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AI-Enabled Peer-to-Peer Energy Trading: Trust, Market Autonomy, Regulatory Oversight, and Prosumer Empowerment

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Abstract

Peer-to-peer energy trading promises decentralized, efficient, and consumer-centric electricity markets, and AI is increasingly proposed as the enabling intelligence for matching, pricing, and execution. However, its deployment raises fundamental questions of trust, autonomy, regulation, and empowerment. Current P2P frameworks often treat AI as a neutral technical layer, neglecting the socio-technical challenges of building trust among peers, balancing market freedom with regulatory mandates, and ensuring that prosumers are empowered rather than sidelined. This creates a risk that decentralization will reproduce new forms of opacity and dependency. This article develops a conceptual framework for AI-enabled P2P energy trading that integrates trust mechanisms, market autonomy, regulatory oversight, and prosumer empowerment as co-equal design dimensions. The aim is to clarify how decentralized energy markets could be governed without suppressing their participatory potential. The framework is constructed through conceptual synthesis of decentralized energy markets, AI governance, trust theory, regulatory economics, and prosumer-centric energy research. No empirical work is performed. The framework maps the interdependencies among trust, autonomy, regulation, and empowerment, and provides design principles for AI systems that support transparent, fair, and inclusive P2P trading. Three tables illustrate trust enablers, autonomy-oversight spectra, and empowerment tools. AI can unlock the potential of P2P energy trading, but only if governed within a framework that explicitly balances its four core dimensions. The article provides a roadmap for researchers, platform developers, and policymakers.

Keywords Trust, AI, Peer-to-peer energy trading, Market autonomy, Regulatory oversight, Prosumer empowerment

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Introduction

Peer-to-peer energy trading has emerged as a prominent model for organizing distributed energy exchange among households, communities, electric vehicles, and small-scale producers. Comprehensive reviews have shown that P2P and community-based markets can support local flexibility, distributed resource coordination, and new forms of energy participation when they are carefully structured [1]. AI could be designed to enhance these markets by forecasting supply and demand, matching buyers and sellers, supporting automated negotiation, and coordinating settlement. As P2P trading moves from conceptual design toward platform-based implementation, AI becomes not only an optimization tool but also a governance-relevant market actor.

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The governance challenge is that many P2P designs emphasize technical efficiency while treating trust, legal accountability, and prosumer agency as secondary concerns. Literature on local energy market models shows that P2P, community self-consumption, and transactive energy systems differ substantially in their institutional assumptions, yet many platform architectures still rely on simplified views of participant behavior and market legitimacy [2]. AI may foster efficient decentralized coordination, but it may also introduce opaque pricing, automated exclusion, and new dependencies on platform operators. This creates a governance vacuum in which decentralized markets appear autonomous while actually being shaped by algorithmic rules that are difficult for ordinary prosumers to contest.

An integrative framework is therefore required because trust, autonomy, oversight, and empowerment cannot be addressed independently. Reviews of P2P trading challenges indicate that market design, network constraints, settlement rules, participant incentives, and data infrastructures are deeply interconnected [3]. AI-enabled P2P markets should be conceptualized as socio-technical systems in which algorithmic decisions, regulatory responsibilities, and prosumer rights interact continuously. A framework that links these dimensions can help avoid both techno-centric optimism and overly restrictive regulation.

This article contributes a conceptual framework for AI-enabled P2P energy trading that positions trust, market autonomy, regulatory oversight, and prosumer empowerment as mutually conditioning design requirements. The framework builds on review work in P2P energy trading, blockchain-enabled energy exchange, game-theoretic coordination, and legal analysis of local electricity markets [4]. It does not report experiments, simulations, or empirical results; instead, it specifies conceptual relationships and governance principles. The article proceeds from background and conceptual foundations to trust mechanisms, the autonomy-oversight spectrum, prosumer empowerment, integration, policy implications, evaluation strategy, limitations, and conclusion.

Background

AI in peer-to-peer energy markets

AI in P2P energy markets could support forecasting, preference learning, price recommendation, automated bidding, contract execution, anomaly detection, and settlement verification. Early microgrid trading models demonstrated that local energy exchange requires mechanisms for matching supply and demand while respecting technical and economic constraints [5]. Later work on peer-to-peer market design showed that local trading becomes more complex when network charges, losses, uncertainty, and participant heterogeneity are included [6]. In a conceptual framework, AI should therefore be understood as a coordination layer that can assist market operation but must remain accountable to rules, participant preferences, and grid constraints.

Trust in decentralized energy systems

Trust in decentralized energy systems is not limited to whether participants believe that a trade will be settled; it also includes confidence in data accuracy, pricing fairness, smart contract execution, identity management, and institutional recourse. Blockchain research in the energy sector highlights the potential of distributed ledgers to strengthen auditability and reduce reliance on centralized intermediaries, but it also identifies scalability, privacy, governance, and implementation challenges [7]. Smart contracts may automate obligations in P2P trading, yet their authority depends on whether participants understand the rules and whether errors can be corrected [8]. Trust must therefore be designed through a combination of technical verification, explainable AI, institutional accountability, and dispute resolution.

Market autonomy vs. regulatory guardrails

P2P energy trading is often framed as a move from centralized utility control toward decentralized market autonomy, but this autonomy must be balanced by regulatory guardrails. Legal analysis of P2P electricity trading shows that local exchanges may conflict with existing licensing rules, consumer protection duties, grid cost allocation, and market

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oversight arrangements [9]. AI may intensify these tensions by allowing autonomous agents to trade rapidly, adapt strategies, or discover loopholes in poorly specified rules. Regulatory oversight should therefore be embedded into the market architecture rather than added only after deployment.

Prosumer-centric design and empowerment

Prosumer empowerment refers to the capacity of distributed energy users to participate meaningfully in energy exchange, shape preferences, obtain fair compensation, and understand the consequences of automated decisions. Research on household attitudes toward P2P trading indicates that participation depends not only on financial incentives but also on trust, usability, fairness, and perceived control. Choice experiment evidence similarly suggests that social fairness and simplicity are central to prosumer acceptance of P2P trading arrangements. AI tools should therefore be designed to enhance agency rather than convert prosumers into passive data sources for automated market platforms.

Gaps in existing P2P AI frameworks

Existing P2P and transactive energy frameworks provide valuable insights into market clearing, game-theoretic participation, distributed ledgers, and community exchange, but they often lack a unified governance structure. Reviews of peer-to-peer energy systems for connected communities show that technical, economic, social, and regulatory issues remain fragmented across separate literatures [10]. Work on transactive energy likewise emphasizes coordination and flexibility while leaving open questions about accountability, equity, and participant comprehension [11]. The gap is not the absence of individual mechanisms, but the lack of a framework that connects AI functionality to trust, autonomy, oversight, and empowerment simultaneously.

Conceptual Foundation

The four-dimensional governance space

The framework conceptualizes AI-enabled P2P energy trading as a four-dimensional governance space formed by trust, market autonomy, regulatory oversight, and prosumer empowerment. P2P market reviews show that decentralized trading depends on technical feasibility, economic incentives, participant participation, and institutional legitimacy rather than on any single design feature [1]. Trust provides confidence in exchange, autonomy enables decentralized coordination, oversight protects public and legal objectives, and empowerment ensures that prosumers remain active market subjects. These dimensions should be treated as co-equal because strengthening one dimension without the others may produce new vulnerabilities. **Figure 1** shows the ecosystem actor network for AI-enabled peer-to-peer energy trading.

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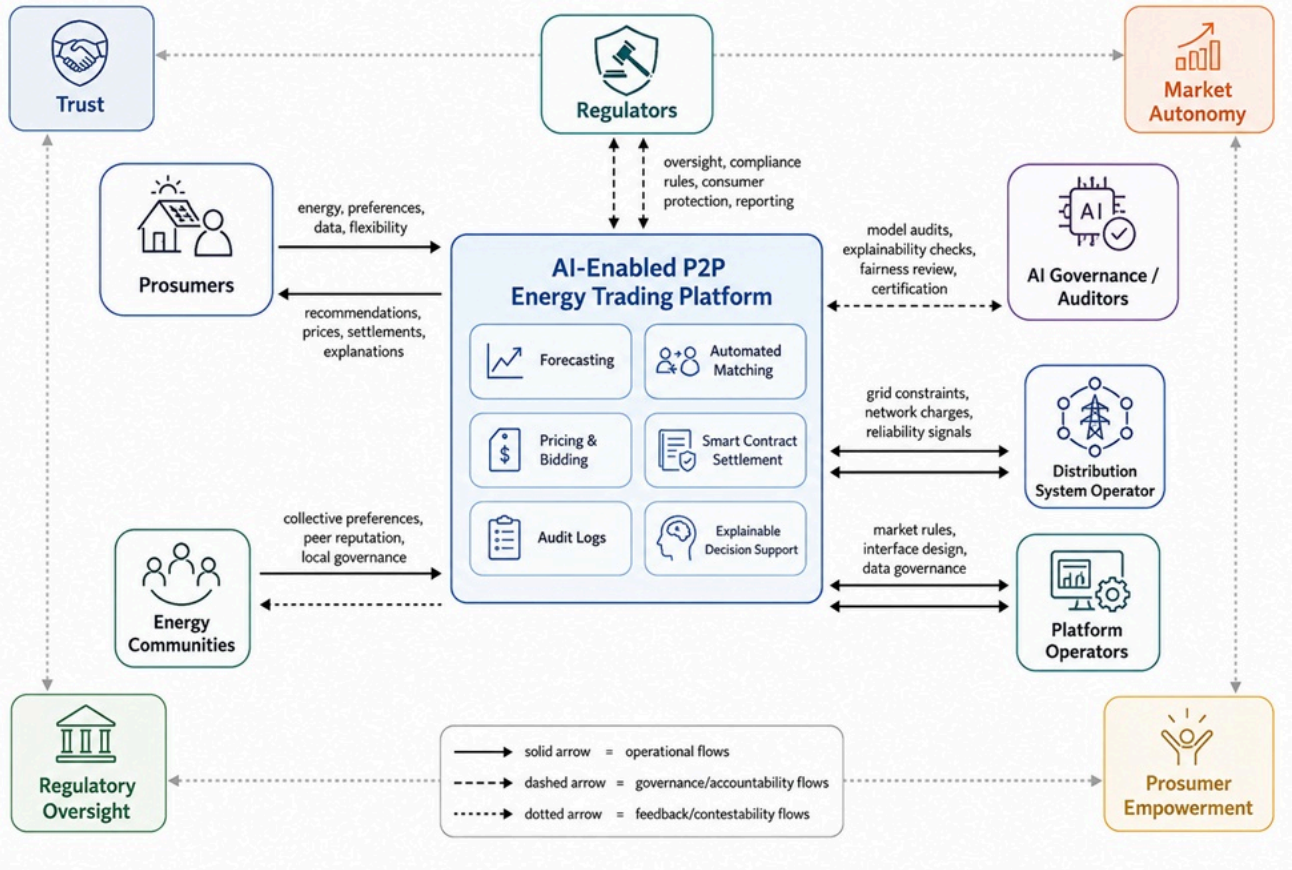

Figure 1. Ecosystem Actor Network for AI-Enabled Peer-to-Peer Energy Trading

AI as a dual-use enabler

AI is dual-use because the same capabilities that support efficient P2P trading can also undermine transparency, fairness, and accountability. Machine learning could improve forecasting and bidding, but automated strategies may obscure how prices are formed or how participants are prioritized [12]. Game-theoretic approaches can motivate sustainable user participation, yet they may also assume rationality and information access that many real prosumers do not possess [13]. AI should therefore be governed as both an enabler of decentralization and a potential source of market power, opacity, and behavioral steering.

Framework scope and design principles

The proposed framework is conceptual and architecture-oriented rather than empirical, and it focuses on how AI-enabled P2P markets could be designed for trustworthy, autonomous, regulated, and empowering exchange. It is informed by market models that include bilateral contracts, grid-influenced trading, auctions, coalitions, and blockchain-supported settlement [14]. The framework does not prescribe a single market algorithm; instead, it identifies design principles for aligning AI functionality with governance requirements. These principles include explainability, contestability, proportional oversight, prosumer control, auditability, and compatibility with grid and consumer protection obligations.

Trust Mechanisms in AI-Enabled P2P Energy Trading

Types of trust required

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AI-enabled P2P energy trading requires transactional trust, data trust, institutional trust, and algorithmic trust. Transactional trust concerns whether trades are executed and settled as agreed, while data trust concerns whether metering, forecasts, identities, and flexibility claims are reliable [15]. Institutional trust concerns whether participants have recourse when disputes occur, and algorithmic trust concerns whether AI recommendations, prices, and automated actions can be understood and challenged. These trust types overlap, because a transparent smart contract cannot compensate for biased AI pricing or weak consumer protection.

AI and technological enablers of trust

AI and supporting technologies could foster trust through explainable price formation, fraud detection, reputation scoring, verifiable metering, smart contract audit trails, and anomaly alerts. Blockchain-enabled P2P trading has been proposed as a way to strengthen integrity and traceability, but the trust benefit depends on how governance, privacy, and participant usability are handled [16]. Consortium blockchain models for localized electricity trading among plug-in hybrid electric vehicles show how distributed validation can support exchange among mobile or distributed actors [17]. However, technological trust enablers should be balanced by human-readable explanations and institutional accountability.

Governance of trust

Trust governance requires rules for identity verification, algorithmic audit, data correction, dispute resolution, smart contract updates, and liability assignment. Distributed ledger studies show that energy crowdsourcing and blockchain-based trading may enable new forms of coordination, but they also require governance mechanisms to address security, scalability, and strategic behavior [18]. AI systems in P2P markets should therefore include audit logs, role-based access, transparent rule libraries, and procedures for suspending flawed automated decisions. **Table 1** maps trust types to technological enablers, governance requirements, and vulnerabilities that must be addressed before AI-enabled decentralization can be considered trustworthy.

Table 1. Trust Dimensions in AI-Enabled P2P Energy Trading

Trust Type	AI/Technological Enabler	Governance Requirement	Potential Vulnerability
Transactional trust	Automated matching, smart contract execution, settlement verification	Clear rules for contract validity, trade reversal, failed delivery, and settlement disputes	Irreversible execution of erroneous or unfair trades
Data trust	Meter validation, anomaly detection, cryptographic data integrity checks	Standards for metering accuracy, data correction, privacy, and authorized access	Manipulated meter data, faulty forecasts, or unverifiable flexibility claims
Algorithmic trust	Explainable pricing, interpretable bidding agents, transparent recommendation logic	Auditability of AI models, explanation rights, contestability, and documentation duties	Opaque optimization that hides bias, discrimination, or platform preference
Institutional trust	Regulatory nodes, certified platform operators, dispute resolution channels	Legal accountability, consumer protection procedures, and platform licensing	Ambiguous responsibility when automated agents cause harm
Community trust	Reputation mechanisms, peer feedback systems, social preference modeling	Safeguards against exclusion, retaliation, manipulation, and reputation gaming	Reinforcement of social inequalities or strategic peer-rating behavior
Infrastructure trust	Secure ledgers, resilient communication, cybersecurity monitoring	Grid-code compatibility, cyber-risk controls, and operational continuity rules	Cyberattacks, ledger congestion, or dependency on brittle digital infrastructure

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Market Autonomy and Regulatory Oversight

The autonomy spectrum

Market autonomy in P2P trading should be understood as a spectrum rather than a binary distinction between centralized regulation and fully decentralized exchange. Bilateral contract network models show that peer-level negotiation can decentralize coordination, but they still require market rules, network constraints, and settlement structures [14]. Grid-influenced trading further demonstrates that local autonomy cannot ignore distribution network impacts, tariffs, or system reliability responsibilities [19]. The autonomy spectrum therefore ranges from tightly supervised local trading to highly automated self-governance, with different oversight needs at each level.

AI for market operation and self-governance

AI could support market operation through automated clearing, adaptive pricing, bidding agents, dispute triage, preference learning, and self-updating rule recommendations. Coalition formation approaches suggest that participants may coordinate in groups to improve trading outcomes, but such coordination requires careful attention to incentives, fairness, and strategic behavior [20]. Motivational game-theoretic models similarly show that participation may depend on how benefits, autonomy, and user incentives are structured [21]. AI-based self-governance should therefore be designed to facilitate coordination while preventing collusion, exclusion, manipulation, and rule capture.

Embedding regulatory oversight

Regulatory oversight can be embedded into AI-enabled P2P markets through automated reporting, regulatory audit nodes, certified algorithms, consumer protection checks, programmable compliance constraints, and emergency intervention mechanisms. Uniform-price auction designs and local market models demonstrate that market rules shape outcomes before any trade occurs, making oversight a design-stage requirement rather than a post-market correction [22]. Smart contract systems similarly require governance for code updates, exception handling, and legal compatibility because automated execution does not remove regulatory responsibility [8]. **Table 2** presents an autonomy-oversight spectrum that links AI functions, regulatory touchpoints, and risk profiles across different market designs.

Table 2. Autonomy-Oversight Spectrum for AI-Enabled P2P Energy Markets

Autonomy Level	AI Functionalities	Regulatory Touchpoints	Risk Profile
Regulator-administered P2P sandbox	AI-assisted matching, supervised pricing, limited automated settlement	Pre-approved rules, participant caps, reporting templates, regulator review	Low innovation risk but limited decentralization and slower adaptation
Platform-mediated local market	Forecasting, recommendation engines, platform-controlled matching, automated billing	Platform licensing, consumer protection obligations, data governance rules	Moderate risk of platform dominance, opaque pricing, and unequal user influence
Rule-constrained autonomous agents	Automated bidding, preference learning, constraint-aware negotiation, smart contract execution	Certified algorithms, audit logs, compliance constraints, dispute procedures	Risk of strategic automation, explainability gaps, and algorithmic unfairness
Community-governed autonomous market	Peer reputation systems, local rule adaptation, AI-supported dispute triage	Community charters, regulator-visible ledgers, fairness reviews, opt-out rights	Risk of exclusion, reputation manipulation, inconsistent protection standards

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Fully automated decentralized market	Self-executing contracts, adaptive pricing agents, automated market rule evolution	Emergency off-switches, regulatory nodes, cybersecurity certification, ex post audits	High risk of manipulation, legal ambiguity, cascading failures, and weak accountability
Hybrid public-interest P2P market	AI market operation with embedded public-value constraints and human oversight	Regulatory APIs, real-time monitoring, prosumer rights, transparent governance boards	Balanced risk if oversight remains meaningful and not merely symbolic

Prosumer Empowerment Through AI

Dimensions of prosumer empowerment

Prosumer empowerment in AI-enabled P2P energy trading can be conceptualized through agency, economic benefit, information access, and participation. Agency concerns whether prosumers can set preferences, override automation, and understand how trading choices are made, while economic benefit concerns whether compensation reflects local value, flexibility, and risk exposure. Information access requires that AI interfaces translate complex market signals into understandable options rather than presenting opaque recommendations. Participation requires inclusive market design so that digitally skilled, asset-rich, or highly automated users do not capture disproportionate benefits.

AI tools for empowerment

AI tools could empower prosumers through personalized decision-support interfaces, automated negotiation agents, tariff comparison tools, flexibility forecasting, and explainable recommendation systems. Reviews of recent P2P advances show that participant engagement depends on usable market interfaces as well as technical exchange mechanisms [23]. AI agents may act on behalf of prosumers by learning comfort preferences, risk tolerance, willingness to trade, and desired community outcomes, but these agents should remain bounded by user-defined constraints. Empowerment therefore requires AI that assists choice rather than silently replacing it.

Risks of disempowerment

AI-enabled P2P markets may disempower prosumers if automation turns them into passive providers of data, flexibility, or surplus electricity while strategic control shifts to platforms and algorithm designers. The Brooklyn Microgrid case illustrates that local energy markets depend not only on technical exchange but also on institutional design, participant understanding, and community legitimacy [24]. If AI systems optimize trades without meaningful explanation, prosumers may lose the ability to evaluate whether participation serves their interests. **Table 3** distinguishes empowerment dimensions from the AI tools that could support them and the risks that could undermine them.

Table 3. Prosumer Empowerment Dimensions and AI-Driven Tools

Empowerment Dimension	AI-Driven Tool	Potential Benefit	Risk of Disempowerment
Agency	Preference-setting dashboards and user-controlled trading agents	Allows prosumers to define price limits, comfort boundaries, sustainability preferences, and participation levels	Automation may override user intent or encourage default settings that favor the platform
Economic benefit	AI-based price recommendation and flexibility	Helps prosumers identify when local generation, storage, or	Complex pricing may obscure fees, risks, or unequal benefit

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	valuation	demand response has market value	distribution
Information access	Explainable forecasts, plain-language trade summaries, and scenario comparison tools	Converts technical market signals into understandable choices	Simplified explanations may hide uncertainty, constraints, or algorithmic bias
Participation	Inclusive interfaces, multilingual support, and low-complexity trading modes	Reduces barriers for households with limited technical expertise	Digitally advanced users may still dominate trading opportunities
Collective influence	Community preference aggregation and participatory rule-setting tools	Supports energy communities in aligning trades with shared values	Majority preferences may marginalize vulnerable or minority participants
Contestability	Dispute support tools, audit trails, and automated evidence summaries	Enables users to question prices, settlements, and automated actions	Contestation may be ineffective if platform rules remain technically or legally inaccessible

Designing for meaningful human control

Meaningful human control requires that prosumers can authorize, constrain, pause, review, and contest AI-mediated trades. Peer-to-peer trading that includes network fees and power losses shows that apparently simple local exchange can involve technical costs that ordinary users may not fully observe [25]. AI interfaces should therefore make constraints visible, explain trade-offs, and provide understandable summaries before high-impact automated actions occur. Human control should not mean constant manual intervention, but it should guarantee informed delegation, reversible choices where feasible, and clear accountability.

Integrating the Four Dimensions

Synergies and conflicts

The four dimensions of the framework interact through both synergies and conflicts. Trust can support autonomy because participants are more likely to accept decentralized exchange when settlement, pricing, and data flows are reliable, yet excessive autonomy may weaken trust if AI decisions become opaque [26]. Regulatory oversight can protect prosumers, but overly rigid oversight may reduce local experimentation and limit the flexibility that P2P markets are designed to unlock. Prosumer empowerment can strengthen legitimacy, but it may also conflict with fully automated efficiency if meaningful choice slows or constrains market optimization.

Dynamic balancing through governance

Dynamic governance is needed because the appropriate balance among trust, autonomy, oversight, and empowerment may shift as markets mature, technologies change, and participant risks become clearer. Blockchain and smart-contract studies show that technical infrastructures require adaptive governance because rules encoded at one moment may become unsuitable as participation, regulation, or grid conditions evolve [7]. AI-enabled P2P markets should therefore include review cycles, model audits, participant feedback channels, and regulatory learning mechanisms. The framework treats governance as continuous recalibration rather than one-time certification.

Illustrative scenario

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A stylized AI-enabled P2P market could allow households with solar panels, batteries, and flexible loads to delegate limited trading authority to AI agents that operate within user-defined boundaries. The agents could recommend trades, negotiate locally, and execute approved contracts while smart ledgers record settlement and regulatory nodes monitor compliance [15]. A prosumer might accept a lower price for community supply during a local constraint event, while another might prioritize revenue, and the platform would need to explain how these preferences shape matching. This scenario illustrates how trust, autonomy, oversight, and empowerment can be integrated without assuming either full central control or unregulated automation.

Implementation pathways

Implementation could proceed through staged pilots that begin with supervised AI recommendations before moving toward constrained automated negotiation and settlement. Research on transactive energy and connected communities suggests that real-world adoption requires coordination among market design, grid operation, user participation, and institutional legitimacy [11]. Platform developers should first define rights, data flows, dispute procedures, and regulatory reporting before expanding algorithmic autonomy. Policymakers could then evaluate whether autonomy should be increased, restricted, or redesigned based on observed governance adequacy rather than assumed technical readiness.

Governance, Policy, and Implementation

Policy recommendations

Policy for AI-enabled P2P energy trading should combine regulatory sandboxes, algorithm certification, standard APIs, consumer protection rules, and transparent platform obligations. Legal analysis indicates that P2P electricity trading must be reconciled with existing electricity regulation, licensing, grid cost recovery, and consumer rights rather than treated as legally separate from the wider system [9]. Sandboxes could allow experimentation while requiring audit trails, opt-out rights, disclosure obligations, and mechanisms for handling failed trades or harmful automation. Regulators should also require that AI systems expose enough information for oversight without forcing disclosure of sensitive personal or commercially protected data.

Platform and market design implications

For platform designers, the framework implies that AI architecture should include modules for market operation, trust verification, regulatory reporting, and prosumer-facing explanation. Blockchain-enabled smart grids show that energy crowdsourcing and peer exchange require coordination between cyber infrastructure, market rules, and participant incentives [18]. A platform that optimizes only price and volume may fail if it neglects fairness, comprehensibility, and accountability. AI-enabled P2P platforms should therefore be designed as governed market infrastructures rather than neutral transaction engines.

Evaluation Strategy for the Framework

Conceptual soundness

The conceptual soundness of the framework can be evaluated by asking whether it captures the core tensions identified in P2P market theory, decentralized energy governance, and AI-mediated trading. Reviews of peer-to-peer trading emphasize that technical, economic, social, and regulatory challenges are interdependent, which supports the framework's four-dimensional structure [4]. Its validity would depend on whether trust, autonomy, oversight, and empowerment are sufficiently distinct to guide analysis while remaining connected enough to explain real governance trade-offs. Conceptual evaluation should therefore examine coherence, internal consistency, and the ability to classify different P2P market designs.

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Stakeholder relevance

Stakeholder relevance could be assessed through structured engagement with prosumers, regulators, platform developers, distribution system operators, consumer advocates, and energy communities. Studies of prosumer preferences show that willingness to participate in P2P trading depends on fairness, simplicity, social purpose, and perceived control, not merely on financial optimization. Regulators may prioritize legality and market integrity, while platform developers may focus on scalability and automation, so the framework should help translate these concerns into shared design language. Such validation would remain conceptual unless future research conducts empirical workshops or field studies.

Transferability

Transferability depends on whether the framework can be adapted across jurisdictions with different retail market rules, distribution network structures, energy community models, and data governance regimes. Peer-to-peer and community-based market reviews indicate that local energy trading can take many institutional forms, from bilateral exchange to community markets and platform-mediated systems [1]. The framework is intended to be flexible enough to apply to these forms while requiring context-specific interpretation of regulatory oversight and prosumer rights. Its transferability should therefore be assessed through comparative conceptual analysis rather than by assuming one universal P2P market model.

Limitations

Conceptual and unvalidated nature

The first limitation is that the article develops a conceptual framework without empirical testing, simulation, or field validation. Game-theoretic and market-design studies provide important foundations for thinking about incentives and coordination, but this article does not test whether the proposed governance relationships would produce specific trading outcomes [21]. The framework should therefore be read as a design-oriented analytical structure rather than a validated operational model. Future research would need to examine how its principles perform under real platform, regulatory, and prosumer conditions.

Technological and regulatory dynamism

The second limitation is that AI-enabled P2P trading is evolving rapidly as distributed ledgers, automated agents, smart contracts, and regulatory approaches continue to change. Smart-contract research shows that implementation models and governance challenges are still developing, which means that any framework must remain adaptable [8]. Regulatory expectations around consumer protection, cybersecurity, data access, and platform accountability may also shift as decentralized markets mature. The framework therefore requires periodic revision as technologies, market practices, and legal interpretations evolve.

Conclusion

AI-enabled P2P energy trading can be conceptualized as a governed decentralization process rather than a purely technical market innovation. The framework developed in this article positions trust, market autonomy, regulatory oversight, and prosumer empowerment as interdependent dimensions that must be designed together. Its central claim is that AI can support decentralized exchange only when its functions are made transparent, contestable, accountable, and aligned with public-interest obligations.

Balancing the four dimensions is essential because each can become problematic when pursued in isolation. Trust without autonomy may reproduce centralized dependence, autonomy without oversight may create legal and fairness

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risks, oversight without empowerment may become paternalistic, and empowerment without trustworthy infrastructure may remain symbolic. A viable AI-enabled P2P market must therefore combine algorithmic capability with institutional safeguards and meaningful prosumer control.

Future work should bring together energy market researchers, AI governance scholars, regulators, platform developers, distribution system operators, and prosumer communities. Interdisciplinary collaboration is needed to translate the framework into design standards, regulatory experiments, and participatory governance models. Such work should ensure that AI-enabled P2P energy trading advances decentralization without sacrificing fairness, legality, trustworthiness, or human agency.

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