Decentralized Energy Systems and Renewable Energy Transition: A Survey

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Abstract

This survey paper provides a comprehensive examination of decentralized energy systems and the renewable energy transition, highlighting key concepts such as citizen participation, energy democracy, grid flexibility, peer-to-peer (P2P) trading, and low-temperature district heating. The paper explores the pivotal role of community engagement and energy cooperatives in fostering social innovation and democratizing energy systems. It also addresses the integration of decentralized energy resources to enhance grid adaptability and efficiency, with a focus on technological innovations in P2P trading and the utilization of excess heat in district heating. The survey emphasizes the importance of social equity and a just transition, discussing policies and initiatives aimed at ensuring equitable energy access and affordability. Regulatory harmonization and sustainable energy policies are examined for their role in facilitating the energy transition, with case studies highlighting successful implementations and innovations. The survey concludes by reflecting on the collective impact of these elements on the energy sector, underscoring the need for continued research and policy development to achieve an equitable and resilient energy future. By integrating insights from existing research, this paper offers a nuanced understanding of the multifaceted aspects of the energy transition, aligning with broader objectives of energy democratization and local empowerment.

1 Introduction

1.1 Structure of the Survey

This survey provides an in-depth analysis of decentralized energy systems and the ongoing renewable energy transition, focusing on critical themes such as citizen engagement in energy communities, energy democracy, grid flexibility for distributed energy resources, and the innovative role of peer-to-peer (P2P) trading mechanisms through technologies like blockchain and multi-agent reinforcement learning. Case studies from regions including Singapore, London, and California, along with practical insights from community-driven projects like the rooftop photovoltaic system at Aarhus University, underscore the social, economic, and technical dimensions of these emerging energy paradigms [1, 2, 3, 4, 5]. The organization of the paper is as follows:

Section 2 offers a comprehensive overview of foundational concepts and definitions essential for understanding decentralized energy systems and the renewable energy transition. It contextualizes the urgent need for this transition amid rising energy costs and geopolitical challenges, emphasizing strategic planning and investment's critical role in achieving energy neutrality by 2050. This section also highlights energy communities and legislative frameworks that empower local stakeholders to engage in sustainable practices, fostering a more equitable and resilient energy landscape [6, 7, 2, 8, 9]. It includes detailed definitions of decentralized energy systems, key concepts related to the renewable energy transition, and an exploration of historical contexts and current trends in the energy sector.

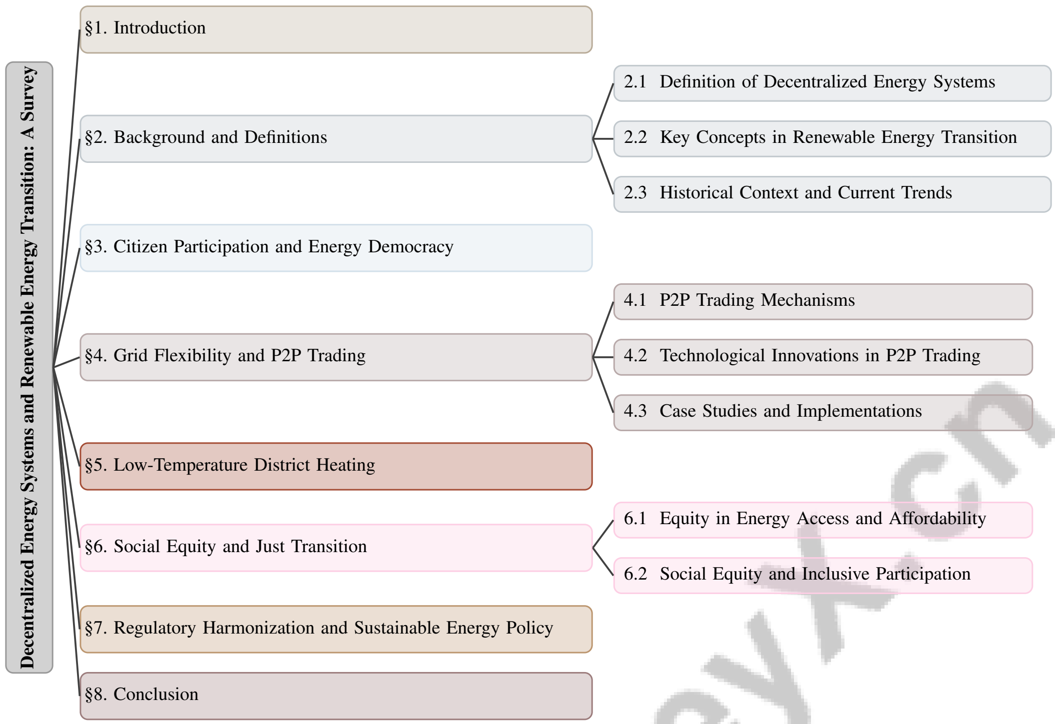

Figure 1: chapter structure

Section 3 explores the pivotal role of citizen participation and energy democracy, examining how communities and individuals are empowered in energy production and decision-making processes. It discusses community engagement, public acceptance, and the contributions of energy cooperatives and community energy projects to social innovation.

Section 4 addresses grid flexibility and P2P trading, emphasizing the necessity of adaptable grid infrastructures to accommodate renewable energy sources. It examines P2P trading mechanisms, recent technological innovations facilitating P2P trading, and presents successful implementation case studies.

Section 5 provides an in-depth examination of low-temperature district heating systems, detailing their advantages—such as enhanced energy efficiency and reduced greenhouse gas emissions—while addressing challenges like infrastructure costs and integration with existing systems. This analysis is particularly relevant in the context of urban climate justice and the transition toward renewable energy as cities aim to meet ambitious net-zero emissions targets [10, 11, 8, 9]. It discusses integrating excess heat from electrolyzers and explores business models that support low-temperature heat utilization.

Section 6 analyzes the social implications of the energy transition, emphasizing social equity and a just transition. The document examines various policies and initiatives designed to promote equitable access to energy and affordability, highlighting the significance of inclusive participation. It underscores the need for innovative financing methods, such as crowdfunding, to support the expansion of electric vehicle (EV) charging infrastructure in disadvantaged communities, ensuring federal investments benefit those most in need. Additionally, it explores urban climate justice concepts in local initiatives, revealing differing interpretations between practitioners and academic perspectives, and offers methodological suggestions for integrating justice into smart city projects at every stage of policy and project design [10, 12].

Section 7 delves into critical themes of regulatory harmonization and sustainable energy policy, highlighting the European Union's legislative framework promoting the transition to renewable energy sources, the establishment of Energy Communities for local energy management, and the integration of innovative strategies to balance energy and water resources in evolving energy systems [13, 9]. It discusses the impact of regulatory frameworks on the energy transition, the need for harmonized policies to promote sustainable practices, and highlights examples of successful policy implementations and innovations.

Section 8 synthesizes the main findings of the survey, emphasizing the significant influence of decentralized energy systems and the renewable energy transition on the energy sector. It stresses the urgent need for strategic investments and reforms, such as those outlined in the National Energy and Climate Plan (NPEC), to achieve energy neutrality by 2050 and address challenges like energy poverty. Furthermore, it reflects on the varying stages of renewable energy policy implementation in regions like Singapore, London, and California, illustrating the importance of community engagement and legislative support in fostering energy independence and sustainability [2, 8, 9]. It also discusses future directions and potential challenges in achieving an equitable and resilient energy future.

This structured approach allows for a nuanced understanding of the multifaceted aspects of the energy transition, integrating insights from existing research on control structures in micro-grid systems [14], strategies for achieving net-zero targets [11], and sustainable energy practices within the IoT ecosystem [15].The following sections are organized as shown in Figure 1.

2 Background and Definitions

2.1 Definition of Decentralized Energy Systems

Decentralized energy systems are pivotal in the energy transition, integrating distributed energy resources (DERs) to enhance power reliability, efficiency, and decarbonization in distribution grids [16]. They enable localized control and optimize energy management through technologies like blockchain and federated learning, crucial for system efficiency and security [17]. These systems address the challenges of variable renewable energy, necessitating grid flexibility for effective resource allocation and stability [13]. By reducing reliance on traditional energy infrastructures, they mitigate environmental impacts, such as minimizing electronic waste and costs associated with IoT devices [18].

In India, decentralized systems help identify cost-effective renewable technologies to meet diverse generation profiles, supporting sustainable transitions [19]. They address technical and economic dimensions while fostering socio-economic engagement through participatory energy management. These systems transform infrastructures into sustainable, resilient models, promoting decarbonization, democratization, and local empowerment. By facilitating self-production and consumption, they enhance energy independence, reduce poverty, and stimulate local innovation. Advanced technologies like blockchain and smart contracts further enhance system efficiency and reliability, supporting an equitable and sustainable energy future [17, 8, 9].

2.2 Key Concepts in Renewable Energy Transition

The renewable energy transition relies on key concepts driving system transformation toward sustainability and resilience. Decentralized systems enhance grid flexibility via advanced control strategies like Rule-Based and Model Predictive Controls, optimizing energy flow in micro-grids [20]. Deploying DER devices is crucial for optimizing strategies under uncertainty, aiding renewable integration into existing grids [16]. The shift from centralized to distributed production is supported by peer-to-peer (P2P) trading systems, democratizing markets by enabling small-scale producer participation [21]. The Energy Internet paradigm furthers decentralization and democratization by promoting interactions among energy resources [22].

Addressing renewable complexities is vital for grid stability. The Multi-Objective Optimal Power Flow (MOPF) problem illustrates smart grid integration challenges [23]. Managing power during renewable droughts, like Dunkelflaute, is critical for reliability [24]. Utilizing excess electrolyzer heat in the Power-to-Hydrogen ecosystem requires business models capturing this resource's value [25]. Integrating energy efficiency and flexibility, monitored through Key Performance Indicators (KPIs), optimizes Positive Energy Districts (PEDs) [26].

Citizen engagement is crucial; however, e-participation initiatives need growth and effectiveness [27]. Addressing these limitations fosters participatory energy management and decision-making. These concepts establish a framework for a sustainable, resilient energy future, addressing climate change and promoting democratization. By integrating community-driven approaches and stakeholder engagement, the transition ensures equitable access and participation, addressing energy poverty and enhancing local autonomy. This aligns with broader goals like the European Green Deal and National Energy and Climate Plan, emphasizing collaborative efforts for a just transition [10, 6, 7, 8, 9].

2.3 Historical Context and Current Trends

The evolution from centralized to decentralized energy systems addresses fossil fuel impacts and enhances energy security [28]. Integrating stochastic renewable sources within power networks historically posed optimization challenges, necessitating innovative control strategies for flexibility [20]. Climate policies targeting decarbonization, with cities pledging net-zero targets, mark significant milestones, though financial costs and energy poverty risks persist [11, 8]. Managing DERs for network stability remains critical [29].

Current trends emphasize efficient energy management to enhance micro-grid performance and optimize renewable utilization [14]. Transitioning to active distribution networks (ADN) requires new operational strategies integrating centralized dispatching with decentralized P2P trading [30]. Optimizing distribution networks is crucial for integrating renewable sources, addressing variable generation challenges [31]. The transition is challenged by regulatory barriers, public awareness deficits, and substantial infrastructure investments [9]. In Singapore, competition in electricity markets supports the transition amid limited resources [2]. Optimal Power Flow (OPF) methods face sub-optimal outcomes and high computational costs, necessitating robust solutions for model mismatch scenarios [32].

Contemporary surveys categorize challenges into legal barriers, stakeholder management, financing, and operational agreements, reflecting the transition's multifaceted nature [1]. The historical context and current trends highlight the complexity of transitioning to decentralized systems and the ongoing efforts needed to overcome barriers for a sustainable, resilient energy future.

In recent years, the discourse surrounding citizen participation and energy democracy has gained significant traction within academic circles. Understanding the complexities of these concepts requires a careful examination of their hierarchical structures. Figure 2 illustrates this hierarchical structure, highlighting the categories of community engagement, public acceptance, energy communities, and social innovation. Each of these primary categories is further delineated into subcategories and significant points, providing a comprehensive overview of how these elements interact and contribute to the broader framework of energy democracy. This visual representation not only enhances our understanding of the relationships among these categories but also serves as a pivotal reference point for discussing the implications of citizen involvement in energy decision-making processes.

3 Citizen Participation and Energy Democracy

3.1 Community Engagement and Public Acceptance

Community engagement and public acceptance are pivotal for the success of energy projects, fostering collaboration and transparency while aligning with community interests. Effective strategies for community involvement are essential, given the integration of diverse energy sources and the necessity for real-time decision-making [14]. Such engagement supports the adoption of innovative technologies and pricing models, like the Dynamic Critical Bandwidth-Dynamic Pricing Model (DCB-DPM), with comprehensive education and awareness initiatives playing a crucial role in gaining community support [33].

Structured frameworks that enhance citizen engagement in urban planning are vital for public acceptance [34]. Workshops empowering community members to define their roles in the energy transition and develop actionable strategies have shown effectiveness, underscoring the importance of community-driven approaches in achieving sustainability objectives [7]. Clear communication and active involvement are critical for meeting climate targets, as evidenced by cities committing to net-zero goals [11].

Direct citizen involvement in energy projects enhances data quality and environmental awareness compared to conventional methods [35]. This participatory approach is bolstered by successful crowdfunding initiatives and stakeholder engagement processes, serving as models for future energy community projects [1]. The use of common evaluation frameworks and Key Performance Indicators (KPIs) amplifies the visibility and impact of Positive Energy District (PED) initiatives, reaffirming the role of community engagement in the energy transition [26].

Challenges persist in achieving effective citizen engagement, particularly due to limited understanding of e-participation's duality and the lack of robust interdisciplinary methodologies [27]. Addressing

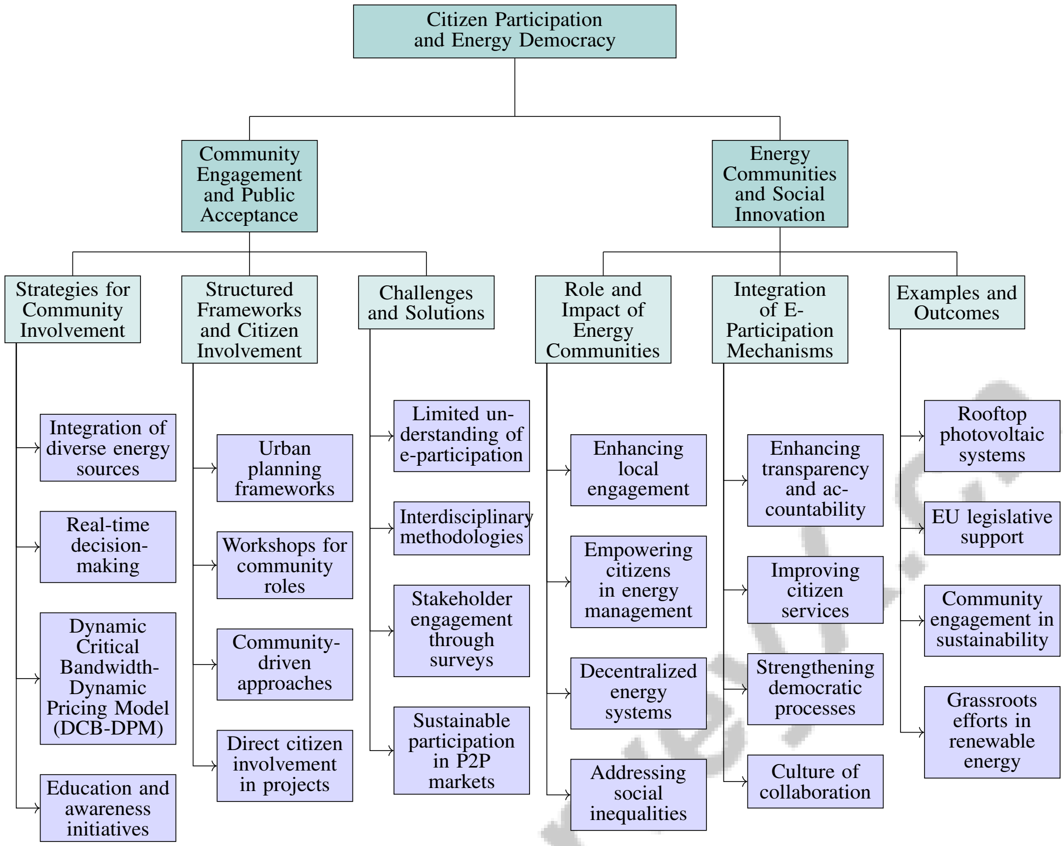

Figure 2: This figure illustrates the hierarchical structure of citizen participation and energy democracy, highlighting the categories of community engagement, public acceptance, energy communities, and social innovation, along with their subcategories and significant points.

these challenges requires developing comprehensive frameworks that facilitate public acceptance and citizen participation. Engaging stakeholders through surveys and discussions can help identify priorities and obstacles, ensuring alignment of community engagement strategies with energy project objectives [36].

Ensuring sustainable participation of prosumers in peer-to-peer (P2P) energy trading markets is challenging, as it requires maintaining grid stability and delivering economic benefits [37]. By leveraging participatory approaches, structured frameworks, and effective communication strategies, energy initiatives can achieve greater sustainability and resilience, ultimately contributing to a more equitable energy future.

3.2 Energy Communities and Social Innovation

Energy communities and social innovation are crucial for the energy transition, enhancing local engagement and empowering citizens to actively participate in energy production and management. These initiatives enable individuals and groups to control their energy supply chains, especially with the increasing reliance on renewable energy sources, as highlighted by recent EU legislative frameworks. By fostering collaboration and creating supportive narratives, energy communities promote sustainable practices and challenge existing energy regimes, advocating for decentralized and resilient energy systems [6, 9]. Energy cooperatives and community energy projects exemplify how collective action can drive sustainable energy practices and strengthen community resilience.

A key aspect of energy communities is their ability to address social inequalities by involving marginalized groups in the design and implementation of energy projects. This inclusion is vital for establishing equitable energy systems that acknowledge the diverse needs and contributions of all community members [38]. However, current studies often inadequately engage with these

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communities, neglecting the social implications of smart initiatives [10]. Bridging this gap is essential for ensuring that energy transitions are not only technologically advanced but also socially inclusive.

Integrating e-participation mechanisms within energy communities can further enhance transparency, accountability, and efficiency in decision-making processes. Digital platforms can improve citizen services and facilitate more effective participation in policy-making, thereby strengthening democratic processes in energy projects [27]. This approach empowers citizens and fosters a culture of collaboration and shared responsibility in managing energy resources.

Successful examples of energy cooperatives and community projects, such as the rooftop photovoltaic system at Aarhus University and various EU initiatives, illustrate the transformative potential of social innovation in reshaping local energy landscapes. These projects empower communities to manage their energy supply chains and underscore the importance of legislative support and community engagement in achieving sustainability goals. By integrating citizen participation and addressing social equity challenges, these initiatives demonstrate how grassroots efforts can significantly contribute to the broader transition towards renewable energy and climate justice [10, 6, 1, 9, 12]. Such initiatives often involve collaborative efforts to develop renewable energy sources, implement energy efficiency measures, and create local jobs, enhancing the overall economic and environmental well-being of communities. Prioritizing community engagement and social equity, energy communities can act as catalysts for systemic change, aligning with the objectives of energy democracy and sustainable development.

4 Grid Flexibility and P2P Trading

Category	Feature	Method
P2P Trading Mechanisms	Blockchain Integration	DBP2P[4]
	Decentralized Systems	MARL[39]
	Optimization Strategies	FP2P-TA[40]
Technological Innovations in P2P Trading	Predictive and Decision-Making Models	TSROM[16]
Case Studies and Implementations	Energy Management	AOPF[41], FB[42], OFO[43]
	System Integration	PHIL[29]
	Decentralized Systems	DPCM[44], EM[45], Consensus-MARL[3]

Table 1: This table provides a comprehensive summary of key methods and innovations in peer-to-peer (P2P) trading mechanisms, highlighting their integration with blockchain technology, decentralized systems, and optimization strategies. It categorizes the methods into P2P trading mechanisms, technological innovations, and case studies, thereby illustrating their role in enhancing grid flexibility and transforming energy markets.

In the context of evolving energy markets, the concept of grid flexibility emerges as a critical component in enhancing the efficiency and resilience of energy systems. This flexibility is particularly vital as it allows for the integration of decentralized energy resources and the facilitation of peer-to-peer (P2P) trading initiatives. Table 1 presents an organized summary of the key methods and innovations in peer-to-peer (P2P) trading, emphasizing their role in transforming energy markets through enhanced grid flexibility and decentralized coordination. Table 4 offers a detailed comparison of key peer-to-peer (P2P) trading methods, elucidating their distinct strategies for optimization, market adaptability, and technological integration in the context of evolving energy markets. The subsequent subsection will delve into the mechanisms that underpin P2P trading, exploring how these frameworks not only promote direct exchanges between prosumers but also contribute to the overall economic efficiency of energy markets. By examining the various P2P trading mechanisms, we can better understand their role in advancing grid flexibility and supporting the transition towards more decentralized energy systems.

4.1 P2P Trading Mechanisms

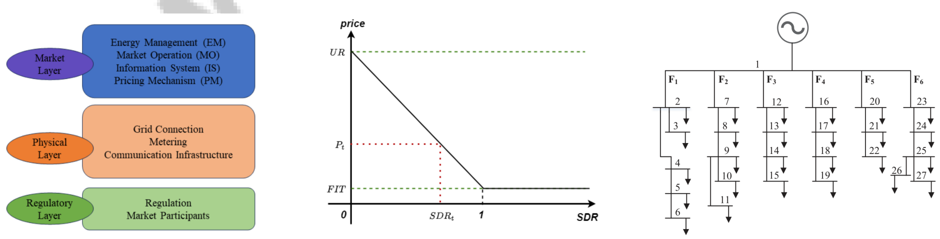
Peer-to-peer (P2P) trading mechanisms are transforming energy markets by enabling direct exchanges between prosumers, thereby reducing reliance on centralized systems and enhancing economic efficiency. A notable approach within this domain is the implementation of the Two-Stage Robust Optimization Model (TSROM), which optimizes capacity expansion in distributed energy resource (DER) deployment by incorporating three-phase unbalanced power flow. This model addresses the uncertainty in energy markets, ensuring that resource allocation is both efficient and resilient [16].

The decentralized stable matching model in P2P trading, as exemplified by the EM algorithm, matches sellers with consumers based on preferences without allowing price negotiations, thus addressing the limitations of existing centralized methods. In contrast, the NEM algorithm introduces price negotiations, providing flexibility and adaptability in energy transactions [45]. These algorithms enhance the dynamism of P2P markets by accommodating varied consumer preferences and market conditions.

Incentives for prosumers to form coalitions are essential for fostering cooperative relationships that ensure mutual benefits in peer-to-peer (P2P) energy markets, as evidenced by game-theoretic approaches that highlight how coalition formation can stabilize trading dynamics, enhance participation through consumer-centric schemes, and optimize trading efficiency by addressing communication challenges and peer selection preferences. [45, 46, 37]. This coalition-based approach encourages collaborative energy management, thereby enhancing market stability and promoting equitable energy distribution. Moreover, the integration of advanced optimization models plays a pivotal role in the economic operation of micro-grids, incorporating demand response mechanisms to minimize operational costs and enhance the utilization of clean energy.

The challenge of insufficient capacity and operational strategies for long-duration storage, particularly during simultaneous drought events, highlights the need for robust P2P mechanisms. To effectively tackle the challenges associated with peer-to-peer (P2P) electricity trading, decentralized markets employing dynamic pricing schemes can enhance transaction fairness by aligning prices with real-time consumer demand and optimizing power flow while addressing physical network constraints. These innovative systems not only minimize costs for prosumers but also ensure equitable treatment for all participants, mitigating the adverse effects of fixed pricing structures. By leveraging blockchain technology, these markets facilitate secure and efficient trading, enabling strategies such as peak load shaving and load shifting, ultimately leading to significant reductions in generation costs and improved social welfare for consumers. [44, 45, 4]. Such mechanisms ensure that energy distribution remains efficient and reliable, even under challenging conditions.

Overall, P2P trading mechanisms are integral to the decentralization of energy markets, promoting grid flexibility, economic efficiency, and prosumer empowerment. The mechanisms discussed are integral to advancing the overarching goals of energy democratization, which emphasizes equitable access and participation in energy production and consumption, as well as facilitating the transition toward more sustainable and resilient energy systems. This transition is essential not only for addressing the urgent challenges posed by climate change but also for fostering local energy independence and innovation, particularly through the establishment of energy communities that empower individuals and neighborhoods to manage their own energy resources. Such initiatives align with broader objectives outlined in the European Green Deal, aiming for energy neutrality by 2050 and addressing social equity by eliminating energy poverty while promoting investment in renewable technologies. [7, 6, 8, 9]



(a) Energy Management and Pricing Mechanism in a Smart Grid System[4]

(b) The graph represents a supply and demand curve for a commodity, with a horizontal supply curve and a vertical demand curve intersecting at a point labeled "UR."[39]

(c) The image depicts a power grid with a transformer at the top, connected to several feeders (F1 to F6) that distribute power to various loads.[40]

Figure 3: Examples of P2P Trading Mechanisms

As shown in Figure 3, In the realm of modern energy solutions, grid flexibility and peer-to-peer (P2P) trading are pivotal concepts that are transforming how energy is managed and distributed. The examples of P2P trading mechanisms illustrated in the provided figures highlight diverse aspects

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of this transformation. The first figure, "Energy Management and Pricing Mechanism in a Smart Grid System," presents a sophisticated layered model essential for managing energy within a smart grid. This model comprises three distinct layers—Market, Physical, and Regulatory—each playing a crucial role in the efficient functioning and pricing mechanisms of energy systems. The second figure delves into the economic principles behind P2P trading, showcasing a supply and demand curve for a commodity, where the intersection point marked "UR" signifies the equilibrium. This representation underscores the balance between supply and demand in energy markets. Lastly, the third figure offers a visual depiction of a power grid infrastructure, featuring a transformer connected to several feeders, illustrating the distribution of power to various loads. Together, these examples provide a comprehensive overview of the mechanisms that underpin P2P trading and grid flexibility, highlighting their significance in advancing sustainable and efficient energy management. [4, 39, 40]

4.2 Technological Innovations in P2P Trading

Recent technological advancements have significantly enhanced the efficiency and scalability of peer-to-peer (P2P) trading systems, fostering a more decentralized and consumer-centric energy market. A notable innovation in this domain is the application of a canonical coalition game (CCG) framework, which creates a stable and consumer-centric P2P energy trading scheme. This framework emphasizes collaboration among prosumers, ensuring mutual benefits and enhancing market stability [37].

The integration of blockchain and federated learning technologies is another critical advancement, with hierarchical models offering better scalability and lower latency than flat models. This integration not only enhances data security and privacy but also improves the efficiency of decentralized energy management systems [17]. Additionally, the introduction of dynamic pricing schemes, such as the unique price scheme (UPS) and differential price scheme (DPS), allows for real-time adaptation to market conditions and participant needs, significantly improving upon traditional fixed pricing methods [44].

The development of online feedback optimization (OFO) methods represents a leap forward in solving optimization problems with minimal model information. This innovation provides a more flexible and robust solution for managing curative actions in real-time, thereby enhancing the adaptability of P2P trading systems [43]. Furthermore, the combination of robust optimization techniques with predictive neural networks facilitates improved decision-making under uncertainty, ensuring efficient resource allocation and grid stability [16].

Decentralized algorithms, such as the EM algorithm, play a crucial role in enhancing grid adaptability by dynamically updating preferences and matches between sellers and consumers. This approach underscores the importance of decentralized mechanisms in managing energy flows and optimizing P2P trading operations [45].

The integration of advanced technological innovations, such as blockchain for secure transaction management and connection-aware algorithms for optimizing peer selection, significantly enhances peer-to-peer (P2P) trading systems. These developments not only foster a more flexible and efficient trading environment but also mitigate the influence of central authorities on energy pricing, ultimately contributing to the creation of a more resilient and competitive energy market. [45, 46]. By integrating advanced algorithms, blockchain technologies, and dynamic pricing models, these innovations align with the broader objectives of energy democratization and sustainability, paving the way for a more equitable and resilient energy future.

4.3 Case Studies and Implementations

Case studies and implementations of peer-to-peer (P2P) trading systems provide valuable insights into the operational dynamics and benefits of decentralized energy markets. Table 2 provides a comprehensive overview of the methods employed in peer-to-peer trading systems, illustrating their operational dynamics, effects on grid stability, and sustainable practices, thereby highlighting their relevance in decentralized energy markets. An experimental setup involving a P2P network with 45 sellers and 45 consumers compared the performance of the EM and NEM algorithms against existing methods such as double auction and first come first serve. This study demonstrated the effectiveness of decentralized stable matching models in optimizing energy transactions and enhancing market efficiency [45].

Method Name	Operational Dynamics	Grid Stability	Sustainable Practices
EM[45]	Energy Transactions Efficiency	-	Reducing Generation Costs
AOPF[41]	Energy Transactions Efficiency	Meshed Grid Environments	Reducing Generation Costs
Consensus-MARL[3]	Energy Transactions Efficiency	Network Constraints Feasibility	Reducing Generation Costs
FB[42]	Energy Consumption Patterns	Grid Flexibility	Demand Response Strategies
OFO[43]	Energy Transactions Efficiency	Grid Operational Efficiency	Reduce Generation Costs
DPCM[44]	Dynamic Pricing Schemes	Congestion Management Effectiveness	Reduces Generation Costs
PHIL[29]	P2p Energy Trading	Network Instability	Supply-demand Balance

Table 2: Comparative Analysis of Various Peer-to-Peer Trading Methods in Decentralized Energy Markets. This table presents a detailed examination of different methods, highlighting their operational dynamics, impact on grid stability, and adoption of sustainable practices. The analysis underscores the diverse approaches and their contributions to enhancing energy transaction efficiency, grid management, and sustainability.

In another study, the ANN-OPF method was evaluated using the SimBench HV grid dataset, focusing on a meshed grid with 100 buses and 22 controllable wind parks. This implementation highlighted the potential of optimal power flow in improving grid stability and operational efficiency in high-voltage networks [41]. Additionally, a simulation using the IEEE 13-bus test feeder with 12 prosumers under various trading scenarios illustrated the adaptability of P2P trading mechanisms in diverse market conditions [3].

A notable implementation in Managua, Nicaragua, involved the deployment of thirty FlexBoxes to monitor energy consumption and environmental conditions across micro-enterprises and households. This case study underscored the potential of P2P frameworks in micro-level demand-side management and grid interaction [42]. Furthermore, the economic benefits of P2P trading were assessed in a low-voltage network model with five prosumers, revealing significant reductions in energy costs and improvements in network efficiency [37].

Experiments conducted on a laboratory distribution grid at RWTH Aachen University, which included PV inverters, a battery energy storage system, and an EV charging point, demonstrated the effectiveness of online feedback optimization methods in real-time energy management [43]. Moreover, experiments integrating renewable energy sources within P2P trading systems achieved a 56.9% reduction in generation costs and a 57.3% decrease in energy consumption from non-renewable sources, while maintaining social welfare levels. This showcases the method's effectiveness in promoting sustainable energy practices [44].

Lastly, a study employing power hardware-in-the-loop (PHIL) testing highlighted the complexities of hardware interactions in P2P trading, emphasizing the importance of robust testing frameworks to address these challenges [29]. Collectively, these case studies and implementations demonstrate the transformative potential of P2P trading systems in enhancing grid flexibility, economic efficiency, and sustainable energy practices, contributing to the broader objectives of energy democratization and resilience in the energy sector.

Feature	Two-Stage Robust Optimization Model (TSROM)	Decentralized Stable Matching Model (EM algorithm)	NEM algorithm
Optimization Method	Capacity Expansion	Preference Matching	Price Negotiations
Market Adaptability	Resilient Allocation	NO Price Negotiations	Flexible Transactions
Technological Integration	Three-phase Power Flow	Not Specified	Not Specified

Table 3: The table provides a comparative analysis of three distinct models applied in peer-to-peer (P2P) trading systems: the Two-Stage Robust Optimization Model (TSROM), the Decentralized Stable Matching Model (EM algorithm), and the NEM algorithm. It highlights their unique approaches to optimization methods, market adaptability, and technological integration, demonstrating their respective contributions to enhancing grid flexibility and decentralized coordination in energy markets.

5 Low-Temperature District Heating

5.1 Integration of Excess Heat from Electrolyzers

Incorporating excess heat from electrolyzers into district heating systems presents a viable strategy to boost urban energy efficiency and sustainability. This process leverages the thermal energy generated

Feature	Two-Stage Robust Optimization Model (TSROM)	Decentralized Stable Matching Model (EM algorithm)	NEM algorithm
Optimization Method	Capacity Expansion	Preference Matching	Price Negotiations
Market Adaptability	Resilient Allocation	NO Price Negotiations	Flexible Transactions
Technological Integration	Three-phase Power Flow	Not Specified	Not Specified

Table 4: The table provides a comparative analysis of three distinct models applied in peer-to-peer (P2P) trading systems: the Two-Stage Robust Optimization Model (TSROM), the Decentralized Stable Matching Model (EM algorithm), and the NEM algorithm. It highlights their unique approaches to optimization methods, market adaptability, and technological integration, demonstrating their respective contributions to enhancing grid flexibility and decentralized coordination in energy markets.

during hydrogen production, repurposing it within district heating networks to minimize waste and optimize energy usage. However, the underutilization of this excess heat necessitates innovative strategies for its effective integration [25].

A flexibility-oriented microgrid optimal scheduling model can manage net load variability while providing flexibility services to the grid, integrating sources like electrolyzer heat to enhance energy network adaptability and efficiency [47, 48]. Advanced forecasting methods, such as hybrid architectures that utilize weather data for photovoltaic power prediction, can optimize this integration by improving resource planning and management [49]. Community engagement models, like the Community Participatory Planning Process (CPPP), ensure equitable benefit distribution, especially in disadvantaged areas [12].

These methodologies support the integration of electrolyzer heat into district heating, contributing to urban energy decarbonization. This approach enhances energy efficiency through innovative technologies and self-sustainable IoT ecosystems, promoting sustainability and social equity. By integrating renewable energy sources and emphasizing recycling, this strategy fosters a resilient and inclusive energy future, supporting economic growth, environmental integrity, and social justice [10, 15].

5.2 Business Models for Heat Utilization

Innovative business models are essential for utilizing low-temperature heat from electrolyzers in district heating systems. Three proposed models involve selling excess heat to district heating networks, enhancing economic viability and promoting sustainable energy practices [25].

The first model involves directly selling electrolyzer heat to district heating providers, reducing hydrogen production costs by 5.6

The second model engages multiple stakeholders, including local governments and community organizations, in managing excess heat. This cooperative approach promotes shared ownership and equitable benefit distribution, enhancing social acceptance and sustainability. It aligns with urban climate justice frameworks, empowering communities in energy management and fostering renewable energy integration [10, 6, 9].

The third model treats excess heat as a marketable asset, enhancing hydrogen production cost efficiency and contributing to energy system decarbonization. By reducing production costs by approximately 5.6

Evaluating these models helps stakeholders choose the best approach for integrating low-temperature heat into district heating, ensuring economic viability and environmental sustainability. These models support urban energy infrastructure decarbonization and address social equity and energy resilience, evidenced by their integration into community-based energy programs and local policies in cities aiming for net-zero targets [10, 11].

6 Social Equity and Just Transition

6.1 Equity in Energy Access and Affordability

Ensuring equitable energy access and affordability is crucial for a just energy transition, necessitating policies that address disparities in energy distribution. Decentralized peer-to-peer (P2P) trading mechanisms democratize energy markets, enhancing access for underserved communities and promoting a consumer-centric approach [37]. The Dynamic Critical Bandwidth-Dynamic Pricing Model (DCB-DPM) further enhances social equity by addressing cross-subsidy and free-rider issues in energy pricing [33].

Electricity grid resilience significantly impacts equitable energy access. State of Resilience (SoR) predictions improve n-Grid management reliability [50], while simplified flexibility assessments for smart grids support policies ensuring equitable access [48]. Financial considerations, such as the risks of violating bus voltage limits during high P2P trading levels, are critical [40]. Multi-objective predictive control strategies that adapt to changing conditions can enhance decision-making in micro-grids, supporting equitable access [14].

Addressing social and operational challenges is essential, particularly regarding the uneven distribution of electric vehicle (EV) charging infrastructure, often concentrated in affluent areas, leaving disadvantaged communities underserved [12]. The Social Equity Driven Optimal Power Flow (SE-OPF) method maximizes social welfare by balancing supply costs with consumer satisfaction [51].

Citizen participation frameworks emphasize equitable involvement, although challenges like legal restrictions on universities' participation in energy communities persist [34, 1]. Addressing these issues requires a nuanced understanding of justice, as varying definitions can lead to different outcomes in tackling social inequalities [10]. Additionally, limited access to public transit exacerbates social inequalities, highlighting the need for targeted restoration strategies for vulnerable populations [52, 53].

Achieving equitable energy access and affordability requires a comprehensive strategy incorporating technological innovations, financial mechanisms, and social equity considerations. This is crucial in transitioning to sustainable energy solutions, ensuring disadvantaged communities benefit from advancements in electric vehicles and renewable energy. Initiatives like crowdfunding for infrastructure, establishing energy communities, and integrating smart city concepts are essential for fostering an inclusive and sustainable energy landscape [10, 6, 9, 12, 15]. Leveraging innovative solutions and collaborative efforts, policies can facilitate a just and inclusive energy transition benefiting all communities.

6.2 Social Equity and Inclusive Participation

Inclusive participation in the energy transition ensures equitable benefits across societal segments. The socioeconomic score (SES) assesses energy burdens and consumer status, guiding resource distribution [51]. This underscores the need to integrate social equity into energy policy, ensuring marginalized communities are not overlooked.

Building trust within citizen networks motivates participation and fosters ownership in energy projects [36]. Trust-building measures are essential for engaging communities in decision-making, promoting a democratic approach to energy management. Crowdfunding programs empower disadvantaged communities to finance energy infrastructure, such as EV charging stations, democratizing access and fostering community-driven initiatives [12].

Optimizing budget allocation between public transit and ride-hailing services maximizes social equity among protected groups, ensuring equitable access to mobility solutions [52]. Computational multi-agent simulation frameworks, considering hazard, infrastructure, and household elements, provide comprehensive tools for evaluating societal impacts and resilience strategies [53].

Prioritizing inclusive participation and social equity in the energy transition enables stakeholders to create a just and resilient future, addressing the need for decarbonization while ensuring equitable access to benefits for all communities. Empowering stakeholders through community-driven initiatives facilitates knowledge sharing and collaboration, fostering local agency and addressing energy poverty. Strategies promoting self-production and self-consumption of energy enhance energy democracy, supporting environmental sustainability and social equity [7, 12, 8]. This involves actively engaging all community members in energy solution design and implementation, ensuring equitable benefit distribution.

7 Regulatory Harmonization and Sustainable Energy Policy

7.1 Role of Regulatory Frameworks in Energy Transition

Regulatory frameworks are essential for advancing the energy transition by creating the necessary legal and policy structures for incorporating renewable energy sources and decentralized systems. These frameworks address challenges like battery system degradation that affect long-term performance assessments [54]. Customizing regulatory contracts for various energy markets enhances adaptability and effectiveness across different conditions [55].

Incorporating advanced control strategies, such as topology control, into current market frameworks presents challenges, including the complexity of modeling these controls and the need for operational transparency to ensure informed market participation [31]. Overcoming these challenges requires a deep understanding of market dynamics and the development of transparent regulatory mechanisms that encourage stakeholder involvement.

To scale energy communities effectively and enhance regulatory efficacy, strong collaborations between energy communities and policymakers are crucial. These partnerships facilitate knowledge and resource sharing, leading to innovative solutions aligned with evolving legislative landscapes and sustainability targets. By integrating community-driven approaches with top-down policy interventions, stakeholders can collaboratively remove barriers and enhance energy independence, fostering a more sustainable energy future [7, 6, 11, 9]. Additionally, developing monitoring tools that incorporate diverse stakeholder perspectives ensures that regulatory measures are inclusive and equitable.

Future research should focus on inclusive methodologies addressing intersectional issues within urban climate justice, ensuring regulatory frameworks are both technically sound and socially equitable [10]. By integrating diverse perspectives and addressing the unique challenges posed by decentralized energy systems, regulatory frameworks can effectively support the transition to a more sustainable and resilient energy future.

7.2 Harmonization of Policies for Sustainable Practices

Harmonized policies are crucial for promoting sustainable energy practices, ensuring an efficient and equitable transition to renewable energy systems. The complexity of integrating decentralized energy resources into existing infrastructures necessitates a coordinated policy approach aligning national, regional, and local regulations. Such alignment is vital for overcoming fragmented regulatory environments that often hinder innovative energy solutions and sustainability progress. By fostering community-driven approaches and enhancing stakeholder engagement, a cohesive framework can facilitate knowledge sharing and resource allocation, enabling a smoother transition to sustainable practices and collective climate objectives [7, 6, 8, 9].

Developing harmonized policies requires understanding diverse regulatory landscapes and market conditions across jurisdictions. This understanding is essential for designing flexible policies accommodating local specificities while maintaining consistency in promoting sustainable practices. Integrating advanced technologies, such as blockchain and federated learning, into energy management systems highlights the need for regulatory frameworks supporting innovation while protecting consumer interests [17].

Harmonized policies should emphasize stakeholder engagement and community participation, ensuring the inclusion of all relevant voices in policymaking. This inclusive approach enhances the legitimacy of regulatory measures and fosters public acceptance and support for sustainable initiatives. Establishing common evaluation frameworks and Key Performance Indicators (KPIs) can facilitate the monitoring and assessment of policy impacts, ensuring they effectively promote sustainable energy practices [26].

Addressing legal and institutional barriers impeding the scaling of decentralized energy systems is also critical. These barriers include restrictive regulations on energy trading and the absence of standardized procedures for integrating renewable sources into existing grids. By establishing clear and consistent regulatory guidelines, policymakers can create an environment conducive to the widespread adoption of sustainable technologies and practices, promoting energy independence and facilitating the transition to renewable sources. This proactive approach aligns with the European

Union's legislative framework encouraging renewable energy use and empowers local communities to manage their energy supply chains effectively, contributing to greenhouse gas emission reductions and sustainability targets [7, 6, 13, 9].

7.3 Successful Policy Implementations and Innovations

Successful policy implementations and innovations in the energy sector are vital for advancing the transition to sustainable systems. These initiatives often involve integrating advanced technologies and regulatory frameworks supporting renewable energy sources and decentralized systems. A notable example is the adoption of dynamic pricing models, such as the Dynamic Critical Bandwidth-Dynamic Pricing Model (DCB-DPM), which enhances market efficiency and promotes equitable energy access by addressing cross-subsidy and free-rider issues [33].

The deployment of peer-to-peer (P2P) trading mechanisms has shown significant potential in democratizing energy markets and enhancing grid flexibility. These systems facilitate direct energy exchanges between prosumers, reducing reliance on centralized systems and promoting economic efficiency. Integrating decentralized stable matching models, such as the EM and NEM algorithms, further enhances P2P market adaptability by accommodating varied consumer preferences and market conditions [45].

Innovations in energy storage and management, including robust optimization techniques combined with predictive neural networks, have improved decision-making under uncertainty, ensuring efficient resource allocation and grid stability [16]. Additionally, online feedback optimization (OFO) methods have enhanced the adaptability of energy management systems, providing flexible solutions for real-time energy management [43].

Policies supporting integrating excess heat from electrolyzers into district heating systems have also contributed to decarbonizing urban energy infrastructures. By leveraging flexibility-oriented microgrid optimal scheduling models, these policies facilitate effective utilization of excess heat, enhancing energy efficiency and sustainability [25].

Moreover, successful policy implementations have addressed social equity by promoting crowdfunding programs for disadvantaged communities to finance energy infrastructure, such as electric vehicle (EV) charging stations [12]. These initiatives democratize access to energy resources and foster community-driven energy management.

Successful policies in the energy sector are characterized by their ability to integrate advanced technologies, foster equitable access to resources, and enhance system resilience and sustainability. This includes developing energy communities empowering local stakeholders to manage their energy supply chains effectively, reflecting the European Union's shift toward renewable sources. Initiatives such as community-driven approaches and energy-sustainable Internet of Things (IoT) solutions are critical for achieving long-term sustainability goals. Collectively, these efforts address pressing environmental and social challenges by promoting energy independence, reducing greenhouse gas emissions, and creating self-sustainable ecosystems that efficiently utilize renewable resources [7, 15, 9]. By fostering collaboration and stakeholder engagement, these policies contribute to a more equitable and resilient energy future.

8 Conclusion

The investigation into decentralized energy systems and the renewable energy transition highlights substantial progress in creating sustainable and resilient energy infrastructures. The integration of local resources and innovative technologies remains vital for achieving climate goals, with optimized resource utilization and effective State of Resilience (SoR) predictions playing a crucial role in supporting net-zero carbon objectives. Addressing political and economic challenges is essential to accelerate the transition to renewable energy and maintain global warming at or below 1.5 degrees Celsius.

The transformative potential of peer-to-peer (P2P) trading mechanisms is evident, offering enhancements in energy efficiency and reductions in carbon emissions. However, challenges such as over-voltage and transaction losses must be addressed to fully harness these benefits. The synergy of renewable energy sources with advanced control strategies, including low-voltage Distributed Energy

Resource Management Systems (DERMS), has proven effective in reducing operational costs and enhancing grid flexibility.

Future research should prioritize the development of advanced optimization algorithms, exploration of decentralized control strategies, enhancement of energy storage integration, and adaptation of regulatory frameworks to support the evolving landscape of hybrid power systems. The potential of Room Temperature Ambient Pressure Systems (RTAPS) to revolutionize power system planning and market mechanisms necessitates adjustments to accommodate this emerging technology. Moreover, optimizing distribution market scheduling models to leverage the ramping capabilities of microgrids can mitigate operational challenges and bolster grid stability.

Participatory sensing has demonstrated its effectiveness in increasing citizen engagement and awareness, thereby improving policy outcomes through informed citizen action. The integration of peer-to-peer trading significantly enhances market participation, which is crucial for the future of decentralized energy systems. A proposed dynamic price model addresses chronic issues in existing pricing models, fostering a more equitable energy future. Future research should refine the weighted consumer satisfaction function and explore multi-stage optimization to enhance model effectiveness across various scenarios.

Insights from establishing energy communities indicate the necessity of significant time and effort for success, with policy changes recommended to facilitate this process. An analysis of energy transition policies reveals regional differences in effectiveness, approach, and outcomes, with varying degrees of success in renewable energy generation capacity. The developed methodology demonstrates flexibility capabilities, aligning with benchmark comparisons and underscoring its potential impact on the energy sector. Experiments show that the proposed optimization model effectively reduces operational costs and enhances renewable energy utilization in smart microgrids. Future research should focus on improving model accuracy for Model Predictive Control (MPC), integrating multiple objectives, and exploring flexibility aggregation across multiple buildings.

The survey also underscores the importance of standardized evaluation frameworks, stakeholder engagement, and adaptive governance models to facilitate the successful implementation of Positive Energy Districts (PEDs). Crowdfunding initiatives have shown promise in empowering disadvantaged communities to invest in energy infrastructure, promoting social equity. Additionally, sustainable Wireless Energy Transfer (WET) methods can significantly reduce overall costs and environmental impacts compared to conventional battery-powered solutions.

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