demand for P2P energy trade practices because it offers a robust solution to the third party in the process of energy trading encountered by customers. According to [57], this trading mechanism serves as a catalyst for bolstering collaboration among sharing economies. This has a dual benefit: it not only enhances sustainability but also opens up new avenues for revenue generation. Consequently, despite the economic hurdles, the P2P model of energy trading has garnered global acceptance and is increasingly seen as a vital component of future energy markets.

Junlakarn et al. emphasizes that, in addition to technological challenges, P2P energy trading also encounters regulatory challenges [52]. The study advocates for the amendment of regulatory instruments and elaboration on the role of consumers, arguing that this would enable P2P energy trading to be fully utilized. Clarified third-party access to prosumers is essential for operation within established rules and regulations. This framework also allows the government to monitor and manage the P2P energy trading market to ensure no regulatory violations occur. According to Kirchhoff et al., P2P companies enhance both economic viability and regulatory compliance, contributing to the sustainability of the energy sector [58]. P2P energy trading provides an avenue for developing countries across the globe to secure significant revenues and forge revenue generation opportunities for residents, thereby easing the burden on governmental energy supply efforts.

According to the findings of [59], P2P energy trading has become an important market mechanism. It enables market transactions by facilitating locals of the country. This method has several stakeholder advantages, including revenue generation, tax collection, and hassle-free services. The findings highlight that microgrids and energy economic

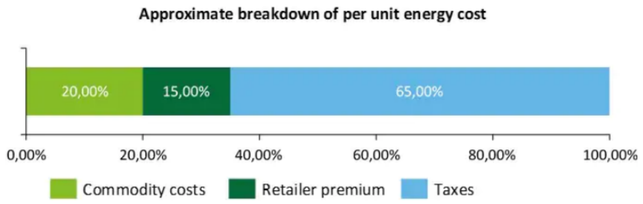

FIGURE 6. **Per unit energy cost adapted from [60].**

operations have not been sufficiently studied. This literature gap makes it challenging to fully comprehend the impact of P2P energy exchange.

According to the findings of Spiliopoulos et al., P2P energy trading has emerged as a pivotal market mechanism [60]. It facilitates market transactions at a local level, offering a multitude of benefits to stakeholders, including revenue generation, tax collection, and streamlined services. The findings underscore that the operational dynamics of microgrids and energy economics remain underexplored, constituting a gap in the existing literature. This shortfall makes it challenging to fully comprehend the impact of P2P energy exchange.

According to the findings of Ruan et al., significant financial benefits can be realized through P2P energy trade. The results deconstruct the approximate cost of energy as depicted in figure6, revealing that the price of commodities accounts for 20% of electricity cost. The premium charged by retailers amounts to approximately more than 14%. Taxes to maintain infrastructure and subsidize renewable energy make up more than 60% of the budget. The findings affirm that this structure yields higher profit margins, positioning revenue generation as a cornerstone advantage of P2P energy trading.

Other challenges encountered by P2P energy trading are elaborated upon in the findings of Hebal et al. The study asserts that prosumers often engage in energy trading among themselves, thereby undermining the role of traditional centralized systems. According to Hebal et al., fostering effective and efficient coordination among prosumers and various stakeholders proves to be a complex task [61]. Facilitating a robust decision-making mechanism is equally challenging, especially when it conflicts with the objectives of other energy producers. When combined with existing technological constraints, these issues pose a formidable barrier that requires proactive solutions. Thus, it becomes evident that P2P energy trading is fraught with multiple challenges, for which comprehensive strategies have yet to be developed. In light of these complexities, the current study endeavors to delve into the P2P energy trading market to gain a nuanced understanding of its present state and inherent challenges.

IV. GAME THEORY AND ENERGY TRADING IN A COMPLEX LANDSCAPE

The findings of Long et al. indicate that in diverse societal contexts where P2P energy trading is employed, the likelihood of conflicting interests among prosumers, consumers, and power producers escalates substantially

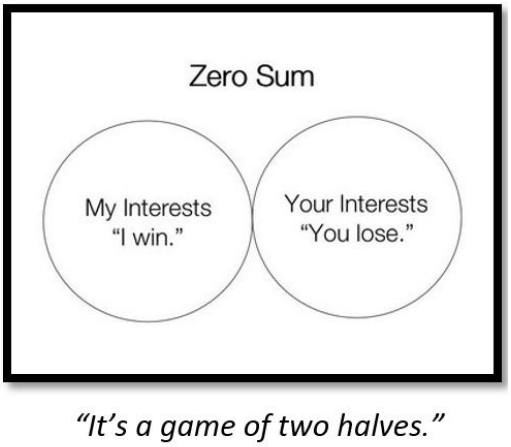

FIGURE 7. **Zero sum game.**

[62]. Prosumers often find their interests misaligned with those of other critical stakeholders, such as consumers and additional power producers, thereby engendering conflicts of interest. The study emphasizes that navigating these intricate webs of conflicting interests becomes increasingly challenging for prosumers. Moreover, the study advocates that a game-theoretic approach is particularly potent in modeling these complex market dynamics, given its capacity to balance both the optimization and fairness in the decision-making processes.

To this end, the current section aims to meticulously dissect the nuanced roles and applications of game theory within the realm of energy trading. The rationale for incorporating game theory stems from its intrinsic ability to capture the interdependent nature of stakeholder actions. In this context, the outcome for each stakeholder is intricately tied to their strategic choices and actions. For instance, one player's gain could potentially translate into another player's loss, which is commonly known as a zero-sum game (as illustrated in figure7)). Conversely, scenarios where all involved parties stand to gain are termed non-zero-sum games [63]. Before delving into the specificities of applying game theory to energy trading, it is imperative to explore its various dimensions and components, aiming to provide a holistic understanding of its mechanisms and implications.

A. THE DYNAMICS OF COOPERATIVE AND NON-COOPERATIVE GAMES IN ENERGY TRADING

According to the findings of Maschler et al., cooperative games in game theory can be conceptualized as strategic interactions characterized by enforceable agreements among the participants [15]. The essence of a cooperative game is collaborative, with a specific focus on investigating strategies for fostering maximum cooperation among stakeholders. It also encompasses equitable distribution mechanisms for benefits accrued amongst participating entities [64]. In this context, cooperative game theory posits that a coalition of groups serves as the fundamental decision-making unit, embodying cooperative behavior among players. This theoretical framework holds particular significance in P2P energy trading. It accentuates the importance of social competencies in negotiating complex group dynamics, thereby enhancing collective decision-making processes. In doing so, it illuminates key facets such as the role of effective collaboration within teams and adaptive responses to varying situational complexities to realize group benefits.

Contrastingly, non-cooperative games in game theory are characterized by individualistic and competitive interactions among players [65]. In such settings, the prospects for genuine cooperation are typically scant, with any semblance of collaboration often contingent upon credible threats or incentives. Non-cooperative game theory necessitates a precise understanding of the number of players involved, their potential strategies, any constraints that might be levied upon them, and the individual payoffs corresponding to various strategies. The theory operates under several assumptions: that players have a memory of past actions, that self-interest is the driving force behind decisions, and that all players possess a mutual comprehension of the game's structure [66]. Functioning as a rigorous mathematical tool for predicting player choices, non-cooperative game theory yields in-depth analytical insights into the strategic decision-making processes of participants. Consequently, it can provide nuanced understanding of the challenges encountered in non-cooperative environments and offers potential solutions for overcoming them.

B. APPLICATIONS AND IMPLICATIONS OF COOPERATIVE & NON-COOPERATIVE GAMES IN P2P ENERGY TRADING

With the surge in energy consumption and demand in modern society, innovative methods for power generation and utilization have become imperative to meet escalating energy needs. In this context, the study by [25] introduced a cooperative scheduling framework called the Scenery Storage Cluster Model, rooted in cooperative game theory. The underpinning objective of this model was not only to enhance revenue streams from storage clusters but also to fortify the stability and resilience of power plants. This suggests that cooperative games can serve as a viable mechanism for optimizing both the robustness and profitability of P2P energy trading systems. Within the ecosystem of P2P energy trading and cooperative game theory, diverse stakeholders such as prosumers and traditional power generation entities can collaborate synergistically to fulfill market demands [11]. Such collaborative endeavors are poised to cater to the burgeoning electricity requirements while simultaneously amplifying revenue streams. In essence, fostering inter-organizational cooperation is likely to stimulate customer engagement, thereby driving increased profitability. Thus, the incorporation of cooperative games into P2P energy trading holds the promise of multifaceted benefits.

The practical viability of employing non-cooperative game models in P2P energy trading is corroborated by empirical research, as illustrated by the study conducted by [67]. This research proposed a competitive framework to analyze the interplay between energy demand and supply. The empirical results, substantiated by a case study in Hawaii, delineate a decision-making algorithm capable of forecasting market energy demands. Employing a non-cooperative approach, the study examined a scenario where two energy sellers were in competition with a third entity. Non-cooperative games in the P2P energy landscape can also be a crucible for innovation, yielding fresh perspectives on market dynamics without sacrificing profitability. At the core of non-cooperative behavior is the intricate analysis of player actions, which often culminates in novel problem-solving paradigms. Consequently, this model can be effectively adapted to P2P energy trading contexts to scrutinize the decision-making processes of various stakeholders, such as prosumers and power producers, thereby offering valuable insights into market strategies and outcomes.

V. UTILIZING AGENT-BASED MODELING IN P2P ENERGY TRADING SYSTEMS

Agent-based modeling (ABM) can be conceptualized as a sophisticated computational framework geared towards simulating complex systems through the iterative interactions of autonomous agents with each other and their environment. While the transition to sustainable energy systems is gaining momentum globally, significant challenges such as affordability, security, and environmental sustainability persist. These obstacles have significantly hampered the seamless transition of energy systems, making the role of frameworks like ABM particularly pivotal. ABM offers a nuanced approach to tackle these complexities by dissecting each issue at the micro-level, simulating various scenarios, and providing actionable insights. The ensuing discussion outlines the core components of agent-based modeling applicable to energy trading, specifically P2P systems.

A. CORE COMPONENTS OF AGENT-BASED MODELING IN ENERGY TRADING

To leverage the full potential of agent-based modeling in any energy market, a structured series of actions or protocols must be formulated and executed. According to Ma et al., these actions typically encompass tasks such as customer billing, market bids, and dynamic pricing strategies to adapt to market fluctuations [68]. Once these action sets are defined, they are aligned with specific roles in the market ecosystem, which can be thought of as a suite of responsibilities that actors must fulfill. The successful implementation of these roles is intrinsically linked to the capabilities and strategies of the market actors. Agents, in the context of P2P energy trading systems, play specific roles that are assigned to different market participants [23]. These roles can range from individual prosumers to large utility companies, each having their own unique actions and responsibilities. Within this framework, agents follow defined rules which encompass market regulations, supply-demand dynamics, and even game theoretic strategies. By making collective decisions based on these rules, agents shape the overall behavior of the market. This approach offers a more detailed understanding of market dynamics, providing policymakers and stakeholders with valuable insights for informed decision making. In the following section, we will explore agent-based modeling as a versatile tool for comprehending, simulating and predicting the intricacies of P2P energy trading systems.

1) ROLES IN AGENT-BASED SIMULATIONS

Roles in agent-based modeling are not static. They can be predefined or evolve dynamically as agents interact within the simulation environment. Assigning these roles is a critical step in the modeling process since they directly influence agent behavior and, consequently, the simulation outcomes. Roles can adapt to changing circumstances based on agent interactions, experiences, and the evolving context of the simulation. This flexibility allows modelers to explore various scenarios and enhance their understanding of system dynamics [19].

Moreover, agents often have the crucial role of assessing the current state of the system transparently and comprehensively. Their decisions are formulated based on this assessment and are guided by established rules, norms, or algorithms. This ability to make independent decisions based on contextual analysis is a cornerstone feature of agents, adding a layer of complexity and realism to the model.

2) AGENTS AND THEIR INTERACTIONS

Agents serve as the fundamental units in the agent-based modeling framework, driving interactions and relationships within the system. Two primary challenges often surface when dealing with agents, as identified by [22]. The first challenge revolves around specifying the connectivity of an agent–essentially, determining with whom an agent can interact. The second challenge pertains to the dynamic nature of these interactions, which may evolve over time or be influenced by various external factors. Addressing these challenges is crucial for effectively implementing the agent-based modeling framework. In this decentralized setup, agents engage with other agents in their local environment, referred to as 'neighbors.' These interactions form the basis for gathering local information and making decisions. Importantly, the composition of these neighbors is not static; it can change dynamically as the simulation progresses and agents adapt within the system. These dynamic interactions add complexity to the model, enabling a deeper understanding of intricate systems [25].

Following are some examples of the neighbors indicated in the study by [25]as shown in figure8.

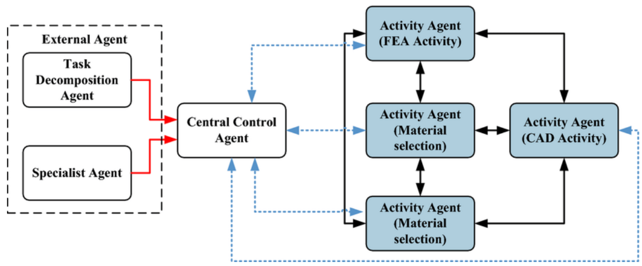

FIGURE 8. Agents in agent-based modelling [25].

B. AGENT BASED MODELLING IN ENERGY TRADING

According to Ma et al., the application of agent-based modelling serves as a viable and robust framework in the energy industry [68]. The system's effectiveness lies in its ability to encapsulate the multifaceted nature of energy trading, taking into account the diverse decision-making capabilities and objectives of various agents. For instance, consumers and prosumers may present divergent needs, such as fluctuating electricity demands and differing capacity and cost structures. In these dynamic landscapes, agent-based modelling offers an agile simulation platform capable of dissecting various trading scenarios, ranging from wholesale electricity markets to more nuanced P2P energy trading mechanisms. Building upon the insights of Heendeniya, the strategic use of agent-based models has been explored in optimizing renewable energy consumption within both isolated and interconnected communities [27]. The rule-driven strategy identified by Heendeniya operates on a two-tiered implementation framework. The first tier necessitates the development of an integrated battery storage system to not only elevate the efficiency of individual consumption but also to harmonize it with grid requirements. The second-tier shifts focus towards a community-oriented operational plan aimed at facilitating collective consumption through large-scale battery storage solutions. Overall, the current discourse underscores the operational feasibility and strategic importance of employing agent-based modelling in navigating the complexities of energy trading. This modelling approach offers a versatile tool for both micro-level and macro-level analysis, thereby enriching our understanding of energy ecosystems.

Building on recent research by Monroe et al., agent-based modeling is identified as a promising tool for navigating the complex uncertainties surrounding managerial strategies in developmental and testing phases of P2P energy trading platforms [49]. The study employs an empirically-based agent-based modeling approach to simulate a decentralized energy-sharing market, aiming to address pressing concerns about the future of energy systems. The results underscore the urgent necessity for designing an energy system that is simultaneously effective, efficient, and sustainable. This involves careful consideration of various trade-offs, including those related to social, technological, economic, and environmental factors Figure9.

In parallel, a study by Guimarães et al. rigorously evaluated the efficacy of an agent-based model in contexts of high prosumer involvement [69]. The findings reveal the model's robustness, demonstrating its feasibility even without the

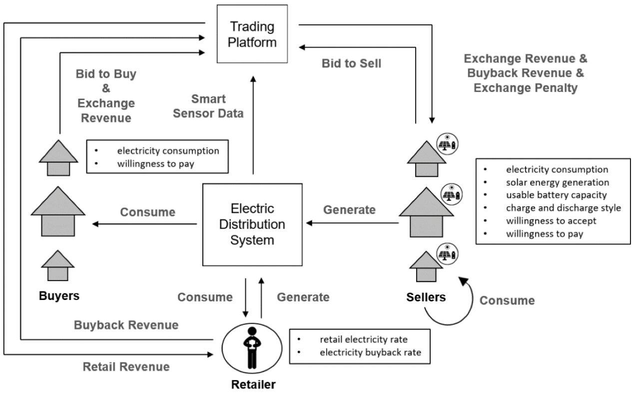

FIGURE 9. Dynamics of agent interactions in agent-based modeling [49].

inclusion of energy storage systems in the simulations. Remarkably, the model was successful in achieving energy savings of over 49% and also facilitated a reduction in grid dependency. Furthermore, the study elaborates that for local P2P energy trading to reach its optimum level–ranging from 49% to less than 76% in energy savings–a majority of the system's participants should ideally be prosumers. This reveals a critical equilibrium point at which the agent-based model yields maximum effectiveness. To encapsulate, the evidence suggests that agent-based modeling is not only a viable but also a highly adaptable framework for examining and optimizing P2P energy trading systems. Its capacity for handling complexity and its flexibility in accommodating various types of agents make it an indispensable tool in the evolving landscape of energy trading.

C. BLOCKCHAIN: A REVOLUTIONARY MECHANISM IN P2P ENERGY TRADING

Blockchain technology has increasingly become a focal point in discussions concerning the enhancement and secure automation of P2P energy trading systems [70]. Utilizing its decentralized digital ledger capabilities, blockchain technology ensures seamless and secure transactions, thereby making it a cornerstone for next-generation energy trading platforms. In essence, a blockchain is a decentralized digital ledger that meticulously records transactions in data structures known as blocks. According to Wang and Su these blocks are interconnected in a chronological manner, forming a chain–hence the term "blockchain [70]." Each block in this digital ledger encapsulates a plethora of transactions, which are then aggregated into a cryptographic hash. Furthermore, each block contains a hash of the preceding block, establishing a secure and immutable record.

A critical component in the operation of blockchain technology is the validation of transactions through a consensus algorithm. This algorithm facilitates the interconnection of transactions across the network's nodes, confirming the occurrence, timestamp, transaction amount, and involved parties. There are two prevalent consensus algorithms employed in blockchain systems: Proof of Work (PoW) and Proof of Stake (PoS) [71]. The Proof of Work algorithm requires nodes in the network to solve a complex computational problem to validate transactions and add a new block to the chain. Any node can partake in this problem-solving process, and the one that solves it first receives a reward, typically in the form of cryptocurrency.

In contrast, the Proof of Stake algorithm utilizes a different validation mechanism. Instead of solving computational problems, nodes, also known as validators, are selected from a pool based on a set of criteria, which may include random sampling, account age or seniority, and asset ownership. This approach offers a more energy-efficient yet equally secure method of transaction validation. In summary, blockchain technology offers groundbreaking solutions for enhancing transparency, security, and efficiency in P2P energy trading systems. Its flexible and robust architecture, underpinned by sophisticated consensus algorithms, promises to revolutionize the way energy transactions are conducted in decentralized markets.

VI. TECHNICAL ISSUES IN THE LANDSCAPE OF P2P ENERGY TRADING

The scope of this research is not merely confined to elucidating the potential of P2P energy trading; it extends to providing a holistic analysis that merges insights from diverse theoretical frameworks such as game theory, agent-based modeling, social network theory, and institutional theory. Additionally, an extensive literature review has been undertaken to further substantiate the critical role that P2P energy trading can play in addressing contemporary energy demands [72]. While developed nations have made strides in integrating P2P energy trading as an alternative to conventional energy systems, developing countries still grapple with numerous obstacles in implementing this innovative model. This section aims to delve into the technical challenges that have impeded the widespread adoption of P2P energy trading, thereby providing a balanced perspective that encompasses both its merits and drawbacks.

A. GRID-RELATED TECHNICAL COMPLICATIONS

The burgeoning interest in P2P energy trading has undeniably established it as a pivotal alternative to traditional energy systems. The inclination towards decentralized trading models has been observed globally, promising both energy self-sufficiency and revenue generation for participants [73]. However, this ascendance does not come without its set of challenges, particularly concerning grid infrastructure. Issues such as overvoltage, unbalanced power flows, and capacity overloading have become increasingly prevalent. The decentralized nature of P2P energy trading often results in a lack of centralized control, making it challenging to regulate these technical limits effectively. Such oversight can quickly result in safety hazards and system failures.

According to [52], the shift from being passive consumers to active 'prosumers'–those who both produce and consume energy–introduces an additional layer of complexity in grid management. Specifically, prosumers frequently generate energy from renewable sources, linking their systems to existing distribution grids. This transition necessitates a far more dynamic approach to managing power flows and system stability. Moreover, [74] notes that this systemic shift significantly increases the likelihood of power losses, thereby inflating the associated costs for prosumers. These costs, stemming from uncertainties in grid management, must be appropriately accounted for in P2P pricing strategies.

Additionally, the use of inverter-based power generation–often involving digital valve positioners–further complicates the situation. Such systems are generally asynchronous, thereby exacerbating issues related to power distribution losses and voltage frequency disturbances. In essence, while P2P energy trading offers tantalizing prospects for sustainable energy systems, it also introduces a host of technical challenges that require meticulous planning and robust solutions.

B. CYBERSECURITY CONCERNS IN P2P ENERGY TRADING

As technology continues to advance at a rapid pace, the challenges it presents, including concerns about data privacy and cybersecurity, are escalating in parallel [75]. This is particularly salient in the realm of P2P energy trading, which involves a multitude of real-time financial and energy transactions. The critical nature of these transactions makes the sector highly susceptible to various forms of cyber threats, ranging from data breaches to unauthorized surveillance [76], [77]. In a system where real-time energy supply and demand dictate the financial transactions, a plethora of sensitive data is generated and circulated. This data, which could include details on production capacities, consumption patterns, and dynamic pricing mechanisms, is integral for optimizing and future-proofing P2P energy trading systems.

Within this framework, Mylrea and Gourisetti emphasizes the necessity for a secure information-sharing network between prosumers and consumers [77]. Such a network would not only facilitate the exchange of accurate, real-time data but also act as a safeguard against unauthorized third-party interventions.Furthermore, Bigerna et al. posits that a robust cybersecurity infrastructure is imperative to ensure data integrity and privacy [78]. Contemporary solutions like blockchain technology could serve as effective platforms for secure information sharing, thereby mitigating risks related to data breaches and other forms of cyberattacks. By adopting such secure platforms, P2P energy trading can fortify its data management systems, thus proactively addressing potential cybersecurity vulnerabilities.

C. CHALLENGES AND STRATEGIES IN INTEGRATING RENEWABLE ENERGY

In today's climate-conscious world, the emphasis on renewable energy sources has gained unprecedented momentum. P2P energy trading presents a promising avenue for integrating these renewable sources, aligning with contemporary environmental imperatives. Yet, this integration is not without its complications. According to Javed et al., the high penetration of renewable energy in transmission networks and distribution points has introduced complex dynamics that challenge both the system's stability and its economic viability [79]. For instance, the fluctuating nature of renewable energy sources like wind and solar leads to unpredictable voltage changes in the electricity grids, thereby complicating the smooth operation of P2P energy trading platforms.

To tackle these challenges, various technological and strategic solutions have been proposed. These range from virtual to physical interventions, tailored to specific operational contexts. Among these, game theory, double auction virtual layers, and constrained optimization stand out as notable approaches advocated by Javed et al. Despite the obstacles, the integration of renewable energy into P2P energy trading remains a crucial and achievable goal [80]. Numerous strategies exist that can effectively and efficiently address these challenges. Thus, this study aims to thoroughly examine these methods, not only to promote the use of decentralized systems in energy trading but also to advance the broader adoption of renewable energy sources.

D. ECONOMIC BARRIERS TO P2P ENERGY TRADING

Beyond the technological and cybersecurity hurdles, economic constraints represent another critical impediment to the widespread adoption of P2P energy trading, especially in developing economies [81]. While the literature has touched upon the financial aspects, it's vital to delve deeper into the nuances of these challenges. A prominent issue is the significant upfront capital needed to establish the foundational infrastructure for P2P energy trading [81], [82]. These initial investments encompass not only the technological hardware, such as smart meters and servers, but also the software solutions needed for digital trading, information technology, and broadband networks.

The investment challenges can be broadly categorized into two types: initial capital expenditure and ongoing operational costs [83]. Countries or regions where these costs prove prohibitive will naturally find the adoption of P2P energy trading more challenging. Furthermore, the deployment of microgrids, which are often integral to P2P systems, also demands substantial initial investments, creating another financial barrier to entry. In conclusion, the economic challenges could very well be the underlying reason for the slow adoption of P2P energy trading in resource-constrained settings [82]. To overcome this, it may be essential to focus on financial models that make it feasible for a broader range of participants, including less economically affluent prosumers, to engage in P2P energy trading.

E. THE ROLE AND IMPACT OF INTERMEDIARIES IN P2P ENERGY TRADING

While P2P energy trading has been lauded for its ability to operate without the need for third-party involvement, this isn't entirely accurate in all scenarios. Though the system is fundamentally designed to be a decentralized marketplace, the presence of intermediaries like suppliers can introduce new complexities [84]. As outlined in the current study, P2P energy trading is largely built around direct relationships between prosumers and consumers, ostensibly eliminating the need for intermediaries. However, contrary to this notion, some research, such as that conducted by Morstyn et al. suggests that suppliers can act as intermediaries in P2P energy transactions [85]. This introduces a set of intermediary-related challenges that warrant attention. For instance, one prominent issue is the potential for price volatility, which can undermine the cost-effectiveness of P2P energy systems. Given that the upfront and operational costs of P2P energy trading are already a barrier for developing countries, as noted by [52], any increase in transaction costs due to intermediary involvement could make the system even less viable. Additionally, supply chain disruptions from intermediaries could also hinder the widespread adoption of P2P energy trading. It is essential to note that the existing literature on this subject is relatively sparse, primarily because the foundational concept of P2P energy trading emphasizes decentralization. Therefore, it's crucial to explore these intermediary-induced challenges further to fully understand their impact on the scalability and efficiency of P2P energy trading systems.

F. UNDERSTANDING AND ADDRESSING COMPLEXITIES IN PRICING MECHANISMS

P2P energy trading originally emerged as a decentralized platform aimed at directly linking prosumers and consumers, thereby bypassing traditional energy suppliers [11]. In recent years, however, it has evolved to become not just a trade platform but also a means to encourage the use of renewable energy. This shift has led to complexities in the pricing structures within the P2P market. According to research by Das et al., there has been a predominant focus on the pricing of energy commodities in isolation, creating a potential barrier to broader market adoption of P2P energy trading [86]. The study identifies a general lack of comprehensive understanding around pricing mechanisms, further complicating the market's structure. Specifically, the study differentiates between two primary categories of pricing mechanisms: energy pricing and network service pricing [85], [86], [87]. While the former is concerned directly with the cost of producing and sharing energy, the latter deals with resolving any financial discrepancies that might arise during energy transactions.

The study also notes that numerous pilot projects have been conducted globally to test the viability of various pricing mechanisms in real-world settings [85]. These experiments take into account multiple factors including geographic location, market objectives, customer volume, and other key performance indicators. The interaction of these variables can significantly influence the choice and effectiveness of pricing strategies [57], [86]. Therefore, it becomes imperative to conduct a nuanced evaluation of different pricing mechanisms before rolling out P2P energy trading platforms. This approach will help in anticipating and mitigating any challenges that might affect the seamless implementation of such systems.

G. NAVIGATING THE REGULATORY MAZE IN P2P ENERGY TRADING

Despite the burgeoning interest and potential advantages of P2P energy trading, it faces significant obstacles in the form of existing regulatory frameworks. Studies like those by Junlakarn et al.; Hacher et al., have pointed out the urgent need for regulatory adaptation to fully realize the benefits of this emerging market. The European Commission's findings [57], [87] emphasize that the roles and rights of prosumers need to be explicitly defined and protected under law for P2P energy trading to flourish. The Commission also calls for the introduction of a third-party regime capable of accessing microgrids, aimed at facilitating uninterrupted information flow and compliance monitoring.

Moreover, current regulations are ambiguous about licensing requirements for prosumers, as noted by Gunarathna et al. This lack of clarity can act as a deterrent for potential participants in the P2P energy market. The study suggests that a cohesive, globally recognized regulatory framework could significantly bolster the adoption and effectiveness of P2P energy trading. The field of regulatory considerations in P2P energy trading is relatively under-researched, demanding more scholarly attention. Numerous technical challenges, such as peak-time energy demand reduction, energy reserve management, and network loss minimization, further complicate the regulatory landscape [80].

P2P energy systems, being inherently decentralized, also confront issues related to energy distribution and network management. Key challenges include data management bottlenecks, limited compliance mechanisms, and the complexities of distributed energy resource management [88], [89]. These obstacles necessitate urgent regulatory reforms, including updates in capacity planning and technical specifications, to facilitate more effective communication and energy trading within decentralized systems.

VII. PROSPECTS AND CHALLENGES: THE ROAD AHEAD FOR P2P ENERGY TRADING

Research conducted by the Oxford Martin School [90] has revealed a diverse landscape in P2P energy trading, encompassing various business models. This diversity enables the development of tailored applications to meet different market conditions and customer preferences, granting consumers greater control over their choice of energy sources. A growing consensus suggests that traditional energy suppliers are shifting their focus toward user-centric platforms, potentially rendering third-party suppliers outdated. The advent of blockchain technology is regarded as a transformative force in this domain, offering increased transparency and security for P2P energy transactions.

Contemporary shifts in energy consumption patterns, as highlighted by Perger et al., emphasize the urgent need to discover innovative solutions for meeting the increasing global energy demands [91]. In this context, P2P energy trading emerges as a promising approach that combines decentralization with efficiency in energy distribution. However, the adoption of P2P energy trading globally varies considerably due to several challenges outlined in this study. While the potential for P2P energy trading to revolutionize how we think about energy supply and consumption is evident, a multitude of barriers–technical, economic, and regulatory–must be overcome for global adoption. The current state of affairs suggests that P2P energy trading is at a crossroads, holding the promise for substantial evolution and impact in the coming years.

Farmer points out a growing trend of entrepreneurial success stories in the realm of P2P energy trading [92]. Companies like Centrica, SunContract, and Piclo have not only experimented with P2P energy trading but have also successfully integrated it into their operations. This successful integration is manifested through tangible benefits like reduced operational costs and lower energy bills for consumers. Numerous pilot projects have been initiated in countries such as the United Kingdom, Germany, and the United States, further solidifying the feasibility and scalability of this trading model.These success stories indicate that P2P energy trading is not just a theoretical concept but a practical solution that addresses modern energy challenges. The rate at which pilot projects are converting to full-scale operations suggests that the future for P2P energy trading is promising.

Another aspect influencing the future of P2P energy trading is the transformation of renewable technologies, as outlined by [93]. Digital advancements are making it increasingly convenient for consumers to transition into prosumers, fundamentally altering how households interact with energy markets. This shift, combined with the increasing affordability of renewable energy systems, points towards a sustainable future for P2P trading. However, it's not all smooth sailing.

The same study Wu et al. also identifies challenges that could stymie the progress of P2P energy trading [93]. While renewable energy sources are abundant, meeting the expected surge in energy demand by 2030 remains a formidable challenge. Thus, while the horizon looks promising for P2P energy trading, a cluster of challenges looms large, warranting comprehensive solutions for sustainable growth.

VIII. CONCLUDING INSIGHTS: BALANCING OPPORTUNITIES AND CHALLENGES IN P2P ENERGY TRADING

This study aimed to comprehensively examine the multifaceted landscape of P2P energy trading. Its primary focus was on identifying the challenges and potential solutions within this emerging field. It delved into the role of game theory, scrutinized pricing mechanisms, and investigated the economic and regulatory challenges involved. The study found that game theory emerged as a powerful tool for understanding and optimizing P2P energy trading. It highlighted the value of both cooperative and non-cooperative strategies, which can be effectively integrated to facilitate smoother and more efficient energy transactions. Another important area of exploration in the study was agent-based modeling. This approach proved invaluable for optimizing P2P energy trading systems due to their adaptability and wide range of applications. Agent-based modeling particularly enabled a nuanced understanding of the roles played by agents, thereby enhancing operational efficiency and overall effectiveness in these trading systems. However, despite its potential and growing traction, P2P energy trading faces several significant challenges. These range from technical difficulties in managing energy inflow and outflow to broader economic and regulatory barriers. The study affirms that while the sector is gradually gaining acceptance, a myriad of challenges persists that hampers its widespread adoption globally. This comprehensive study aimed to dissect the intricate landscape of P2P energy trading. It did so by identifying the challenges and potential solutions, focusing on game theory, scrutinizing pricing mechanisms, and investigating economic and regulatory hurdles. Game theory proved to be an invaluable framework, facilitating a more structured approach to P2P energy trading. Both cooperative and non-cooperative strategies were found to be integral for the smooth functioning of these systems. Agent-based modeling was another key focus, revealing its wide applicability and flexibility in understanding and optimizing P2P energy trading platforms. However, the study also illuminated the dual nature of technology in this sector. While technological advancements have undoubtedly facilitated the growth of P2P energy trading, they simultaneously raise critical concerns around data privacy and transactional security. Further, the study found that the high penetration of renewable energy presents a unique set of challenges, particularly in maintaining the stability of electrical grids. This confirms the necessity for innovative technological solutions and optimized operational strategies. Regulatory frameworks were identified as another significant barrier. For P2P energy trading to achieve global implementation, especially in light of increasing energy demands, existing regulations will need comprehensive amendments to fully support this new trading paradigm and its stakeholders.Upon a critical review of existing literature, this study concludes that the future of P2P energy trading is largely optimistic. Despite the diverse challenges identified, the concept has gained varied degrees of acceptance worldwide. This suggests that while hurdles remain, the potential for P2P energy trading to revolutionize the energy sector is immense. In summary, P2P energy trading stands as a complex yet promising solution to modern energy challenges. While it offers a new frontier in how energy is traded, consumed, and generated, its full potential can only be realized through proactive and systematic addressing of the multifaceted challenges it faces.

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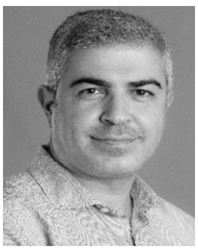

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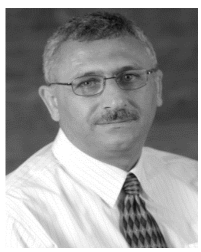

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