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(Review Article)

Peer-to-peer energy trading: Innovations, regulatory challenges, and the future of decentralized energy systems

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Abstract

Peer-to-peer (P2P) energy trading represents a transformative approach to energy distribution, where consumers, referred to as prosumers, generate and exchange electricity directly with one another. This decentralized model promotes local generation and consumption balancing, reducing reliance on centralized grids and encouraging the use of renewable energy. The development of platforms and technologies, such as blockchain, smart contracts, and Internet of Things (IoT)-)-enabled devices, has enabled secure, transparent, and automated transactions. These innovations facilitate real-time monitoring and energy matching, while artificial intelligence (AI) optimizes pricing and supply-demand dynamics. Microgrids and energy storage solutions further enhance the efficiency and reliability of local energy balancing in P2P systems. However, the widespread adoption of P2P energy trading faces significant regulatory and market challenges. Current regulatory frameworks, designed for traditional, centralized energy markets, often lack provisions for decentralized trading models. Key issues include grid access, tariffs, consumer protection, and data privacy. Furthermore, regulatory barriers differ widely by region, affecting the pace of P2P adoption. Market mechanisms that support P2P energy trading, such as dynamic pricing, demand-response programs, and real-time settlement systems, are also critical for its success. The role of aggregators and intermediaries in facilitating transactions is evolving, as regulatory bodies explore sandbox environments to test these innovative models. This review explores the technological advancements and regulatory landscape shaping P2P energy trading, highlighting successful case studies and identifying future trends. It underscores the need for adaptable policies and robust platforms to unlock the potential of P2P energy trading in building resilient, sustainable, and decentralized energy systems.

Keywords: Peer-to-Peer Energy; Smart Contracts; Energy Storage; Local Generation

1. Introduction

The global energy landscape is undergoing a profound transformation driven by technological advancements, growing environmental concerns, and the need for more sustainable energy solutions (Gielen *et al.*, 2019; Pastukhova and Westphal, 2020). Centralized energy systems, long the dominant model, are increasingly being challenged by decentralized, renewable energy technologies. A key innovation within this shift is Peer-to-Peer (P2P) energy trading, which enables individuals and small-scale energy producers, known as prosumers, to directly trade electricity with each other through digital platforms (Mazzola *et al.*, 2020; Wu *et al.*, 2022). This model decentralizes energy distribution, allowing for greater local control over energy production and consumption.

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Peer-to-peer energy trading refers to a decentralized system in which consumers and producers of energy engage directly in buying and selling electricity without the need for a central utility or grid operator to mediate the transactions (Khorasany *et al*., 2020; De Almeida *et al*., 2021). This form of energy exchange is typically facilitated by digital platforms that use blockchain, smart contracts, and the Internet of Things (IoT) to automate, secure, and optimize transactions. Blockchain technology ensures transparency and immutability in energy trades, while smart contracts enable the automation of agreements between buyers and sellers. IoT devices such as smart meters monitor energy production and consumption in real time, providing the data necessary to match supply and demand efficiently (Avancini *et al*., 2021). The key principles of P2P energy trading include decentralization, transparency, and autonomy. By allowing prosumers to trade directly with their neighbours or within a local community, this system reduces dependence on large-scale power plants and centralized grids. The decentralization of energy production and consumption aligns with global efforts to promote renewable energy, as P2P systems encourage the integration of solar panels, wind turbines, and other renewable technologies into local energy markets. Additionally, P2P energy trading fosters competition, leading to more flexible pricing models and giving consumers greater control over their energy costs. As the world shifts towards more decentralized energy systems, P2P energy trading becomes increasingly relevant (Soto *et al*., 2021). Traditional energy markets are highly centralized, with power generated at large plants and distributed over long distances. This model is not only inefficient but also limits consumer participation in the energy economy. In contrast, P2P energy trading allows for localized energy production, aligning with the ongoing transition toward smart grids and microgrids that prioritize renewable energy integration, grid flexibility, and user autonomy (Tushar *et al*., 2021; Bjarghov *et al*., 2021).

A significant advantage of P2P energy trading is its ability to promote local generation and consumption balancing (Khalid *et al*., 2020). Local generation refers to the production of energy close to where it will be consumed, while consumption balancing ensures that energy supply matches demand within a specific area. This local balancing plays a critical role in enhancing energy efficiency and sustainability. By enabling localized energy trading, P2P platforms minimize energy losses associated with long-distance transmission (Malik *et al*., 2022). Traditional centralized grids often suffer from transmission inefficiencies, particularly when energy must travel over vast distances. These losses can account for a substantial portion of the total energy produced. P2P energy trading, on the other hand, reduces transmission distances by facilitating local exchanges of energy, allowing prosumers to sell surplus electricity to their neighbours (Paudel *et al*., 2020; Zhu *et al*., 2022). This results in a more efficient energy system with fewer losses and a higher overall energy yield. Moreover, P2P energy trading promotes energy sustainability by encouraging the use of renewable energy sources like solar and wind. Localized energy generation using renewable technologies reduces reliance on fossil fuels and lowers greenhouse gas emissions. P2P platforms make it easier for small-scale renewable energy producers to monetize their surplus energy, incentivizing further investment in clean energy technologies (Menzel and Teubner, 2021). This localized approach to energy production aligns with broader environmental goals, including decarbonization and the mitigation of climate change. Additionally, local generation and consumption balancing enhance the resilience of energy systems. By decentralizing energy production, P2P trading can alleviate pressure on centralized grids, particularly during periods of high demand or in the event of a grid failure. This resilience is especially important as extreme weather events and other disruptions become more frequent due to climate change. Peer-to-peer energy trading represents a significant shift towards decentralized energy systems, offering a flexible, efficient, and sustainable approach to energy distribution (Soto *et al*., 2021). Through local generation and consumption balancing, P2P energy trading reduces transmission losses, promotes renewable energy integration, and enhances the overall resilience of energy systems. As digital platforms and regulatory frameworks evolve, P2P energy trading is poised to play a crucial role in the future of energy markets.

2. Development of Platforms and Technologies for Peer-to-Peer Energy Trading

As the global energy system transitions toward decentralized and sustainable energy models, the development of platforms and technologies for peer-to-peer (P2P) energy trading has gained significant attention (Zhou *et al*., 2020; Esmat *et al*., 2021). P2P energy trading allows prosumers those who both produce and consume energy to directly buy and sell electricity within localized energy markets as explained in Figure 1 (Doan *et al*., 2021). This model encourages local generation and consumption balancing, leading to improved energy efficiency, reduced transmission losses, and increased use of renewable energy. Several key technologies, including blockchain, smart contracts, the Internet of Things (IoT), and artificial intelligence (AI), have emerged as enablers of this decentralized energy trading system as explained in Table 1 (Yapa *et al*., 2021). Moreover, platforms that support P2P trading, combined with microgrids and energy storage solutions, offer the infrastructure necessary to realize the potential of this innovative energy model.

Blockchain technology plays a fundamental role in facilitating secure and transparent transactions within P2P energy trading systems (Zhou *et al*., 2020). A blockchain is a decentralized, immutable ledger that records transactions across a network of computers. In the context of energy trading, blockchain enables the verification and validation of energy exchanges between prosumers without the need for intermediaries, such as utility companies. This ensures that energy trades are tamper-proof, traceable, and secure. Additionally, blockchain technology automates the settlement of energy transactions, streamlining the process of buying and selling electricity (Nour *et al.*, 2022). It reduces the need for complex billing systems and prevents fraudulent transactions. By providing a transparent record of energy trades, blockchain also fosters trust among participants, making it a crucial component in the development of P2P energy trading systems. Smart contracts are self-executing contracts with the terms of the agreement written directly into code. They are deployed on blockchain platforms and automatically execute energy trading agreements when predefined conditions are met. For example, a smart contract could facilitate an energy trade between two prosumers when the buyer's energy demand matches the seller's supply, and the agreed-upon price is reached. The automation provided by smart contracts reduces the administrative burden associated with energy trading, allowing for seamless, real-time exchanges. Furthermore, smart contracts eliminate the need for third-party intermediaries to enforce agreements, thus lowering transaction costs and enhancing the efficiency of P2P energy markets (Kirli *et al.*, 2022).

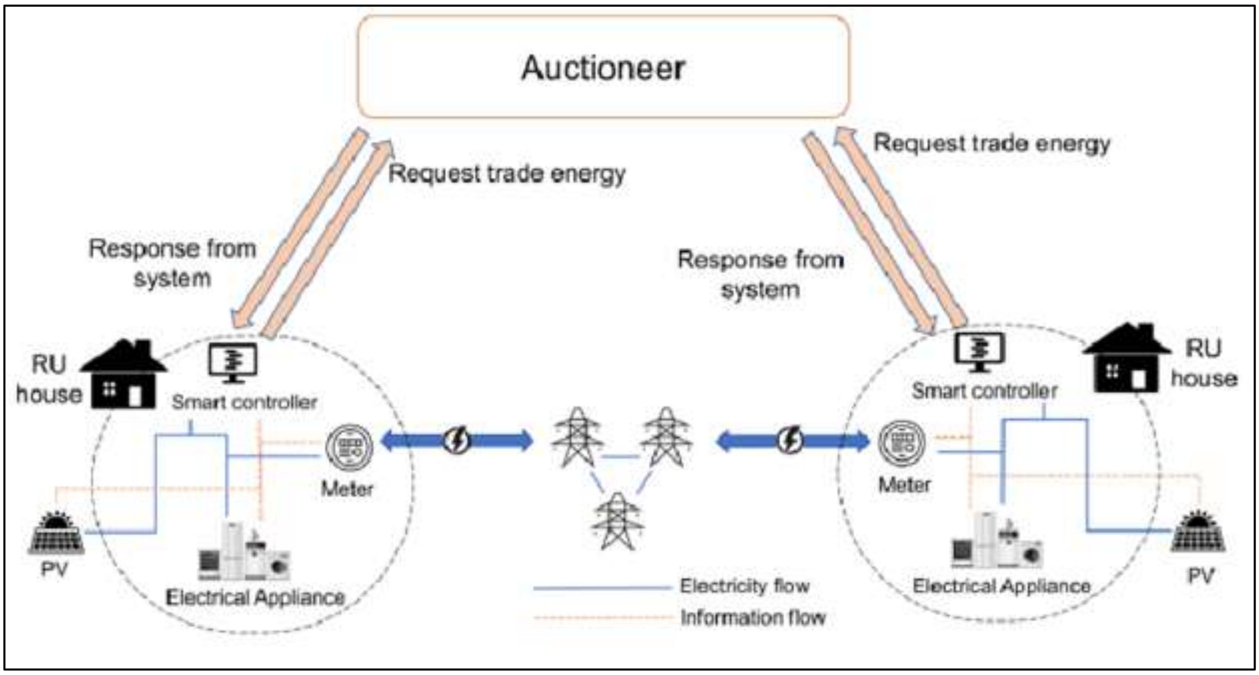

Figure 1 Peer-to-Peer Energy Trading Overview (Doan *et al.*, 2021)

The Internet of Things (IoT), in conjunction with smart meters, enables real-time monitoring and data exchange between energy producers and consumers in P2P energy trading systems (Zafar and Ben Slama, 2022). Smart meters track the energy production and consumption of prosumers in real-time, providing the data needed to optimize energy trading decisions. IoT devices connect these smart meters to the digital energy marketplace, where energy supply and demand can be matched dynamically. This real-time data flow is critical for balancing local energy generation and consumption. IoT technology ensures that energy is traded efficiently and that prosumers are charged or credited accurately based on their energy usage or production. By leveraging IoT and smart meters, P2P platforms can optimize energy distribution and reduce waste, contributing to overall system sustainability.

Artificial intelligence (AI) and machine learning (ML) technologies enhance the efficiency of P2P energy trading by optimizing supply-demand matching and pricing algorithms (Ahmad *et al.*, 2021). AI systems analyze vast amounts of data generated by smart meters, IoT devices, and market platforms to predict energy demand and supply patterns. Machine learning algorithms can identify trends, such as peak demand periods or renewable energy generation fluctuations, allowing the platform to adjust prices and trading conditions accordingly. These predictive capabilities enable P2P energy markets to function more efficiently, ensuring that prosumers receive fair compensation for their surplus energy and that consumers can purchase energy at competitive rates. Additionally, AI can help platforms adapt to market conditions in real-time, making them more resilient to fluctuations in energy supply and demand. Several platforms have been developed to facilitate P2P energy trading, each offering unique capabilities that enable prosumers and consumers to trade energy seamlessly. Power Ledger is one such platform that leverages blockchain technology to enable energy trading across local communities. The platform allows users to trade energy in real-time, and it provides transparency, security, and automated transaction settlement using smart contracts (Vieira and Zhang, 2021). Power Ledger also integrates renewable energy sources, ensuring that prosumers can monetize their surplus energy effectively. WePower is another P2P energy trading platform that enables renewable energy producers to sell energy directly to consumers. WePower's platform integrates AI and blockchain technologies to match supply and demand efficiently and uses smart contracts to automate trading agreements (Prokopenko, 2022). Digital marketplaces such as these provide the necessary infrastructure for prosumers and consumers to engage in energy trading without relying on centralized utility companies. However, these platforms face technical challenges, including scalability, latency, and user adoption. As the number of participants in P2P energy trading grows, platforms must be able to handle larger transaction volumes while maintaining fast, secure, and efficient operations. Ensuring that these platforms are user-friendly and accessible is also essential for widespread adoption.

Table 1 Key technologies in their role in decentralized energy trading (Yapa *et al*., 2021)

Technology	**Description**	**Role in Decentralized Energy Trading**
Blockchain	A decentralized digital ledger technology that records transactions securely and transparently across multiple systems.	- Ensures transparency, security, and immutability of energy transactions. - Facilitates peer-to-peer (P2P) energy trading by removing intermediaries.
Smart Contracts	Self-executing contracts with the terms of the agreement are directly written into code on a blockchain.	- Automates energy trading agreements and transactions. - Enables faster, trustless execution and settlement of energy trades.
Internet of Things (IoT)	A network of interconnected devices capable of collecting and exchanging real-time data.	- Monitors energy generation and consumption in real time. - Provides data for dynamic pricing and energy trade optimization.
Artificial Intelligence (AI)	Advanced computing systems capable of simulating human intelligence, including learning, decision-making, and prediction.	- Enhances predictive analytics for energy demand and supply. - Optimizes energy trading algorithms for cost and efficiency.

Microgrids play a critical role in P2P energy trading systems by enabling local energy generation, distribution, and balancing. A microgrid is a localized energy network that can operate independently from the central grid, often powered by renewable energy sources such as solar panels or wind turbines (Agupugo *et al.,* 2024*;* Tomin *et al*., 2022). Microgrids are ideal for P2P energy trading because they promote the use of locally generated energy, reduce transmission losses, and improve energy resilience. Energy storage is another essential component of P2P trading systems. Battery storage systems allow prosumers to store surplus energy generated during peak production periods, such as when solar panels produce excess energy on sunny days. This stored energy can then be sold during periods of high demand, ensuring that the local energy supply is balanced with consumption. The integration of renewable energy sources like solar and wind into microgrids and energy storage systems enhances the sustainability of P2P energy trading (Huang *et al*., 2020). These technologies not only reduce reliance on fossil fuels but also allow prosumers to maximize the value of their renewable energy investments by trading excess energy.

The development of platforms and technologies for P2P energy trading is reshaping the way energy is generated, distributed, and consumed. Blockchain, smart contracts, IoT, and AI are key enablers of this decentralized energy system, ensuring transparency, security, and efficiency (Yapa *et al*., 2021). Platforms such as Power Ledger and WePower provide the infrastructure needed for P2P trading, while microgrids and energy storage systems support local energy generation and consumption balancing. As these technologies continue to evolve, P2P energy trading is poised to play a significant role in the future of sustainable, decentralized energy systems.

2.1. Local Generation and Consumption Balancing

In the evolving landscape of energy systems, local generation and consumption balancing has emerged as a critical strategy for enhancing energy efficiency and sustainability (Thornbush and Golubchikov, 2021). By focusing on generating and consuming energy at the local level, communities can reduce reliance on centralized power plants, lower transmission losses, and better integrate renewable energy sources. This approach not only fosters a more resilient and sustainable energy grid but also contributes to broader environmental and economic benefits.

One of the primary benefits of local generation is the reduction of transmission losses. Transmission losses occur when electricity is transported over long distances from power plants to end-users. These losses, which can account for up to 7-10% of generated energy, are due to resistance in power lines and other inefficiencies in the grid infrastructure. By generating energy locally near where it is consumed these losses can be minimized as explained in Figure 2 (Raza and Jiang, 2019). This localized approach reduces the need for extensive transmission infrastructure and mitigates energy losses, leading to more efficient use of generated power. Local generation also facilitates the integration of renewable energy sources such as solar panels, wind turbines, and biomass (Iweh *et al*., 2021). By generating energy locally, communities can harness renewable resources that may not be available or practical at a larger scale. This localized use of renewable energy not only reduces greenhouse gas emissions but also supports sustainability goals. Communities can become more self-reliant, decreasing their dependence on fossil fuels and contributing to a reduction in overall carbon emissions. Local generation and consumption balancing play a crucial role in stabilizing local grids. Traditional centralized power grids often face challenges related to grid stability and reliability, particularly with fluctuating demand and supply. Local energy generation allows for better alignment of energy supply with local demand, reducing the risk of grid imbalances and blackouts. Additionally, localized energy systems can provide resilience against disruptions in the central grid, enhancing the overall reliability and security of the energy supply (Xu *et al*., 2021). Local generation reduces the need for large, centralized power plants that may be located far from the end-users. This reduction in reliance on centralized plants has several benefits. It minimizes the environmental impact associated with large-scale power generation and reduces the risks associated with transporting fuel and electricity over long distances. Moreover, by decentralizing energy production, communities can support local economies and create jobs related to the installation and maintenance of renewable energy systems.

Energy storage systems, such as batteries and microgrids, are integral to local generation and consumption balancing. Batteries allow for the storage of excess energy generated during periods of high production, such as sunny or windy days (Gomes *et al*., 2020). This stored energy can be used during periods of low production or high demand, ensuring a continuous and reliable energy supply. Microgrids, which are localized energy systems capable of operating independently from the central grid, provide additional support for energy storage and management. They can integrate various energy sources and storage solutions to optimize local energy balance and enhance grid reliability. The integration of energy storage with local renewable energy production creates a synergistic effect that maximizes the benefits of both technologies. By storing excess energy generated from renewable sources, communities can smooth out the variability inherent in renewable energy production. This synergy enables a more consistent and reliable supply of clean energy, reduces the need for backup fossil fuel generation, and enhances the overall sustainability of the energy system (Niet *et al*., 2022).

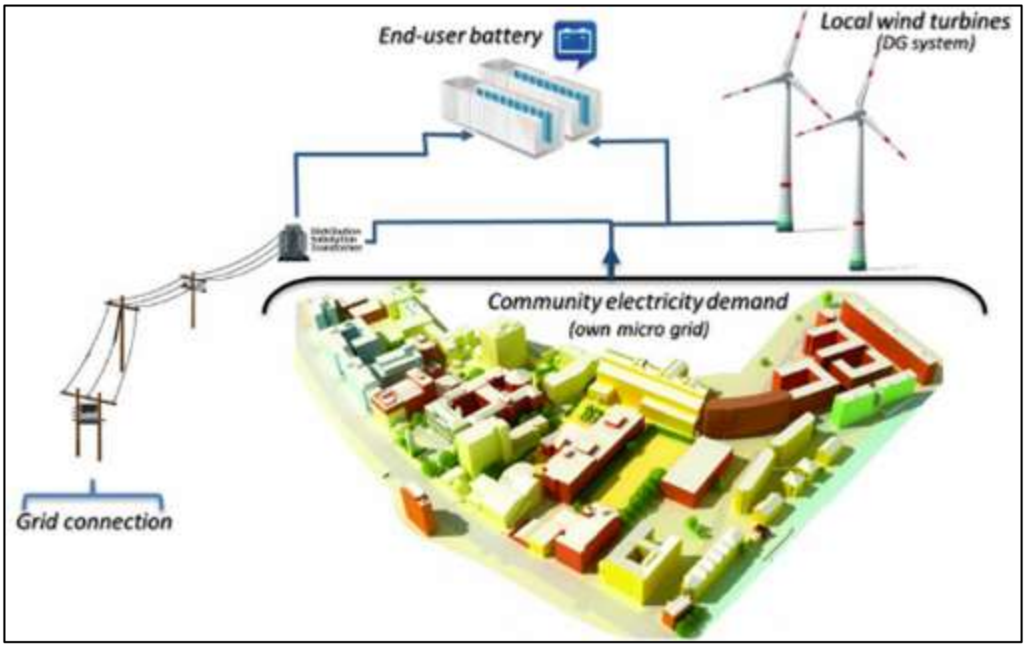

Figure 2 Systematic illustration diagram of local generation and consumption (Raza and Jiang, 2019)

Local generation and consumption balancing represents a transformative shift in energy systems, offering significant advantages in terms of energy efficiency and sustainability (Ford *et al*., 2021). By reducing transmission losses, promoting the use of renewable energy, stabilizing local grids, and minimizing reliance on centralized power plants, this approach addresses many of the challenges associated with traditional energy systems. The integration of energy storage solutions, such as batteries and microgrids, further enhances the effectiveness of local balancing, ensuring a reliable and resilient energy supply. As communities and policymakers continue to embrace these strategies, local generation and consumption balancing will play a crucial role in advancing a more sustainable and decentralized energy future.

2.2. Examination of Regulatory Frameworks for Peer-to-Peer Energy Trading

As peer-to-peer (P2P) energy trading gains traction, the regulatory landscape becomes a crucial factor in its development and implementation. P2P energy trading allows energy consumers to directly trade electricity with other consumers or prosumers (producers-consumers), fostering decentralized energy markets and increasing the role of renewable energy sources explained in table 2 (Zhou *et al*., 2020). However, the regulatory frameworks governing P2P trading vary significantly across different regions, and challenges persist in aligning these new models with traditional utility regulations. Despite these obstacles, opportunities for regulatory innovation are emerging, creating pathways for a more flexible and resilient energy market.

The regulatory environment for P2P energy trading is highly varied across Europe, the United States, and Asia (Wongthongtham *et al*., 2021). In Europe, several countries, such as Germany and the Netherlands, are leading the way in embracing decentralized energy models. The European Union's Clean Energy Package supports the development of energy communities, promoting prosumer participation and fostering local energy markets. In these regions, P2P energy trading is gaining legal recognition, with regulatory frameworks evolving to accommodate small-scale energy producers and traders. In the United States, the regulatory landscape is more fragmented due to the state-based nature of energy regulations. States such as California and New York have introduced policies that allow for decentralized energy systems and P2P trading pilots. However, the broader U.S. regulatory framework is still catching up with the technological innovations of decentralized energy markets. The Federal Energy Regulatory Commission (FERC) and state-level utility commissions have traditionally focused on centralized, vertically integrated utilities, which creates barriers to the widespread adoption of P2P trading models. In Asia, the regulatory approach to P2P energy trading is still in its infancy, though there are notable exceptions (Chen *et al*., 2021). Japan, for example, is moving toward energy deregulation and has seen pilot projects in P2P energy trading, especially in response to its energy transition policies post-Fukushima. Australia, though technically outside of Asia, has also been a leader in P2P energy trading experiments, particularly through its use of blockchain-based platforms like Power Ledger. In contrast, other countries in the region are slower to adopt, primarily due to monopolistic utility structures and underdeveloped regulatory frameworks.

The most significant challenge facing P2P energy trading comes from traditional utility regulations that were designed for centralized energy generation and distribution. In many regions, monopolistic control over energy grids by large utility companies creates significant barriers to the development of decentralized energy markets. Utilities often own the infrastructure and control access to the grid, making it difficult for small-scale producers and prosumers to participate in energy trading without paying high fees (Kuznetsova and Anjos, 2020). Another challenge lies in grid access, tariffs, and fees for prosumers. Many regulatory frameworks impose high grid access fees or restrictive tariffs on those wishing to trade energy directly with others. These costs discourage participation and make P2P trading less economically viable for smaller players. Additionally, feed-in tariffs, which provide financial compensation for feeding renewable energy into the grid, are often structured in ways that do not accommodate the flexibility of P2P trading. These frameworks need to evolve to better support prosumers and incentivize localized energy trading.

Despite these challenges, there are growing opportunities for regulatory innovation to facilitate the adoption of P2P energy trading (Junlakarn *et al*., 2022). One promising avenue is the use of regulatory sandboxes. Regulatory sandboxes are controlled environments where new business models and technologies can be tested without the usual regulatory constraints. In the energy sector, these sandboxes allow for decentralized energy models, including P2P trading, to be tested and refined before they are fully integrated into the regulatory framework. Countries like the United Kingdom and Australia have already implemented such sandboxes, allowing stakeholders to experiment with P2P models and develop data-driven policies for wider adoption. Another area for innovation is policy reform to support small-scale energy production. Policymakers can update existing frameworks to include provisions for P2P energy trading, such as adjusting grid access fees, introducing dynamic pricing models, and ensuring that prosumers are adequately compensated for the energy they provide. Reforms could also focus on encouraging the integration of renewable energy sources into P2P trading systems, further aligning these models with sustainability goals. In some regions, policies are also being developed to encourage energy sharing within local communities, such as creating energy cooperatives that allow prosumers to trade excess energy directly within their neighbourhood (Reis *et al*., 2021; Wu *et al*., 2022).

Table 2 The regulatory criteria and considerations of peer-to-peer energy trading systems (Zhou *et al.*, 2020)

Aspect	**Description**	**Considerations for P2P Energy Trading**
Legal Definition of P2P Energy Trading	The legal status and definition of P2P energy trading in national or regional legislation.	- Clarification on whether P2P energy trading is legally recognized. - Adaptation of existing electricity market regulations to accommodate P2P trading.
Licensing Requirements	The permits or licenses required to engage in P2P energy trading as an individual or entity.	- Whether participants must be licensed. - Potential relaxation of regulatory requirements for small-scale producers and consumers.
Energy Tariffs and Pricing	Policies related to the pricing mechanisms for energy trading, including tariffs and taxes.	- Integration of dynamic pricing based on supply and demand. - Regulation of transaction fees and fair pricing in decentralized markets.
Grid Access and Integration	Rules governing how distributed energy resources interact with the main grid and infrastructure.	- Ensuring grid stability while allowing energy prosumers to connect. - Regulation of feed-in tariffs and net metering.
Consumer Protection	Measures to protect participants in P2P energy trading, including data privacy and transaction security.	- Safeguards against fraud or unfair practices. - Ensuring transparency and consumer rights within decentralized systems.
Data Security and Privacy	Standards for the handling, sharing, and storage of energy data in a decentralized system.	- Compliance with data protection laws (e.g., GDPR). - Security protocols for IoT devices and blockchain-based systems.
Environmental Impact and Sustainability	The role of regulation in promoting renewable energy sources and reducing carbon emissions.	- Incentives for trading clean energy. - Integration of environmental goals within P2P energy trading frameworks.
Market Structure and Competition	How regulatory frameworks foster or hinder competition among energy providers, including traditional utilities.	- Ensuring fair competition between traditional energy providers and decentralized networks. - Prevention of monopolistic practices.
Cross-Border Trading	Regulations allowing or restricting energy trading across regional or national borders.	- Harmonization of policies to enable cross-border P2P energy trade. - Addressing technical and regulatory barriers for international trade.

The regulatory frameworks governing P2P energy trading are still in their early stages, with significant variations between regions like Europe, the U.S., and Asia. While some regions are making strides in embracing decentralized energy models, others face challenges due to entrenched utility monopolies and outdated regulations. However, opportunities for regulatory innovation, such as regulatory sandboxes and policy reforms, are emerging as key drivers for change. By updating regulations to support decentralized, community-driven energy markets, policymakers can unlock the potential of P2P energy trading, fostering a more sustainable, resilient, and efficient energy system for the future.

2.3. Market Mechanisms to Support P2P Energy Trading

The rise of peer-to-peer (P2P) energy trading is transforming traditional energy markets by enabling decentralized and localized energy transactions between prosumers (producers-consumers) and consumers as explained in Figure 3 (Ninomiya *et al.*, 2020; Nadeem, 2022). To facilitate these new energy trading dynamics, appropriate market mechanisms are required to optimize transactions, ensure efficiency, and maintain grid stability. Key mechanisms include dynamic pricing, demand-response programs, aggregators, and various market structure models that range from decentralized to hybrid approaches. These tools are essential for balancing supply and demand in real-time, maximizing market efficiency, and enabling greater participation from small-scale energy producers.

Dynamic pricing plays a crucial role in optimizing energy trades in P2P markets. Unlike traditional fixed-rate pricing, dynamic pricing adjusts the cost of electricity based on real-time supply and demand conditions. In a P2P energy trading system, dynamic pricing encourages consumers and prosumers to respond to price signals, ensuring that energy is used more efficiently (Amin *et al*., 2020). For example, during periods of high renewable energy generation, prices may decrease, encouraging consumers to use more electricity. Conversely, when supply is low, prices may increase, incentivizing consumers to reduce their demand or draw on stored energy. This dynamic pricing model is particularly beneficial for renewable energy sources like solar and wind, where generation is often intermittent and fluctuates throughout the day. By aligning energy prices with the availability of renewable energy, dynamic pricing can promote the consumption of clean energy and reduce reliance on fossil fuel-based electricity. In doing so, it fosters a more sustainable energy system while optimizing the cost-effectiveness of energy trades. Demand-response programs complement dynamic pricing by allowing consumers to adjust their energy usage in response to real-time supply and price signals (Stanelyte *et al*., 2022). In a P2P energy market, demand response can be leveraged to balance supply and demand more effectively. For instance, when demand exceeds supply, consumers can voluntarily reduce their energy consumption or shift their usage to off-peak periods, thus preventing grid overloads and ensuring a stable energy supply. In exchange, consumers may receive financial incentives or lower energy costs, further encouraging participation. Demand-response programs, when integrated with P2P trading platforms, offer flexibility to the grid and enhance overall market stability.

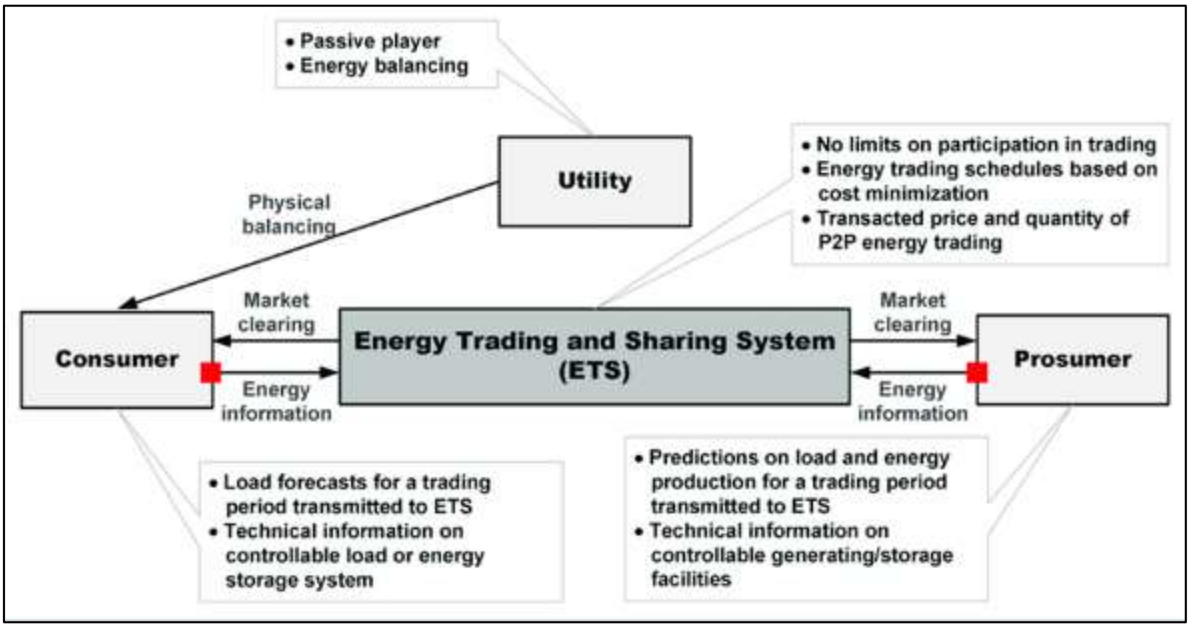

Figure 3 The concept of the P2P energy trading scheme (Chung and Hur, 2020)

In P2P energy markets, aggregators play a pivotal role in enhancing market efficiency by pooling energy from multiple prosumers and acting as intermediaries between prosumers and consumers. Aggregators can consolidate small-scale energy production from a variety of sources, such as solar panels, wind turbines, and battery storage systems, creating a larger, more reliable supply of electricity (Utkarsh *et al*., 2021). This pooled energy can then be traded on P2P platforms, providing consumers with greater access to locally generated energy while reducing the complexity of managing individual energy trades. The use of aggregators simplifies transactions, especially for smaller prosumers who may not have the capacity to participate directly in the market. By aggregating energy, these intermediaries can ensure that even small amounts of excess generation are efficiently utilized, and prosumers can receive fair compensation for their contributions. Aggregators also offer additional services, such as optimizing energy trades, managing energy storage, and balancing supply and demand across the network, further enhancing the overall efficiency of P2P energy markets.

Decentralized market models represent the most direct form of P2P energy trading, where prosumers and consumers engage in transactions without the involvement of intermediaries or centralized entities (Adams *et al*., 2022). In these systems, energy prices are determined through real-time bidding processes, with prices fluctuating based on local supply and demand conditions. Decentralized models are ideal for communities with high levels of renewable energy production and self-sufficiency, allowing for direct energy exchanges between neighbours or within localized grids. However, decentralized models also face challenges, such as the need for sophisticated digital platforms and technologies to facilitate real-time energy trading, and ensure grid stability when dealing with fluctuating energy supply and demand. Moreover, decentralized systems may struggle to scale efficiently in larger markets with more complex energy needs. Hybrid market models, on the other hand, incorporate both decentralized P2P trading and traditional utilities or intermediaries. In hybrid systems, utilities may still play a role in providing grid access, managing energy storage, or acting as a backup source of electricity when local generation is insufficient. Hybrid models offer greater flexibility and scalability, as they combine the benefits of decentralized trading with the reliability and resources of centralized entities. Additionally, utilities in hybrid systems can offer services such as demand management, balancing services, and grid stabilization, ensuring that energy supply remains reliable and secure even in times of fluctuating renewable generation (Komala *et al*., 2021). In these hybrid models, intermediaries such as platform operators or regulators may also help facilitate transactions, manage energy flows, and ensure compliance with market rules and regulations. This involvement of third parties can help reduce the risks associated with direct P2P trading, such as price volatility or grid imbalances, and provide a more structured and stable trading environment.

Market mechanisms are essential to the successful implementation and scaling of P2P energy trading. Dynamic pricing and demand-response programs enable real-time optimization of energy use, ensuring that supply and demand are balanced while promoting energy efficiency and sustainability. Aggregators enhance market efficiency by pooling energy from multiple prosumers, enabling smaller players to participate in the market and ensuring that energy is utilized effectively (Botelho *et al*., 2021). Meanwhile, different market structure models, including decentralized and hybrid systems, offer varying levels of flexibility and scalability to meet the needs of local energy markets. As these mechanisms continue to evolve, they will play a crucial role in advancing the future of decentralized energy trading and fostering a more resilient, sustainable, and consumer-driven energy system.

2.4. Policy Recommendations for Supporting Peer-to-Peer Energy Trading

As peer-to-peer (P2P) energy trading continues to gain momentum, it becomes essential to adapt current energy policies to accommodate this decentralized model. P2P energy trading has the potential to revolutionize the energy sector by empowering consumers and prosumers to trade energy directly, improving energy efficiency, and promoting renewable energy sources (Gunarathna *et al*., 2022). To ensure the successful development and integration of P2P trading, policymakers must consider several critical areas: the adaptation of energy policies, encouragement of innovation, and regulatory support, including the use of regulatory sandboxes for testing.

One of the first steps in promoting P2P energy trading is to update grid access tariffs and the legal frameworks governing energy markets. Traditional energy markets are structured around centralized utilities that control the generation and distribution of electricity. However, in a decentralized P2P market, energy is produced and traded locally, often from renewable sources such as solar and wind power. Existing regulations regarding grid access and tariffs need to be revised to reflect the new dynamics of decentralized markets. Current grid access fees, in many cases, are designed for large-scale energy producers, making them prohibitive for small-scale prosumers. Policymakers should revise these tariffs to lower the barriers for prosumers to participate in energy trading (Lin *et al*., 2022). This would involve developing new pricing mechanisms that reflect the actual costs and benefits of grid access for small-scale producers. Moreover, legal frameworks should formally recognize and regulate P2P energy trading as a legitimate market activity, providing clear guidelines on how prosumers and consumers can participate while maintaining the integrity of the grid.

To encourage the growth of renewable energy production within the P2P market, governments should introduce subsidies and tax incentives. These financial incentives can promote the adoption of clean energy technologies, such as solar panels, wind turbines, and energy storage systems (Radpour *et al*., 2021). For instance, prosumers who install renewable energy systems could benefit from tax rebates, making the initial investment more attractive. By reducing the financial burden on small-scale energy producers, these incentives can help accelerate the transition to a decentralized, renewable-based energy system. Additionally, innovation in energy technologies should be encouraged through research and development grants. Governments can support startups and companies working on P2P trading platforms, blockchain technology, smart contracts, and energy storage solutions. By fostering innovation, policymakers can ensure that the technical challenges associated with P2P trading, such as scalability, security, and interoperability, are effectively addressed.

A crucial mechanism for supporting innovation in P2P energy trading is the expansion of regulatory sandboxes. A regulatory sandbox is a controlled environment where new business models, technologies, and regulatory frameworks can be tested without the usual regulatory constraints (Makarov and Davydova, 2020). In the context of P2P energy trading, regulatory sandboxes can provide a platform for stakeholders to experiment with decentralized energy systems, smart contracts, and dynamic pricing models. By expanding the use of regulatory sandboxes, governments can allow energy companies, startups, and utilities to test innovative solutions in a safe environment. Sandboxes enable regulators to gather data on how P2P energy trading models perform in practice, helping them craft policies that address potential risks while promoting innovation. Countries such as the United Kingdom and Australia have already adopted regulatory sandboxes for energy trading, and this approach could be replicated in other regions to facilitate the development of decentralized markets.

The rise of P2P energy trading represents a transformative shift in the energy sector, offering a more flexible, consumer-driven, and sustainable approach to energy distribution (Neagu *et al*., 2020; Aoun *et al*., 2021). However, to unlock its full potential, policymakers must implement adaptations in energy policies, including updating grid access tariffs and legal frameworks. Incentivizing innovation through subsidies and tax incentives will further promote renewable energy adoption while expanding the use of regulatory sandboxes will ensure that new technologies and market models can be safely tested. These policy recommendations will be crucial in driving the successful integration of P2P energy trading into the broader energy market, paving the way for a decentralized, efficient, and renewable energy future.

2.5. Case Studies in Peer-to-Peer Energy Trading

Peer-to-peer (P2P) energy trading is gaining traction globally as a means to decentralize energy markets and empower consumers and prosumers (Abdeljawed and El Amraoui, 2021). Several successful projects across different regions have demonstrated the viability of this model, offering valuable insights into its benefits and challenges. This examines case studies from the Brooklyn Microgrid in the United States, Piclo in the United Kingdom, and SonnenCommunity in Germany, highlighting their impact on energy cost reduction, grid stability, and renewable energy integration. Additionally, lessons learned from these projects regarding regulatory flexibility, technology adoption, and user engagement are discussed.

One of the most well-known P2P energy trading projects is the Brooklyn Microgrid in New York, USA. This project allows residents in Brooklyn to trade excess solar energy directly with their neighbours using blockchain technology. By enabling local energy exchanges, the Brooklyn Microgrid has helped reduce energy costs for participants while increasing grid stability. The project has also facilitated the integration of renewable energy by encouraging more households to install solar panels, thus contributing to a more sustainable energy system. In the United Kingdom, Piclo has emerged as a leading P2P energy trading platform. Piclo operates an online marketplace where consumers can purchase electricity directly from local renewable energy producers (Anaya, 2021). The platform promotes transparency in energy trading and offers consumers the ability to choose the source of their electricity, often at lower costs than traditional suppliers. Piclo's success has demonstrated the potential of digital marketplaces to drive renewable energy adoption and empower consumers in the energy market. SonnenCommunity in Germany is another notable example. This community-based energy trading platform allows members to share and trade self-generated renewable energy, primarily from solar panels. By connecting prosumers and consumers within the community, SonnenCommunity has significantly reduced energy costs and enhanced energy independence. The platform also plays a critical role in stabilizing the local grid by efficiently managing energy supply and demand, particularly during periods of high renewable generation.

These case studies offer several important lessons for the successful implementation of P2P energy trading. Firstly, regulatory flexibility is crucial. Projects like Brooklyn Microgrid benefited from supportive local regulations that allowed for the testing of new energy trading models. This highlights the need for policymakers to create adaptable regulatory environments that can accommodate innovative energy solutions. Secondly, technology adoption is a key factor in the success of P2P energy trading. Blockchain, smart contracts, and digital platforms like those used in Piclo and Brooklyn Microgrid are essential for ensuring transparency, security, and efficiency in energy transactions (Henninger and Mashatan, 2022). Investments in these technologies are necessary to scale P2P trading systems effectively. Lastly, user engagement is vital. Projects such as SonnenCommunity demonstrate the importance of involving consumers and prosumers in the energy trading process. By offering tangible benefits, such as cost savings and greater energy autonomy, these platforms have successfully encouraged widespread participation and fostered a sense of community ownership in energy production and consumption. The success of P2P energy trading projects like Brooklyn Microgrid, Piclo, and SonnenCommunity underscores the potential of decentralized energy markets to deliver economic, environmental, and social benefits. The lessons learned from these case studies emphasize the importance of regulatory flexibility, technology adoption, and user engagement in driving the growth of P2P energy trading globally.

2.6. Future Trends and Challenges in Peer-to-Peer Energy Trading

Peer-to-peer (P2P) energy trading is poised for significant growth, with advancements in technology and increasing demand for decentralized energy systems driving the market forward (Strielkowski *et al*., 2021). While there is substantial potential for global adoption, the path ahead is not without challenges. Technological innovations such as artificial intelligence (AI), blockchain, and the Internet of Things (IoT) are shaping the future of P2P energy trading, but regulatory alignment, scalability, cybersecurity, and consumer trust will need to be addressed for this model to thrive.

The rapid development of AI, blockchain, and IoT technologies is transforming P2P energy trading by optimizing energy exchange and increasing market efficiency. AI, for instance, plays a critical role in managing supply-demand matching, allowing for more accurate pricing algorithms and improved energy flow predictions. These algorithms can automate decision-making processes, enabling efficient energy trading between prosumers and consumers based on real-time data. Blockchain technology is vital for ensuring transparency, security, and trust in P2P transactions (D'Hauwers *et al*., 2020). Its decentralized ledger system allows for seamless recording and validation of energy trades, reducing the need for intermediaries while ensuring transaction integrity. Smart contracts, built on blockchain, enable automated execution of trading agreements, further simplifying the process. Meanwhile, IoT devices, such as smart meters, provide real-time monitoring of energy production and consumption, allowing for more dynamic and responsive trading systems. IoT facilitates the exchange of data between energy producers, consumers, and platforms, ensuring that energy flows efficiently and equitably across decentralized networks.

The global energy market is evolving towards greater decentralization, and P2P energy trading has the potential to reshape these markets by empowering local communities to generate, trade, and consume energy directly (Adams *et al*., 2021). As more countries seek to integrate renewable energy into their grids, P2P trading offers a scalable and flexible solution that can accommodate the variability of renewable sources, such as solar and wind power. In regions with limited access to centralized energy infrastructure, such as rural areas in developing countries, P2P energy trading can provide an innovative way to improve energy access. With the increasing affordability of renewable energy technologies and the rise of digital platforms, P2P trading could significantly accelerate the adoption of clean energy worldwide.

Despite its promise, P2P energy trading faces several key challenges. Regulatory alignment remains one of the most significant obstacles, as current energy regulations in many regions are designed for centralized systems. Aligning these regulations with decentralized energy markets will require policymakers to rethink traditional grid models and provide legal frameworks that support P2P trading. Scalability is another challenge, as expanding P2P energy trading to larger markets demands robust technological infrastructure (Kalbantner *et al*., 2021). As more participants join the network, managing energy flow, data processing, and real-time transactions will require platforms to handle increasing complexity without compromising efficiency. Cybersecurity is a growing concern in P2P energy trading, given the reliance on digital platforms and IoT devices. Protecting sensitive consumer data and ensuring the integrity of energy transactions are critical for maintaining trust in the system. Without strong security measures, P2P platforms could become vulnerable to cyberattacks, potentially undermining their credibility. Finally, consumer trust must be earned. While technological advancements can enhance the efficiency of P2P energy trading, ensuring that users feel confident in the fairness, reliability, and safety of these platforms is essential for widespread adoption.

As technological advancements continue to shape P2P energy trading, the model has the potential to revolutionize global energy markets, especially as renewable energy becomes more widespread. However, addressing challenges related to regulation, scalability, cybersecurity, and consumer trust will be critical for realizing this future.

3. Conclusion

Peer-to-peer (P2P) energy trading holds immense potential in driving the transition towards sustainable, decentralized energy systems. By enabling local energy generation, consumption balancing, and the direct exchange of renewable energy between consumers and prosumers, P2P trading offers a viable solution for reducing reliance on centralized power grids and fostering energy independence. It also supports the integration of renewable energy sources, contributing to global sustainability goals. The model's ability to reduce transmission losses and optimize energy distribution makes it a critical component in the future of energy markets.

To fully realize the benefits of P2P energy trading, continued technological development is essential. Advancements in blockchain, AI, smart contracts, and IoT will further enhance the transparency, efficiency, and scalability of decentralized energy markets. These technologies must be refined to support real-time energy exchanges, secure data processing, and automated decision-making that optimizes supply and demand. In addition to technological innovations, the evolution of regulatory frameworks is crucial for the widespread adoption of P2P energy trading. Policymakers must work to update grid access tariffs, legal frameworks, and consumer protection regulations to accommodate decentralized energy systems. The creation of regulatory sandboxes to test and refine P2P models in real-world scenarios can further accelerate this process. Incentives such as subsidies and tax breaks for renewable energy adoption and innovative energy trading models will also play a key role in fostering market growth. By addressing these technological and regulatory needs, P2P energy trading can become a cornerstone of future energy systems, driving sustainability and energy democratization on a global scale.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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