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Artificial Intelligence in Blockchain-Based Energy Markets: Regulatory and Technological Perspectives

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ABSTRACT

The move to phase out fossil fuels has become a global priority, driven by the pressing need to address climate change and promote sustainable development. This shift is transforming energy systems from traditional centralised models into dynamic peer-to-peer (P2P) marketplaces. In these new ecosystems, prosumers (referring to individuals or entities that produce and consume energy) emerge as active participants who autonomously trade energy while leveraging distributed energy resources, fundamentally changing how we produce and consume power. At the forefront of this shift is the powerful combination of artificial intelligence (AI) and blockchain technology in P2P energy trading. Together, these innovations are reshaping decentralised energy systems, creating more scalable and resilient energy networks that grow from the ground up. This raises a crucial question: What are the key regulatory and technological issues arising from the integration of AI into blockchain-based energy trading systems, and how do these perspectives shape the future of such markets? As we explore this possibility, we uncover the remarkable potential of these technologies to fundamentally alter the energy sector while acknowledging both their promise and their challenges. The rapid progress of AI in this field presents a modern version of the tortoise and hare paradox. While technological innovation races ahead at breakneck speed, regulatory frameworks struggle to keep pace, creating growing gaps between what is technically possible and what is legally permitted. The barriers examined here are framed socio-legally, a crucial aspect that includes a holistic discussion of the broader tensions between technological architectures (AI and blockchain) and foundational principles of data protection, transparency, accountability, and energy governance. This area of study is a topic of significant importance in the current technological landscape.

Keywords: Artificial intelligence; Blockchain; Energy trading

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1. Introduction

The persistent shortcomings of traditional electrification models,[1] particularly in terms of affordability, reliability, and energy autonomy, necessitate a fundamental rethinking of energy security through decentralised solutions. We are witnessing a paradigm shift where technological innovation fosters greater inclusivity and resilience, challenging the dominance of institutional utilities, state monopolies, and third-party intermediaries that characterise conventional energy systems. This transformation reflects an evolution in energy governance, now shaped through dynamic, platform-mediated negotiations among diverse stakeholders who are increasingly taking control of their energy production and management.[2]

While many technologies rely on the 'human-in-the-loop' (HITL) mechanism, blockchain stands out as a revolutionary technology in the energy paradigm. Unlike HITL-dependent models, blockchain enables autonomous value creation without central intermediaries while still preserving accountability. This decentralised, distributed technology offers transformative potential for decentralised energy systems (DESs), particularly in managing distributed energy resources (DERs), issuing green certificates, optimising grid operations, and supporting peer-to-peer (P2P) energy trading platforms. When integrated with Internet of Things (IoT) devices that provide real-time operational data, blockchain applications become even more powerful and versatile, offering a promising vision for the future of energy technology.[3]

The convergence of artificial intelligence (AI) with blockchain-based P2P energy trading is reshaping the core of modern energy markets. This powerful combination enables the development of scalable, resilient energy ecosystems featuring real-time decision-making,

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[1] The term 'electrification models' is used in the plural to reflect the fact that electrification is pursued through multiple, distinct approaches, differing in governance structure, technological configuration, and policy objectives. For example, centralised, utility-led electrification, decentralised micro-grid models, and off-grid household electrification each constitute different models of delivering electricity access. Giampaolo Buticchi and others, 'Analysis of the Frequency-Based Control of a Master/Slave Micro-Grid' (2016) 10 The Institution of Engineering and Technology Renewable Power Generation 1570; Gregoire Jacquot and others, 'Reaching Universal Energy Access in Morocco: A Successful Experience in Solar Concessions' (2021) Massachusetts Institute of Technology Energy Initiative; Subhes C Bhattacharyya, 'Review of Alternative Methodologies for Analysing Off-Grid Electricity Supply' (2012) 16 Renewable and Sustainable Energy Reviews 677.

[2] Mohsen Khorasany and others, 'A New Method for Peer Matching and Negotiation of Prosumers in Peer-To-Peer Energy Markets' (2020) 12 Institute of Electrical and Electronics Engineers Transactions on Smart Grid 2472.

[3] Sanjeev Kumar Dwivedi and others, 'Blockchain-Based Internet of Things and Industrial IoT: A Comprehensive Survey' (2021) 2021 Security and Communication Networks 1; Claudia Pop and others, 'Blockchain-Based Scalable and Tamper-Evident Solution for Registering Energy Data' (2019) 19(14) Sensors 3033; Yue Qi and others, 'Research of Energy Consumption Monitoring System Based on IoT and Blockchain Technology' (2021) 1757 Journal of Physics: Conference Series 012154.

automated smart contracts, and secure distributed data exchange.[4] AI significantly enhances blockchain-powered P2P systems through dynamic supply-demand matching, intelligent pricing optimisation, and improved market responsiveness.[5] By processing data streams from smart meters, IoT networks, and other digital infrastructure, AI algorithms extract meaningful patterns from energy trading behaviours, transforming raw data into predictive insights and actionable intelligence.

These AI-enhanced systems process multidimensional data in real-time, incorporating meteorological information, grid status updates, and market fluctuations to enable autonomous trading decisions and sophisticated demand-side management.[6] The integration of predictive analytics into decentralised platforms not only boosts operational efficiency but fundamentally reconfigures relationships between energy producers, consumers, and traditional intermediaries. The result is a more responsive, adaptive, and democratised energy marketplace that points toward a transformative future for energy technology.

However, the integration of AI invites renewed scrutiny of regulatory frameworks, data governance norms, and the distribution of control within energy infrastructures that were conventionally centralised. AI technologies may obscure data processing and use pathways, resulting in a lack of transparency.[7] There are difficulties in interpreting or predicting their internal decision-making processes. This lack of explainability risks creating discriminatory outcomes and undermining the democratic principles that motivate decentralised energy systems. Furthermore, AI systems create persistent data storage challenges, as completely erasing information often requires specialised overwriting procedures rather than simple deletion.[8]

The security implications are equally significant, as these complex computational systems present dual risks: they can be both targets for sophisticated cyberattacks and potential tools for malicious actors.[9] Such vulnerabilities threaten the fundamental principle of energy security, which is a reliable and consistent power supply for all consumers.

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[4] Weiqi Hua and others, 'Applications of Blockchain and Artificial Intelligence Technologies for Enabling Prosumers in Smart Grids: A Review' (2022) 161 Renewable and Sustainable Energy Reviews 112308.

[5] Kelvin Edem Bassey, Shahab Anas Rajput and Kabir Oyewale, 'Peer-To-Peer Energy Trading: Innovations, Regulatory Challenges, and the Future of Decentralized Energy Systems' (2024) 24(2) World Journal of Advanced Research and Reviews 172.

[6] Alexander A Hernandez and others, 'Peer-To-Peer Energy Resource Sharing in Rural Communities: Enabling Technologies, Applications, and Challenges' (2025) 13(13) Institute of Electrical and Electronics Engineers Transactions Access.

[7] Alexander Buhmann and Christian Fieseler, 'Towards a Deliberative Framework for Responsible Innovation in Artificial Intelligence' (2021) 64 Technology in Society 101475.

[8] Aleksandr Kesa and Tanel Kerikmae, 'Artificial Intelligence and the GDPR: Inevitable Nemeses?' (2020) 10(3) TalTech Journal of European Studies 68.

[9] Ekene Cynthia Onukwulu and others, 'The Role of Blockchain and AI in the Future of Energy Trading: A Technological Perspective on Transforming the Oil and Gas Industry by 2025' (2023) 5(2) International Journal of Advanced Multidisciplinary Research and Studies 48.

Both developed and developing nations face similar regulatory hurdles in implementing AI-enabled P2P energy trading, given the nascent state of relevant institutional frameworks. This includes the definitional conundrum regarding the rights, responsibilities, and liabilities of both prosumers and the algorithmic agents that facilitate autonomous trading.[10] Furthermore, the absence of non-discriminatory prosumer access to the public grid and proper network tariff methodologies undermines the efficiency gains promised by AI-optimised P2P trading, as they hinder the emergence of responsive pricing mechanisms.[11] Lastly, technological barriers, namely high initial execution costs, the lack of interoperability and standardised protocols, and the absence of high-quality energy data, complicate the training and deployment of AI models, highlighting the complexity and challenges of integrating AI into energy policies.[12]

This paper aims to underscore the potential that AI holds in blockchain-powered peer-to-peer energy trading systems. AI, with its ability to analyse large datasets and make real-time decisions, could revolutionise energy trading. This research raises the question: What are the key regulatory and technological issues arising from the integration of AI into blockchain-based energy trading systems, and how do these perspectives shape the future of such markets? To unpack this question, we look at the following sub-questions:

(i) How can the integration of AI in blockchain-based systems facilitate peer-to-peer energy trading frameworks?

(ii) How do regulatory and technological factors affect the adoption of AI in blockchain-based peer-to-peer energy trading?

This research adopts a socio-legal approach to examine the regulatory and technological factors influencing AI adoption in blockchain-enabled energy systems in a social context. AI-blockchain energy applications operate across multiple regulatory domains, including energy law, data protection, cybersecurity, transparency, accountability, and emerging AI governance, none of which were designed for these integrated technologies. Socio-legal research examines law within its operational context, which refers to the practical application of law in real-world situations. The 'socio' element refers not simply to sociology but to law's interface with the contexts within which it operates, which is essential when examining decentralised energy systems that challenge traditional regulatory boundaries and require understanding how technological innovation intersects with legal frameworks,

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[10] Stefan Englberger and others, 'Evaluating the Interdependency Between Peer-To-Peer Networks and Energy Storages: A Techno-Economic Proof for Prosumers' (2021) 3 Advances in Applied Energy 100059; Michael J Fell, 'Anticipating Distributional Impacts of Peer-To-Peer Energy Trading: Inference From a Realist Review of Evidence on Airbnb' (2021) 2 Cleaner and Responsible Consumption 100013; Thomas Morstyn, Iacopo Savelli and Cameron Hepburn, 'Multiscale Design for System-Wide Peer-To-Peer Energy Trading' (2021) 4(5) One Earth 629.

[11] Karisma Karisma and Felicity Deane, 'Empowering Energy: Legal and Regulatory Perspectives on Blockchain-Enabled Trading in Malaysia and Australia' (2024) 11(4) Asian Journal of Law and Society 507.

[12] Musa Adekunle Adewoyin, Olugbenga Adediwin and Audu Joseph, 'Artificial Intelligence and Sustainable Energy Development: A Review of Applications, Challenges, and Future Directions' (2025) 6(2) International Journal of Multidisciplinary Research and Growth Evaluation 196.

market structures, and policy objectives.[13] This approach, unlike doctrinal analysis, does not confine analysis to legal texts. Instead, it combines social science methods with legal analysis, treating law as embedded within broader social, technological, and regulatory systems.

A socio-legal approach allows examination of how existing regulatory structures interact with technological innovation, identifying gaps and tensions that purely doctrinal analysis would miss. This methodology is particularly valuable for emerging technologies like AI in blockchain energy systems, where legal frameworks are still developing and where regulatory responses vary significantly across jurisdictions. By focusing on the social and regulatory context, a socio-legal approach can provide a more comprehensive understanding of the challenges and opportunities presented by these technologies.

2. Enhancing Energy Security Through Decentralised Energy Systems

The global imperative to phase out fossil fuels stems from the urgent need to mitigate anthropogenic climate change and advance sustainable development. The combustion and extraction of fossil fuels, such as oil, coal, and natural gas, are intrinsically linked to environmental degradation and an increase in greenhouse gas emissions.[14] Overreliance on fossil fuels and extensive exploitation have underscored their unsustainability in terms of environmental degradation and geopolitical vulnerabilities, prompting the global community to reassess the energy landscape.[15]

Furthermore, consistent overdependence exacerbates energy poverty by intensifying the challenges of energy affordability and accessibility,[16] particularly in the Global South, a term used to refer to the less economically developed countries in Africa, Asia, and Latin America. Marginalised communities bear a disproportionate burden as they often struggle to obtain reliable and affordable access. The systemic inequalities have catalysed a growing consensus in facilitating a resilient, equitable, and diversified low-carbon energy paradigm. International agreements and multilateral initiatives have significantly elevated global awareness of the climate crisis. A landmark development is the United Nations Framework Convention on Climate Change, an international treaty adopted in 1992. The treaty institutionalises global cooperation on climate mitigation and adaptation while

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[13] Sally Wheeler and PA Thomas, 'Socio-Legal Studies' in DJ Hayton (eds), *Law(s) Futures*, (Oxford, Hart Publishing 2000); Reza Banakar and Max Travers, *Theory and Method in Socio-Legal Research*, (Bloomsbury Publishing 2005).

[14] Md Abubakkor Siddik and others, 'Current Status and Correlation of Fossil Fuels Consumption and Greenhouse Gas Emissions' (2021) 28(2) International Journal of Energy Environ Econ 103.

[15] Daquan Gao, Songsong Li and Zhihong Tian, 'Geopolitical Risk, Energy Market Volatility, and Corporate Energy Dependence: The Role of Green Total Factor Productivity and Decentralized Top Management Team Network' (2025) 148 Energy Economics 108545; Mustafa Tevfik Kartal and others, 'Impact of Renewable and Fossil Fuel Energy Consumption on Environmental Degradation: Evidence From USA by Nonlinear Approaches' (2022) 29 International Journal of Sustainable Development and World Ecology 738.

[16] Gonzalo H Soto and Xavier Martinez-Cobas, 'Green Energy Policies and Energy Poverty in Europe: Assessing Low Carbon Dependency and Energy Productivity' (2024) 136 Energy Economics 107677.

acknowledging the joint responsibility and shared accountability of countries to ensure that governance responses are not only practical and coordinated but also aligned with the socio-economic development priorities of countries.[17]

Aligned with the shift to low-carbon setups, energy security is a central priority for all nations, encompassing four integrated dimensions: availability, affordability, accessibility, and acceptability.[18] Availability refers to the presence and continuity of energy supply, which is critical for economic and social workings.[19] Affordability is salient for developing nations, as volatility in energy prices can trigger and destabilise economies.[20] Furthermore, the rising energy costs burden low-income and marginalised households. Accessibility pertains to the reliability and equitable distribution of energy across spatial and socio-economic contexts.[21] Finally, acceptability pertains to environmental and societal implications, requiring alignment with international norms, global sustainability standards and public expectations.[22] High energy security plays a critical role in enhancing economic competitiveness and facilitating commercialisation outcomes, particularly in energy-intensive areas.

A reliable, sustainable, and cost-effective energy framework is crucial for attracting high-value technological investments, spurring innovation, and fostering new business models. Hence, robust energy security not only strengthens industrial efficiency but is also a key determinant of long-term economic growth and attractive investment opportunities. Ensuring energy security is not merely a policy or economic imperative but also an essential social one, as it underpins the vital services and infrastructure that modern life depends on. Energy disruptions can significantly impact the quality of life and social inclusion.

Decentralised energy systems (DESs), fuelled by the rise of decentralised technologies, offer robust models to (a) enhance energy security, (b) augment the decarbonisation process, and (c) achieve economic, environmental, and social benefits.[23] While nationalised industries

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[17] Alaa Mohammed Hassan and Saif Nussrat Tawfeeq, 'The Role of the United Nations in Mitigating Global Climate Change' (2023) 11 Russian Law Journal 521.

[18] Ayyoob Sharifi and Yoshiki Yamagata, 'Principles and Criteria for Assessing Urban Energy Resilience: A Literature Review' (2016) 60 Renewable and Sustainable Energy Reviews 1654.

[19] Bert Kruyt and others, 'Indicators for Energy Security' (2009) 37 Energy Policy 2166; Jingzheng Ren and Benjamin K Sovacool, 'Quantifying, Measuring, and Strategizing Energy Security: Determining the Most Meaningful Dimensions and Metrics' (2014) 76 Energy 838.

[20] Larry Hughes, 'A Generic Framework for the Description and Analysis of Energy Security in an Energy System' (2012) 42 Energy Policy 221; Ren and Sovacool, 'Quantifying, Measuring, and Strategizing Energy Security: Determining the Most Meaningful Dimensions and Metrics' (2012) 42 Energy Policy 221.

[21] Saskia Lavrijssen and Arturo Carrilo, 'Radical Innovation in the Energy Sector and the Impact on Regulation' (2017) Social Science Research Network Energy Law and Policy eJounal.

[22] Aleh Cherp and Jessica Jewell, 'The Concept of Energy Security: Beyond the Four As' (2014) 75 Energy Policy 415; Ren and Benjamin (n 19).

[23] Ksenia Chmutina and Chris I Goodier, 'Case Study Analysis of Urban Decentralised Energy Systems' (2013) International Conference on Technology Transfer and Renewable Energy 501; Aran Eales, 'Global Perspectives on Community Energy for a Just Transition: The Case for UK-Africa Community Energy Twinning' (University of Strathclyde, July 2024).

have long dominated energy markets, politicising them through top-down utilities and creating monopolistic structures that are difficult to penetrate.[24] Centralised control has regulated energy value chains for decades, but the transition toward decentralisation through bottom-up initiatives introduces radical and unprecedented disruptions.

3. Reimagining Peer-To-Peer Energy Trading Through Blockchain Technology and the Integration of AI

3.1 Blockchain-Based Peer-To-Peer Energy Trading

Blockchain redefines the foundations of trust by embedding cryptographically verifiable mechanisms and incentive-driven protocols within its technical architecture to facilitate 'trustless trust'. It establishes a framework where it can generate consensus on the validity of transactions without relying on centralised authorities or third-party intermediaries.[25] Operating through a distributed system of nodes and publicly accessible proofs, blockchain eliminates the need to designate a sole actor as the custodian of trust. Through mechanisms such as cryptographic validation and consensus protocols, it enables secure, autonomous, and synchronised interactions among participants, eliminating the need for prior trust relationships or mechanisms.[26]

Blockchain's distinct technological features, such as decentralisation, autonomy, transparency, auditability, permanence, immutability, and anonymity of data records, as well as real-time digital transactions, function in concert to profoundly reshape a wide array of business operations, transactional frameworks, and organisational models.[27] The potential of blockchain to reshape these aspects is not just a theoretical concept but a practical reality that is already being witnessed in various industries, including the energy sector.[28]

To provide a comprehensive analysis within this paper, it is essential to illustrate how these characteristics displace conventional trust mechanisms. Equally important is the inquiry into whether blockchain's structural design, inherent capabilities, and defining traits are adequately compatible with the operational and regulatory demands of the energy sector.

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[24] Karisma and Deane (n 11).

[25] Natalia Chaudhry and Muhammad Murtaza Yousaf, *Consensus Algorithms in Blockchain: Comparative Analysis, Challenges and Opportunities* (Institute of Electrical and Electronics Engineers 2018).

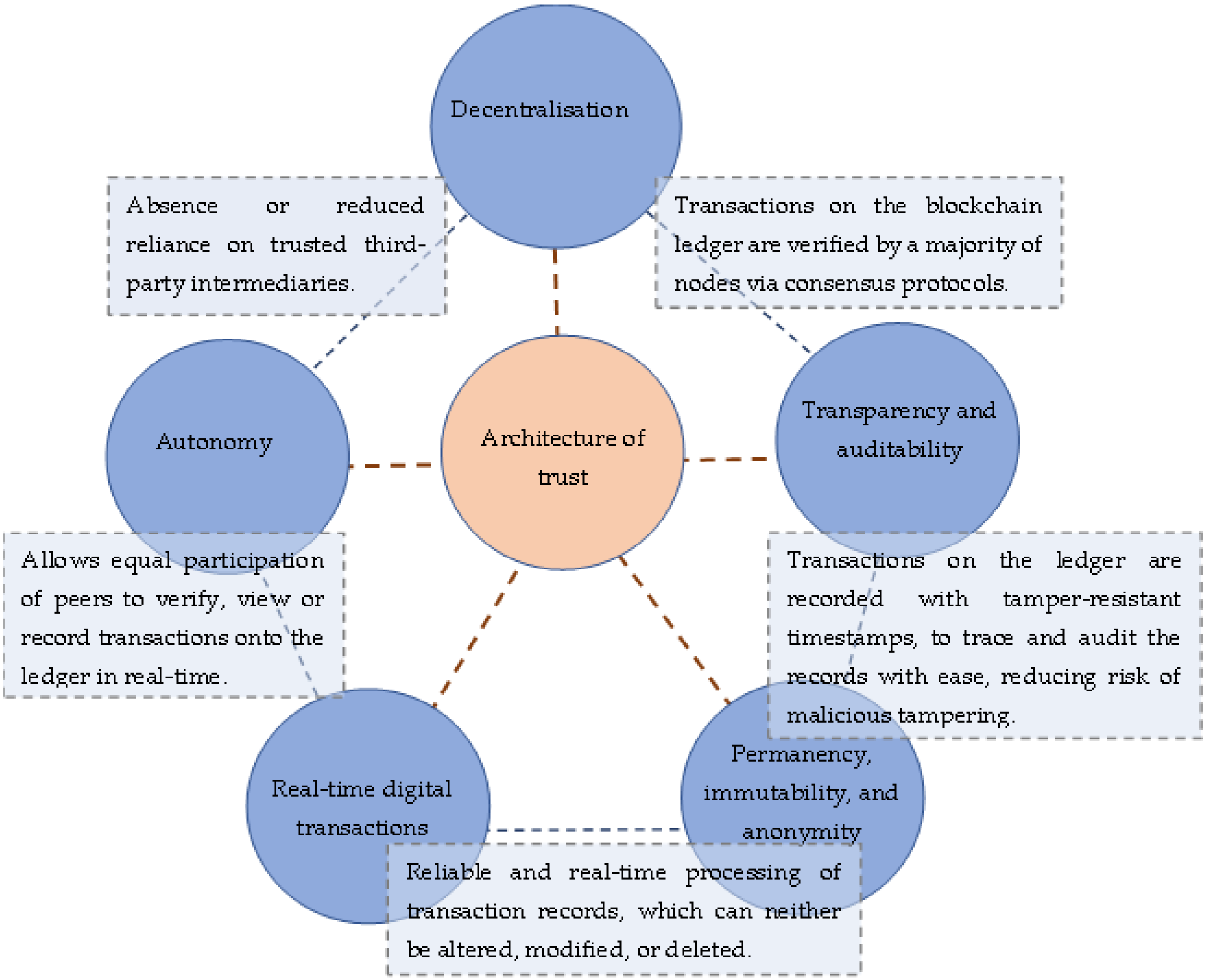
[26] Merlinda Andoni and others, 'Blockchain Technology in the Energy Sector: A Systematic Review of Challenges and Opportunities' (2019) 100 Renewable and Sustainable Energy Reviews 143; Simona-Vasilica Oprea and Adela Bara, 'Devising a Trading Mechanism With a Joint Price Adjustment for Local Electricity Markets Using Blockchain. Insights for Policy Makers' (2021) 152 Energy Policy 112237; Ernest Barcelo and others, 'Regulatory Paradigm and Challenge for Blockchain Integration of Decentralized Systems: Example—Renewable Energy Grids' (2023) 15(3) Sustainability 2571.

[27] Shi Dong and others, 'Blockchain Technology and Application: An Overview' (2023) 9 PeerJ Computer Science e1705.

[28] Andoni and others (n 26).

3.2 Blockchain as an Architecture of Trust

Blockchain's transformative potential hinges on the following core features.



(Source: Author's own)

3.2.1 Decentralisation

Conventional business models typically rely on centralised infrastructures and trusted intermediaries to verify and validate transactions between parties. However, the emergence of blockchain technology has introduced a paradigm shift, placing decentralisation at the core of its functionality. Unlike traditional systems, where data is stored in a centralised node, blockchain distributes transactional records across all nodes in the network, ensuring simultaneity and synchronised data access. These remove the need for institutional gatekeepers or centralised authorities, thereby reducing intermediary and transactional costs associated with intermediary oversight.[29] In the context of transitioning to renewable energy

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[29] Md Ashraf Uddin and others, 'A Survey on the Adoption of Blockchain in IoT: Challenges and Solutions' (2021) 2(2) Blockchain: Research and Applications 100006.

(RE), maintaining energy affordability and accessibility for all consumer segments is a fundamental concern.

Centralised RE infrastructures introduce high intermediary costs, which undermine affordability and equitable access. Furthermore, such infrastructures are vulnerable to single points of failure and are increasingly susceptible to cyber-attacks, thereby compromising their overall resilience.[30] In contrast, decentralised energy infrastructures are emerging as a promising alternative due to their modularity and flexibility. From this discussion, while centralised systems have long been favoured for their operational efficiencies, the evolving landscape of renewable energy and increased exposure to physical and cyber vulnerabilities drive a shift towards decentralised, more resilient energy systems.[31]

Decentralised approaches can more effectively address peak demand loads and foster energy resilience through independence and adaptability by reducing dependence on large, interconnected systems.[32] Blockchain-enabled, decentralised energy systems present a transformative opportunity, enabling prosumers to manage renewable energy (RE) infrastructures more effectively. Blockchain's decentralised architecture supports real-time matching of energy supply and demand through automated bid and offer mechanisms, enabling transparent and real-time broadcasting of transaction data to all participants within the network.[33] This feature of blockchain not only ensures the security of transactions but also enhances the efficiency of the energy trading process, thereby instilling confidence in the audience about the potential of blockchain technology.

3.2.2 Transparency

Generally, blockchain leverages an open-source framework embedded with transparency to ensure data integrity and trust while minimising the risks of malicious tampering with records. Network peers can assess, view, and trace transactions on the blockchain ledger to facilitate transparency.[34] Further, new blocks are generated by verifying and confirming the majority of nodes via consensus protocols. Peer-to-peer energy trading is a compelling use case that presents a transformative approach to energy distribution, furthering the development of Distributed Energy Systems (DESs).

The pivotal question is whether a foolproof system can record energy transactions between peers transparently and audibly. The question follows: Are these features readily

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[30] Dinh C Nguyen and others, 'Blockchain for 5G and Beyond Networks: A State of the Art Survey' (2020) 166 Journal of Network and Computer Applications 102693.

[31] Horst Treiblmaier, 'Blockchain and Tourism: Paradoxes, Misconceptions, and a Research Roadmap' (2020) 28(7) Tourism Economics 1956.

[32] Shivam Saxena and others, 'Design and Field Implementation of Blockchain-Based Renewable Energy Trading in Residential Communities' (2nd International Conference on Smart Grid and Renewable Energy 2019).

[33] Andoni and others (n 26).

[34] Jigar Mehta, Nikunj Ladvaiya and Vidhi Pandya, 'Exploration of Blockchain Architecture, Applications, and Integrating Challenges' in A Pasumpon Pandian, Xavier Fernando and Syed Mohammed Shamsul Islam (eds), *Computer Networks, Big Data and IoT* (vol 66, Springer 2021).

realised through other mechanisms and platforms? This research argues that transparency and auditability are essential blockchain features that prevent information asymmetry, which can potentially increase transaction costs. Since every transaction on a blockchain ledger is recorded with a tamper-resistant timestamp, participants can easily trace and audit peer-to-peer energy transactions in real time without needing to confirm or reconcile records.[35]

Furthermore, while existing digital registries may be equally effective in certain situations, they often do not provide the same level of security and transparency as blockchain in a cost-effective manner. In such registries, data manipulation risks and the lack of transparency remain pertinent. Peer-to-peer energy trading, a cornerstone of Distributed Energy Systems (DES), is significantly enhanced by blockchain technology. Prosumers and consumers can conduct energy transactions smoothly, effectively, and flexibly on a virtual basis, given the interoperability and transparency features.[36] This blockchain-powered peer-to-peer energy trading system is likely to gain traction by enabling decentralised market participation, enhancing prosumer agency, and reshaping traditional energy value chains from top-down to bottom-up transitions. Similarly, blockchain-assisted DER management systems (DERMS) improve robustness, transparency, and system reliability, leveraging broader DER applications by addressing the challenges faced in centralised DERMS.[37] It primarily ensures the delivery of critical information, such as DER data status and control commands, securely through blockchain nodes, facilitating broader and more secure applications of DERs within the grid.

3.2.3 Autonomy

Blockchain operates as a self-regulating system maintained by a decentralised network of participants without requiring oversight from centralised intermediaries. In public blockchain systems, all network peers possess equal rights to join, verify, view, or record transactions. As blockchain technologies become increasingly integrated into energy markets, new business models are emerging that grant prosumers enhanced control over their participation. This includes the ability to independently or collaboratively trade energy and offer electricity-related services without the involvement of intermediaries. For instance, prosumers can increasingly act as providers of DERs by engaging in asset-sharing schemes to facilitate access to unused energy assets through sharing platforms.

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[35] Srinath Perera and others, ‘Blockchain Technology: Is It Hype or Real in the Construction Industry?’ (2020) 17 Journal of Industrial Information Integration 100125.

[36] Jiabin Bao and others, ‘A Survey of Blockchain Applications in the Energy Sector’ (2021) 15(3) Institute of Electrical and Electronics Engineers Systems Journal 3370; Karisma and Deane (n 11).

[37] Seerin Ahmad and others, ’Blockchain-Assisted Resilient Control for Distributed Energy Resource Management Systems’ (2024) 12 Institute of Electrical and Electronics Engineers 191748.

3.2.4 Permanency, Immutability, and Anonymity of Data Records

Once data is recorded on a blockchain ledger, it becomes immutable, meaning it is resistant to modification, deletion, or alteration.[38] Each block containing transactional data is timestamped and cryptographically secured through hash functions. The integrity of the chain is preserved by embedding the hash of the previous block into each subsequent one, creating an interlinked structure.[39] These features can ensure data integrity and trust among blockchain participants. Despite the advantages, the same attributes, namely, immutability and irreversibility, may lead to unfavourable outcomes.

In the event of an error or compliance violation the distributed networks execute automatically, potentially disregarding the parties' contractual intention.[40] Therefore, it is imperative to design blockchain frameworks that mitigate these risks and enhance scalability and processing capacity. The anonymity of shared data is preserved through cryptography. Blockchain systems employ asymmetric encryption using a pair of public and private keys, enhancing resilience against centralised points of failure and external security breaches.[41] More importantly, participant identities within the blockchain network are decoupled from their real-world counterparts.[42]

The emergence of blockchain has captured the attention of platform providers, technology developers, start-ups, and prosumers as they navigate the transformative potential it holds for energy systems. In the coming decade, we are witnessing a paradigm shift toward decarbonisation, decentralisation, and digitisation in energy systems, creating an urgent need to address the intricacies of global governance instruments. These material features, salient qualities, and characteristics are a primary impetus for improving the operability, performance scalability, and functionality of decentralised energy systems.

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[38] Wattana Viriyasitavat and Danupol Hoonsopon, 'Blockchain Characteristics and Consensus in Modern Business Processes' (2019) 13 Journal of Industrial Information Integration 32; Alex Marthews and Catherine Tucker, 'What Blockchain Can and Can't Do: Applications to Marketing and Privacy' (2023) 40(1) International Journal of Research in Marketing 49.

[39] Mallikarjun Reddy Dorsala, VN Sastry and Sudhakar Chapram, 'Blockchain-Based Solutions for Cloud Computing: A Survey' (2021) 196 Journal of Network and Computer Applications 103246.

[40] Joseph Lee and Vere Marie Khan, 'Blockchain and Smart Contract for Peer-to-Peer Energy Trading Platform: Legal Obstacles and Regulatory Solutions' (2020) 19(4) University of Illinois Chicago Review of Intellectual Property Law 159.

[41] Arshdeep Singh and others, 'A Survey and Taxonomy of Consensus Protocols for Blockchains' (2022) 127 Journal of Systems Architecture 102503.

[42] Hsiang-Jen Hong and others, 'Robust P2P Networking Connectivity Estimation Engine for Permissionless Bitcoin Cryptocurrency' (2022) 219 Computer Networks 109436.

3.3 Convergence of AI in Blockchain-Driven Energy Trading Systems

3.3.1 Defining AI

Defining AI is an inherently complex and contested task, as conceptualisations of AI vary widely across disciplines and regulatory contexts. This interdisciplinary nature of AI, which spans various fields, is a testament to the breadth and depth of its impact, making it a fascinating and far-reaching subject. Researchers have yet to reach a consensus on its precise definition.

Some definitions conceptualise AI as a field of science, with John McCarthy famously describing it as 'the science and engineering of making intelligent machines, especially intelligent computer programs'. He further defines intelligence as the 'computational part of the ability to achieve goals in the world'.[43] Similarly, Nilsson characterises AI as being concerned with 'making machines intelligent, [where] intelligence is that quality that enables an entity to function appropriately and with foresight in its environment'.[44]

Building on this, scholars such as William Rapaport have contextualised AI within computer science, positioning its role in exploring which problems and tasks can be computationally addressed and how algorithmic solutions can be developed to do so 'efficiently, practically, physically, and ethically'.[45] Others centre on the degree of autonomy that characterises AI systems. For instance, Scherer emphasises autonomous decision-making as the distinguishing feature of AI compared to earlier computational technologies. Several perspectives link AI to human-like intelligence, attributing to it characteristics such as reasoning, perception, and language processing.

The Oxford English Dictionary defines AI as 'the theory and development of computer systems able to perform tasks normally requiring human intelligence, such as visual perception, speech recognition, decision-making, and translation between languages'.[46] This widely cited definition offers a foundational understanding of AI's purpose, which involves emulating human cognitive functions through computational means. Similarly, it is often described as encompassing machines that perform tasks which, if executed by humans, would require intelligence. While the definitional debate continues, it is essential to recognise the growing societal and regulatory significance of AI, necessitating a coherent and context-sensitive legal articulation.

Stuart Russell and Peter Norvig famously define AI as the study of 'intelligent agents'. Agent means 'a software system which perceives its environment through sensors and acts

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[43] John McCarthy, 'What is Artificial Intelligence?' (Stanford University 2007).

[44] Nils J Nilsson, *The Quest for Artificial Intelligence* (Cambridge University Press 2009).

[45] Nilsson (n 44).

[46] *Artificial Intelligence, Oxford Dictionaries* (2nd edn, OUP 2006) <https://premium-oxforddictionaries-com.ezproxy.um.edu.my/definition/english/artificial-intelligence?q=artificial+intelligence&searchDictCode=all>.

upon that environment through actuators'.[47] This emphasis on the practical applications of AI is inspiring, given its potential. AI's ability to select actions that maximise performance measures raises ethical concerns, particularly when these actions impact human lives.

The agent-based definition of AI, which frames intelligence as a range of capabilities and optimal actions to improve performance in a given environment, can be operationalised through an array of computational techniques such as reinforcement learning, supervised learning, and unsupervised learning. This definition offers a sound theoretical understanding of AI while also highlighting the importance of incorporating ethical considerations into the development and deployment of AI systems, underscoring the responsibility and impact of AI on society. Agentic AI builds upon this foundational agent-based conception by extending these capabilities. Agentic AI represents a transformative advancement in energy systems, where AI operates with autonomous decision-making capabilities. These self-learning systems exhibit goal-directed behaviour, dynamically interacting with energy infrastructure to optimise efficiency and minimise costs through independent action.[48] Agentic systems make context-aware decisions that continuously adapt to evolving grid conditions, enabling them to autonomously optimise energy generation, consumption, trading, and distribution without human oversight.

A key strength of Agentic AI is in its collaborative potential.[49] Multiple intelligent agents can work in concert to manage decentralised grids, balance intermittent renewable inputs, and respond to real-time fluctuations in energy demand. Through continuous grid monitoring and predictive analytics, these systems dynamically coordinate energy flows while anticipating usage patterns, substantially enhancing grid efficiency, resilience, and sustainability.[50]

3.3.2 Leveraging AI in Blockchain-Driven Systems to Revolutionise Energy Markets

Integrating AI-driven trading intelligence with blockchain-based mechanisms presents a transformative opportunity for peer-to-peer (P2P) energy markets. This convergence ensures scalable and operationally efficient trading environments, enabling real-time decision-making, automated transactions, and secure data exchange, thereby supporting the evolution of decentralised, digitalised, and resilient energy systems.

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[47] Stuart J Russell and Peter Norvig, *Artificial Intelligence: A Modern Approach* (Pearson 2016).

[48] Soodeh Hosseini and Hossein Seilani, 'The Role of Agentic AI in Shaping a Smart Future: A Systematic Review' (2025) 26 Array 100399.

[49] Laurie Hughes and others, 'AI Agents and Agentic Systems: A Multi-Expert Analysis' (2025) 65(4) Journal of Computer Information Systems 489.

[50] Qian Zhang and Le Xie, 'PowerAgent: A Roadmap Towards Agentic Intelligence in Power Systems: Foundation Model, Model Context Protocol, and Workflow' (2025) 23(5) Institute of Electrical and Electronics Engineers Power and Energy Magazine 93.

Blockchain enables real-time monitoring, processing, audit, verification, and validation of transaction records stored permanently on a blockchain ledger.[51] AI plays a pivotal role in increasing the operability of blockchain-powered peer-to-peer energy trading systems by improving the efficiency of matching energy availability with consumer needs and adjusting prices accordingly.[52] AI optimisation algorithms can infer and analyse energy production, consumption, and trading data gathered from smart meters, IoT devices, and other supporting infrastructures to facilitate real-time and precise energy demand and supply forecasting.[53] This ensures responsive energy allocation tailored to consumption profiles and instantaneous energy demand. These are essential components to contribute to the dynamic optimisation of energy transactions.

The integration of AI into energy trading systems enables advanced functionalities, including dynamic and optimal pricing models and demand-side response optimisation through reinforcement learning.[54] More importantly, AI empowers the system with the ability to make predictive adjustments to trading parameters, showcasing its adaptability and forward-thinking nature. This empowerment is a promising sign for the future of energy trading and fair and equitable distribution of energy.

AI-enabled transactive energy systems play a pivotal role in the energy sector by ingesting historical and real-time and multidimensional energy market data from diverse sources.[55] These sources include energy supply and demand trends, political developments, collective market behaviours, and trading participants' sentiments.[56] AI enhances trading efficiency by providing informed and actionable insights to trading participants and facilitating a shift from intuition to algorithmic driven decision making with improved accuracy and speed.[57] By continuously optimising trading strategies and identifying arbitrage opportunities, AI further enhances trading efficiency and mitigates exposure to market volatility. In decentralised energy system contexts, particularly those powered by blockchain, these capabilities contribute to seamless energy transactions and increased profitability.

While blockchain offers a transparent and immutable ledger that deters fraudulent conduct, such as double spending or tampering, it does not eliminate all sophisticated

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[51] Yanjun Zuo and Zhenyu Qi, ‘A Blockchain-Based IoT Framework for Oil Field Remote Monitoring and Control’ (2021) 10 Institute of Electrical and Electronics Engineers 2497.

[52] Bassey, Rajput and Oyewale (n 5).

[53] Bassey, Rajput and Oyewale (n 5).

[54] Pravesh Raghoo and Kalim Shah, ‘Bridging Theory and Practice in Peer-To-Peer Energy Trading: Market Mechanisms and Technological Innovations' (2025) 5(1) Environmental Research: Infrastructure and Sustainability.

[55] Mohammad Parhamfar, Iman Sadeghkhani and Amir Mohammad Adeli, ‘Towards the Net Zero Carbon Future: A Review of Blockchain-Enabled Peer-To-Peer Carbon Trading’ (2024) 12(3) Energy Science and Engineering 1242; Badr Lami and others, ‘A Smart Microgrid Platform Integrating AI and Deep Reinforcement Learning for Sustainable Energy Management’ (2025) 18 Energies 1157.

[56] Onukwulu (n 9).

[57] Onukwulu (n 9).

attacks.[58] AI analytical functionality complements blockchain in detecting anomalies present in decentralised energy trading systems, such as inefficiencies in energy systems, sudden price spikes, and abnormal trade volumes, that could indicate potential fraud.[59] It also enhances the robustness of fraud detection frameworks by identifying any irregularities and deviations in real time that may indicate fraudulent conduct, allowing for immediate and effective intervention. The system intervenes instantly, triggering alerts the moment something is amiss, enabling a swift response before any damage can spread. Such real-time detection capabilities offer blockchain-powered energy trading systems greater stability, integrity, and resilience.

Negotiation-based mechanisms offer a distinctly decentralised model of peer-to-peer energy trading. These transactions can be autonomously executed through AI-driven negotiation autonomous agents, which simulate and automate strategic bargaining processes between participants.[60] Unlike centralised intermediaries that traditionally set energy prices, this approach empowers localised participants to initiate offers. To operationalise such negotiations, participants exchange key transactional parameters, including energy quantity, transactional timing, and pricing, with their counterparty, thereby communicating individual preferences and transaction parameters with precision.[61] This decentralised architecture enhances the system's responsiveness by allowing real-time adjustment of terms to reflect such preferences of trading parties. Consequently, negotiation-based trading fosters customisation and market inclusivity, reinforcing the potential for a fully decentralised and participatory energy marketplace.[62]

Network load applications result in increased costs of capital, overhead, and grid investments and reinforcements. AI ensures efficient load management, enabling the smoother integration of distributed energy resources (DERs) and maintaining grid

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[58] Andoni and others (n 26); Manish Kumar Thukral, 'Emergence of Blockchain-Technology Application in Peer-To-Peer Electrical-Energy Trading: A Review' (2021) 5(1) Clean Energy 104; Cletus Crasta, Hannes Agabus and Ivo Palu, 'Blockchain for EU Electricity Market' (Institute of Electrical and Electronics Engineers International Conference on Environment and Electrical Engineering 2020 and Institute of Electrical and Electronics Engineers Industrial and Commercial Power Systems Europe 2020); Amanda Ahl and others, 'Exploring Blockchain for the Energy Transition: Opportunities and Challenges Based on a Case Study in Japan' (2020) 117 Renewable and Sustainable Energy Reviews 109488; Barcelo (n 26); Anera Alahbabi and others, 'Establishing Security Controls For Blockchain Technology In P2P Energy Trading' (Institute of Electrical and Electronics Engineers Power and Energy Society Conference on Innovative Smart Grid Technologies–Middle East 2023); Amanda Ahl and others, 'Challenges and Opportunities of Blockchain Energy Applications: Interrelatedness Among Technological, Economic, Social, Environmental, and Institutional Dimensions' (2022) 166 Renewable and Sustainable Energy Reviews 112623.

[59] Onukwulu (n 9).

[60] Hernandez (n 6); Xihai Zhang and others, 'Distributionally Robust Optimization for Peer-To-Peer Energy Trading Considering Data-Driven Ambiguity Sets' (2023) 331 Applied Energy 120436.

[61] Bidan Zhang and others, 'Assessment of the Economic Impact of Forecasting Errors in Peer-To-Peer Energy Trading' (2024) 374 Applied Energy 123750.

[62] Zhang and others (n 61).

stability.[63] Such integration allows for the flattening of the load curve and efficient network utilisation. Furthermore, in light of the intermittent nature of RE systems and DERs, AI predicts demand and generation to ensure continuity of supply and prevent sporadic and variable energy availability.

With heterogeneous load profiles on blockchain-based energy trading systems, AI algorithms play a crucial role in forecasting peak demand and suggesting appropriate price signals. This position not only encourages prosumers to respond to network conditions but also promotes a shift in energy consumption patterns, effectively encouraging load-shifting to off-peak periods and preventing network congestion.

The Brooklyn Microgrid Project represents a pioneering initiative in which community members produce and exchange solar energy using a decentralised mechanism. AI enhances this system by forecasting generation and consumption, thereby optimising energy flow and efficiently aligning producers with consumers. This blockchain-AI model illustrates the potential of advanced technologies to reconfigure local energy governance, promoting greater sustainability, democracy, resilience, and most importantly, community autonomy in energy provision.

4. Regulatory and Legal Barriers to AI Integration in Blockchain-Based Energy Trading Systems

4.1 Privacy and Cybersecurity Barriers

The rapid adoption of AI in energy systems presents a complex web of regulatory challenges, with privacy and cybersecurity issues at the forefront. AI, particularly when deployed for data analytics or autonomous decision-making, is fundamentally dependent on large-scale, heterogeneous datasets. These technologies require vast quantities of data, as well as detailed information on energy consumption patterns, grid interactions, and user behaviours to enhance algorithmic accuracy, speed, scale, and performance, feeding what many describe as an insatiable algorithmic appetite.[64] In the context of blockchain-enabled energy systems, large amounts of consumer energy usage and data are frequently collected from distributed energy resources, smart meters, and IoT-enabled devices, often without users fully understanding how their information is stored, processed, or leveraged. The result is a growing tension between deploying AI-driven autonomous systems and individual autonomy, where personal data becomes fuel for systems that users neither control nor fully comprehend.

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[63] Hua and others (n 4).

[64] Onukwulu (n 9).

4.1.1 Erosion of User Control and Challenge to Energy Democracy

The potential risks of this integration should be felt, as AI's ability to mine transaction histories and infer behavioural patterns transforms seemingly anonymous data into detailed profiles, revealing when homes are occupied, what appliances they run, or even their financial flexibility.[65] When paired with blockchain's unalterable ledger, this creates a perfect storm of permanent exposure. The implications extend beyond theoretical risks; they challenge the core principles of energy democracy, which holds that users should retain control over both their energy choices and the data generated by those choices. Even blockchain's celebrated immutability introduces risks, as every transaction, once recorded, becomes permanent and visible across the network's nodes, a feature that, without safeguards, leaves sensitive consumption patterns exposed indefinitely.[66]

Further, every node on the network stores complete copies of the ledger to achieve immutability. Such data is not limited to participants but to every node on the blockchain system.[67] Without robust, privacy-preserving technical and organisational mechanisms at the architectural level, such as zero-knowledge proofs, homomorphic encryption, or secure off-chain data handling, users may be exposed to permanent exposure of personal data.[68] The convergence of AI and blockchain amplifies these privacy dilemmas exponentially.

Navigating this landscape requires more than technical solutions; it demands a fundamental rethinking of how regulatory frameworks approach AI-driven energy systems. The urgency of this need is not to stifle innovation but to align it with principles of privacy-by-design, ensuring that the march toward smarter grids does not come at the cost of individual rights. Only by addressing these challenges head-on can the promise of decentralised, AI-optimised.

4.1.2 Opaque Nature of AI Decision Making

AI thrives on data to optimise everything from demand forecasting to dynamic pricing. The underlying rationale is that increased data availability leads to improved model training, enabling more precise demand forecasting, dynamic pricing, and decentralised energy

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[65] Parhamfar, Sadeghkhani and Adeli (n 55); Felix Gonzalez, Paul Arevalo and Luis Ramirez, 'Game Theory and Robust Predictive Control for Peer-To-Peer Energy Management: A Pathway to a Low-Carbon Economy' (2025) 17(5) Sustainability 1780.

[66] According to scholars, '[…] right to be forgotten have arisen in different countries in Europe, and also outside, and demonstrate the need to define a clear balance between information and oblivion and between public interest and personal rights'; Alessandro Mantelero, 'The EU Proposal for a General Data Protection Regulation and the Roots of the "Right to Be Forgotten"' (2013) 29(3) Computer Law and Security Review 229; Ricardo Martins Goncalves, Miguel Mira da Silva and Paulo Rupino da Cunha, 'Implementing GDPR-Compliant Surveys Using Blockchain' (2023) 15(4) Future Internet 143; Mateusz Godyn and others, 'Analysis of Solutions for a Blockchain Compliance with GDPR' (2022) 12 Scientific Reports 15021.

[67] Karisma Karisma and Pardis Moslemzadeh Tehrani, 'Blockchain: Legal and Regulatory Issues' in *Sustainable Oil and Gas Using Blockchain* (Springer 2023).

[68] Gonzalez, Arevalo and Ramirez (n 65).

transactions.[69] However, AI technologies may obscure data processing and use pathways, resulting in a lack of transparency wherein end-users are unable to ascertain how their data is utilised, repurposed, or inferred within algorithmic decision-making processes.[70]

Users might see the outcomes, adjusted energy rates, tailored recommendations, or trading suggestions, but the pathways from raw data to these conclusions remain obscured. This opacity creates fertile ground for unintended consequences: pricing models that inadvertently discriminate, algorithms that reinforce biases, or systems that compromise foundational principles of energy security, including reliable and equitable access to energy.

AI systems often operate as ‘black boxes’, characterised by significant opacity in both their operation and decision rationale.[71] These systems frequently operate with alarming opacity, where even their designers struggle to trace how inputs are transformed into outputs.[72] This fundamental lack of transparency extends across multiple layers, from how data is processed and weighted to why specific decisions are made. The implications become increasingly severe as these systems are deployed in critical domains, such as energy management, where understanding an algorithm’s rationale is not only about accountability but also about ensuring fair and safe outcomes.

As the Commission Nationale de l’Informatique et des Libertés (CNIL), the French data protection authority, observes, ‘algorithms are not only opaque to their end users […] the designers themselves are also steadily losing the ability to understand the logic behind the results produced’.[73] CNIL is instrumental in understanding and addressing the challenges of AI transparency, providing valuable insights and recommendations in this complex field. It warns that we have reached a point where not only end-users but even algorithm creators are losing the ability to comprehend the logic of their systems. This computational complexity, lack of algorithmic transparency, and decisional unexplainably present a fundamental challenge to information privacy, as neither users nor system developers can fully account for how personal data is processed or utilised within automated decision-making processes.[74]

The roots of this opacity are multifaceted. Machine learning architectures achieve their remarkable effectiveness precisely through complex, layered transformations of input data, a process that inherently obscures interpretability. This structural opacity is compounded by widening gaps in technical literacy, leaving most users unequipped to question or challenge

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[69] Hua and others (n 4).

[70] Manuel Carabantes, ‘Why Artificial Intelligence Is Not Transparent: A Critical Analysis of Its Three Opacity Layers' in *Handbook of Critical Studies of Artificial Intelligence* (Edward Elgar Publishing 2023).

[71] Warren J Von Eschenbach, ‘Transparency and the Black Box Problem: Why We Do Not Trust AI’ (2021) 34 Philosophy & Technology 1607.

[72] Lilian Mitrou, ‘Data Protection, Artificial Intelligence and Cognitive Services: Is the General Data Protection Regulation (GDPR) “Artificial Intelligence-Proof”?’ (2018) Social Science Research Network.

[73] Mitrou (n 72).

[74] R Machlev and others, ‘Explainable Artificial Intelligence (XAI) Techniques for Energy and Power Systems: Review, Challenges and Opportunities’ (2022) 9 Energy and Artificial Intelligence 100169.

system outputs. The consequences ripple across society: individuals lose agency over decisions affecting their energy access and pricing, while regulators struggle to enforce laws written for more transparent technological eras.[75]

What makes this challenge particularly concerning is its self-reinforcing nature. The same characteristics that make AI systems powerful—their ability to find non-intuitive patterns in vast datasets, also make them fundamentally different from traditional software, where inputs cleanly map to outputs. The encoding of input parameters by machine learning models have made it difficult to interpret or predict their internal decision-making processes.[76] As these systems are increasingly deployed in peer-to-peer energy trading and grid management, we must confront challenging questions about how to maintain human oversight in an era of increasingly complex AI.

Individuals hold a significant right not only to access information about the data collected on them but also to receive intelligible explanations of the decision-making processes and principles underlying their data collection. To understand how individuals can meaningfully exercise agency in the face of algorithmic decision-making, it is necessary to examine the legal frameworks that articulate such rights. This right is enshrined in Article 86 of the European Union Artificial Intelligence Act, which states that 'any affected person […] shall have the right to obtain from the deployer clear and meaningful explanations of the role of the AI system in the decision-making procedure and the main elements of the decision taken'.[77] The European Union's Artificial Intelligence Act, currently the most comprehensive legislative proposal in this domain, provides an instructive example.

However, the recourse under Article 86 is limited to certain significant and adverse decisions that impact health, safety, or fundamental rights. The limitations of Article 86 become starkly apparent when examining its narrow scope. By focusing only on high-stakes decisions, the legislation leaves vast swaths of everyday algorithmic governance, from dynamic energy pricing to trading prioritisation, operating in a twilight zone of unaccountability. This regulatory blind spot is exacerbated by AI's inherent characteristics, including predictive analytics and data mining techniques that transform inputs through layers of nonlinear computations, producing decisions even their designers struggle to reconstruct.

The issue is further compounded by the fact that AI systems rely heavily on predictive analytics and data mining techniques, which further obscure the mechanisms through which decisions are made. This opacity often falls outside the threshold as it may not rise to the

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[75] Carabantes (n 70); Marten HL Kaas, 'The Perfect Technological Storm: Artificial Intelligence and Moral Complacency' (2024) 26 Ethics and Information Technology 49.

[76] Simon Chesterman, 'Through a Glass, Darkly: Artificial Intelligence and the Problem of Opacity' (2021) 69(2) The American Journal of Comparative Law 27.

[77] European Union, Regulation (EU) 2024/1689 of the European Parliament and of the Council of 13 June 2024 laying down harmonised rules on artificial intelligence and amending Regulations (EC) No 300/2008, (EU) No 167/2013, (EU) No 168/2013, (EU) 2018/858, (EU) 2018/1139 and (EU) 2019/2144 and Directives 2014/90/EU, (EU) 2016/797 and (EU) 2020/1828 (Artificial Intelligence Act) (2024).

level of severity or seriousness under Article 86, leaving a wide range of algorithmic outcomes unaccountable and unchallengeable by affected individuals.[78] The urgency of this issue is underscored by the significant impact of AI opacity on energy consumers.

Prosumers, the pioneering individuals who both produce and consume energy, navigate trading platforms where algorithms silently shape their experience in profound ways. As a result, prosumers in P2P energy trading networks, are often unaware of how algorithmically generated outcomes, such as dynamic pricing or supply-demand matching, affect their consumption behaviours, market participation, and access to energy resources. In this context, the absence of transparency is not merely a technical limitation; it reflects a deeper normative failure that undermines key principles of transparency and accountability in the governance of decentralised energy systems.[79]

When energy consumers cannot understand the rules governing their participation, the promise of decentralised systems as democratic alternatives to traditional utilities rings hollow. True energy democracy requires transparency not just in market outcomes but in the very algorithms that constitute these new digital energy landscapes. The challenge ahead is to develop accountability mechanisms that match the pervasive nature of algorithmic decision-making. This means moving beyond binary distinctions between ‘significant’ and ‘routine’ automated decisions, recognising that in energy systems, as in many AI-governed domains, it is often the daily accumulation of small, opaque determinations that most shape people’s lives.

4.1.3 Immutability by Design

The challenge of data deletion in AI systems reveals a paradox at the heart of modern technology governance. Much like blockchain’s immutable ledgers that permanently etch transactions in digital stone, many AI architectures create their own forms of indelible data persistence.[80] This is not merely a technical limitation; it represents a fundamental clash between cutting-edge systems designed for optimisation and legal frameworks built on principles of user control and data sovereignty.

The problem stems from AI’s very strengths. Self-learning systems that continuously adapt their internal processes do not just store data; they metabolise it, transforming inputs into decision pathways distributed across neural networks.[81] Effective deletion requires identifying and overwriting data residues with random inputs, a technically intricate

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[78] Margot E Kaminski and Gianclaudio Malgieri, ‘The Right to Explanation in the AI Act’ (2025) Social Science Research Network 5194301.

[79] Machlev and others (n 74).

[80] Eduard Fosch Villaronga, Peter Kieseberg and Tiffany Li, ‘Humans Forget, Machines Remember: Artificial Intelligence and the Right to be Forgotten’ (2018) 34(2) Computer Law and Security Review 304.

[81] Lami and others (n 55).

process that is not only complex but also potentially degrading performance in ways that undermine the system's core purpose.[82]

Blockchain's parallel limitations compound these challenges in energy trading platforms. When AI's diffuse data persistence meets blockchain's cryptographic permanence, we create systems where energy consumption patterns, trading histories and personal identifiers become effectively fossilised in digital amber. This creates impossible choices for developers: compromise system efficiency to meet deletion requests or maintain performance at the cost of regulatory compliance.

The implications extend far beyond technical hurdles. These limitations directly challenge foundational data protection principles, such as the right to erasure under data protection regulations, creating governance gaps where individual rights intersect with system architectures. In energy markets, particularly where consumption data reveals intimate details about household behaviours and routines, this persistence risk becomes a structural barrier to trust, potentially slowing the adoption of otherwise transformative technologies. This represents a significant barrier to AI and blockchain-driven energy trading systems, as developers find themselves at a critical juncture with data risks. What emerges is a core tension in our digital transition: how to reconcile the self-reinforcing, persistent nature of advanced technologies with the human-centric principles that should govern their use. Solving this will require more than technical patches; it demands a fundamental rethinking of how we design systems to balance efficiency with erasability from their very foundations.

4.1.4 Dual-Risk Landscape of Exploitation and Attack

The integration of emerging digital technologies into energy systems has introduced unprecedented cybersecurity challenges that threaten the stability and fairness of decentralised power markets.[83] These technologies create a dual-risk landscape in which complex computational systems can be both targets of sophisticated attacks and tools exploited by malicious actors. Adversaries may exploit system vulnerabilities through techniques such as data poisoning or adversarial inputs, which can deliberately alter trading outcomes or skew demand forecasts.[84] Such interference could destabilise grid operations and diminish revenues for energy-producing consumers, prosumers who form the backbone of peer-to-peer trading networks.

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[82] Kesa and Kerikmae (n 8); Nicholas Carlini and others, 'The Secret Sharer: Evaluating and Testing Unintended Memorization in Neural Networks' (Proceedings of the 28th USENIX Conference on Security Symposium, 2019).

[83] Adewoyin, Adediwin and Audu (n 12).

[84] Ravindar Reddy Gopireddy, 'Securing AI Systems: Protecting Against Adversarial Attacks and Data Poisoning' (2024) 11 Journal of Scientific and Engineering Research 276; Adewoyin, Adediwin and Audu (n 12).

Beyond being susceptible to manipulation, these systems can also be weaponised to automate and scale cyber threats.[85] The same digital infrastructures that facilitate energy pricing and distribution may be repurposed to carry out coordinated attacks on grid management platforms or user accounts. This risk intensifies as critical operational functions, such as real-time energy balancing, market clearing, and forecasting, become increasingly automated, amplifying the consequences of any successful breach. The immutable nature of blockchain transactions compounds these dangers by embedding sensitive data permanently within decentralised ledgers. Energy consumption patterns, trading histories, and prosumer identities stored on-chain become persistent targets for exploitation, remaining exposed even after security vulnerabilities are identified.

These cybersecurity challenges are closely tied to broader governance concerns, including the permanence of data and the opacity of automated decision-making processes. The lack of transparency in many digital systems makes it difficult to detect or trace attacks. At the same time, the irreversible nature of distributed ledgers ensures that compromised data cannot be altered or deleted.[86] As a result, participants in decentralised energy markets, already grappling with informational disparities, now face the additional threat of having their data weaponised against them. This introduces a troubling paradox: technologies intended to democratise energy access may inadvertently erode trust through heightened exposure to cyber risk.

In a decentralised energy network characterised by the potential of borderless blockchain transactions that transcend both spatial and temporal limitations, crucial questions emerge regarding the attribution of responsibility and liability. These borderless paradigms, if harnessed effectively, can operate as a shield to avoid attracting the scrutiny generally present in centralised systems. However, if not managed properly, they can also provide opportunities for malicious adversaries to mount attacks via new attack vectors that can expose critical infrastructures to outages and distortions. Further, decentralised actors may fall outside the current oversight mechanism due to the lack of a structured and architecture-targeted legislation tailored specifically for AI-blockchain-related cyberattacks. Considering the severity of the threats, vulnerabilities, and impact, institutional and normative oversight mechanisms, safety standards, and certification features are necessary to address technical, organisational, and systemic vulnerabilities.

Addressing these challenges requires a multi-layered approach that combines robust technical safeguards with adaptive regulatory oversight. Systems must be rigorously tested to detect anomalies and withstand deliberate manipulation. Privacy-enhancing mechanisms, such as zero-knowledge proofs, should be integrated into blockchain-based platforms to

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[85] Aftab Arif, Muhammad Ismaeel Khan and Ali Raza A Khan, 'An Overview of Cyber Threats Generated by AI' (2024) 3 International Journal of Multidisciplinary Sciences and Arts 67.

[86] Adewoyin, Adediwin and Audu (n 12); Caixiang Fan, Amirhossein Sohrabbeig and Petr Musilek, 'Zero-Knowledge Machine Learning Models for Blockchain Peer-To-Peer Energy Trading' (2025) 32 Internet of Things 101638.

protect sensitive data while maintaining transactional integrity and security.[87] Regulatory frameworks must keep pace with these innovations, establishing precise accountability mechanisms and minimum security standards for all actors within the energy ecosystem. As the sector evolves toward more decentralised and digital models, cybersecurity must be recognised as not just a technical concern but a foundational pillar of system resilience, market fairness, and public confidence.

4.2 Industry-Specific Barriers

The successful integration of AI into decentralised energy trading systems requires fundamental reforms to existing legal and regulatory frameworks. Current national energy policies remain rooted in centralised models of generation and distribution, creating structural incompatibilities with the data-intensive, peer-to-peer nature of AI in blobkchain-driven energy markets. This regulatory misalignment generates significant uncertainty regarding the rights, responsibilities, and liabilities of both prosumers and the algorithmic agents that facilitate autonomous trading. The lack of clear governance parameters for AI applications, ranging from automated trading algorithms to predictive grid-balancing systems, hinders their responsible deployment while leaving critical questions unanswered regarding compliance with existing energy laws, liability regimes, and data protection standards. This regulatory vacuum not only discourages investment in AI-enabled energy solutions but also threatens to stifle innovation in precisely those technologies needed to accelerate the clean energy transition.

A significant barrier to peer-to-peer energy trading on the utility grid lies in the lack of access prosumers have to the public grid, which prevents them from exchanging surplus energy with other market participants. This lack of third-party access presents two core challenges. First, prosumers and energy communities are often required to invest in and build their own energy infrastructure before participating in decentralised markets, thereby imposing prohibitive barriers to market entry.[88]

Second, such regulatory and infrastructural limitations restrict the adoption of advanced technologies, particularly AI, which plays a critical role in enabling energy flexibility, predictive load management, and real-time optimisation of trading decisions. Without seamless access to the grid, AI systems cannot fully leverage distributed data flows or interact with broader grid infrastructures, diminishing their capacity to automate energy transactions, optimise grids, and support dynamic pricing mechanisms. The absence of standardised third-party access rules further obstructs the development of local spot markets, which serve as critical infrastructure for the AI-driven responsiveness that characterises next-generation energy systems. Without regulatory intervention to guarantee fair grid access, the potential synergies between distributed energy resources and AI will remain substantially unrealised.

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[87] Fan, Sohrabbeig and Musilek (n 86).

[88] Hojckova and others (n 88).

The conventional tariff structure remains a significant barrier, as it offers limited incentives for the dynamically efficient behaviour of individual and collective prosumerism on the distribution network and the deployment of technologies that can revamp energy systems.[89] It is crucial to align economic incentives with network constraints. Compounding these challenges are outdated tariff structures that fail to align economic incentives with the technical realities of decentralised energy networks. Conventional volumetric tariff methodologies provide inadequate price signals for managing network congestion or encouraging peak load reduction.[90] In such systems, network operators struggle to recover infrastructure costs, particularly as decentralised energy flows become more complex and dynamic. Moreover, the imposition of fixed tariffs within peer-to-peer energy trading schemes undermines price responsiveness and fails to incentivise prosumers to reduce grid usage during peak periods.[91] Fixed charges disproportionately burden smaller prosumers regardless of their actual energy contributions.[92] These rigid pricing frameworks actively undermine the efficiency gains promised by AI-optimised peer-to-peer trading, as they prevent the emergence of responsive pricing mechanisms that could better reflect real-time supply and demand conditions. The resulting market distortions not only reduce the economic viability of distributed energy participation but also perpetuate systemic inequities that disadvantage smaller-scale renewable generators. Developing adaptive tariff structures capable of accommodating AI-driven market dynamics represents both a technical and regulatory imperative for realising the full potential of decentralised energy ecosystems.[93]

Together, these regulatory gaps, spanning market access, liability frameworks, and tariff design, create interdependent barriers to the sustainable scaling of AI-enhanced energy

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[89] Alex Felice and others, ‘Renewable Energy Communities: Do They Have a Business Case in Flanders?’ (2022) 322 Applied Energy 119419; Karisma Karisma and Pardis Moslemzadeh Tehrani, ‘Legal and Regulatory Challenges of Blockchain-Enabled Renewable Energy Systems’ (Proceedings from the International Conference on Hydro and Renewable Energy, 2022).

[90] Philip Baker, ‘Challenges Facing Distribution System Operators in a Decarbonised Power System’ (Regulatory Assistance Project, 2020) <https://www.raponline.org/wp-content/uploads/2023/09/rap-baker-dso-challenges-june-2020-final.pdf>; Viktorija Dudjak and others, ‘Impact of Local Energy Markets Integration in Power Systems Layer: A Comprehensive Review’ (2021) 301 Applied Energy 117434; Mercedes Valles and others, ‘Regulatory and Market Barriers to the Realization of Demand Response in Electricity Distribution Networks: A European Perspective’ (2016) 140 Electric Power Systems Research 689; Karisma and Deane (n 11).

[91] Nesanthan Srianandarajah, Stephen J Wilson and Archie Chapman, ‘From Green to Amber: Is Australia’s National Electricity Market Signalling a Financial Warning for Wind and Solar Power?’ (2022) 167 Energy Policy 113052.

[92] Donal Brown and others, *Policies for Prosumer Business Models in the EU* (Prosumers for the Energy Union: Mainstreaming Active Participation of Citizens in the Energy Transition, 2020); Tim Schittekatte and Leonardo Meeus, ‘Limits of Traditional Distribution Network Tariff Design and Options to Move Beyond’ (Florance School of Regulation 2018); Vedika Kulkarni and Kalyani Kulkarni, ‘A Blockchain-Based Smart Grid Model for Rural Electrification in India’ (8th International Conference on Smart Grid, 2020).

[93] Ibtihal Abdelmotteleb, Elena Fumagalli and Madeleine Gibescu, ‘Assessing Customer Engagement in Electricity Distribution-Level Flexibility Product Provision: The Norwegian Case’ (2022) 29 Sustainable Energy, Grids and Networks 100564.

trading. Addressing them will require coordinated policy interventions that recognise the unique requirements of algorithmic energy markets while safeguarding principles of equity and system reliability. The alternative is a continued mismatch between technological capability and regulatory permission that slows the transition toward more resilient, efficient, and participatory energy systems.

5. Technological Barriers to AI Integration in Blockchain-Based Energy Trading Systems

5.1 Energy-Intensive AI and the Sustainability Paradox

AI in blockchain-powered energy trading systems require considerable computational resources. These requirements have been growing in light of advanced AI models, often supported by large-scale data centres and high-performing computing resources.[94] This paradox is evident when we consider that training a single large-scale AI model consumes as much electricity as several households in an entire year. The large energy footprint of AI models undermines the sustainability goals they aim to advance. To better manage the environmental concerns associated with AI computing, we must strike a balance between the costs and externalities and the potential benefits. Introducing low-carbon computational resources and integrating energy-efficient algorithmic design is not just a choice but a necessity for developing advanced AI models that are both sustainable and effective, offering a promising future for sustainable energy systems

5.1.1 Technological Silos, Fragmented Infrastructures and the Lack of Interoperability

The lack of interoperability presents a fundamental barrier to the effective deployment of AI and blockchain technologies within peer-to-peer (P2P) energy trading. Without interoperability, these systems operate in silos, impeding real-time responsiveness and efficient decision-making. Despite the potential of AI to enhance energy forecasting and optimise operations, the lack of standardised, interoperable protocols limits the seamless coordination between prosumers (consumers who also produce energy), service providers, network operators, and diverse digital platforms.[95] The absence of harmonised energy data standards, such as consistent units of measurement and reporting formats, further complicates the training and deployment of AI models, undermining their effectiveness.

From an operational perspective, integrating novel AI models necessitates an interoperable infrastructure, which includes converge of digital and physical layers. The transformative potential of AI and blockchain technologies for sustainable energy solutions is inspiring, but their feasibility is contingent upon overcoming interoperability challenges through standardised protocols and cross-platform compatibility.

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[94] Onukwulu (n 9); Adewoyin, Adediwin and Audu (n 12).

[95] Adewoyin, Adediwin and Audu (n 12); Karen Gah Hie Kong and others, 'Fuzzy Optimization For Peer-To-Peer (P2P) Multi-Period Renewable Energy Trading Planning' (2022) 368 Journal of Cleaner Production 133122.

5.1.2 Capital Intensity of AI-Driven Energy Systems

The integration of AI within P2P energy ecosystems demands substantial initial capital, encompassing investments in developing predictive and autonomous decision-making algorithms.[96] However, the effectiveness of AI is subject to the availability of high-quality, granular data and time-intensive training processes, which are often overlooked but crucial for its success.

Regulatory uncertainties and bureaucratic hurdles, such as complex approval processes or conflicting regulations, may delay the process, but stakeholders must maintain a long-term perspective. While AI enhances demand forecasting, real-time pricing optimisation, and decentralised transaction facilitation, its financial benefits typically accrue gradually. This understanding is important for achieving full deployment and monetisation of AI in P2P energy ecosystems.

5.1.3 Limited Availability of High-Quality Energy Data

A substantial impediment to the effective deployment of AI in P2P energy trading lies in the limited availability of high-quality, decentralised energy data.[97] However, the potential benefits of AI in overcoming these challenges should inspire and motivate us. Traditional energy systems are predominantly centralised and vertically integrated, often controlled by monopolistic utilities that manage generation, transmission, and distribution. These incumbent market players possess vast repositories of operational and consumer energy data, yet such data is rarely disclosed due to commercial confidentiality or regulatory inertia. Without diverse, real-time, and context-specific datasets reflecting prosumer behaviour, local generation patterns, and transaction flows, AI systems cannot accurately learn or adapt to the complex and distributed nature of decentralised energy markets.

This paradox can be addressed through a three-pronged phased approach:

(i) Implementing peer-to-peer energy trading systems at scale in pilot or sandbox environments to generate real-world, distributed data. AI can be trained post-deployment, removing the need for centralised datasets.

(ii) The utilisation of privacy-centric solutions such as federated learning and differential privacy to enable AI deployment while minimising exposure to raw data. Technology developers, having identified the privacy threats, can seamlessly embed suitable data-oriented and process-oriented strategies to deploy privacy-aware systems and AI architectures.

(iii) Legal frameworks should require utilities to make non-personal datasets available for public and research use, thereby generating the data ecosystem from which AI can learn and adapt responsibly.

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[96] Adewoyin, Adediwin and Audu (n 12).

[97] Onukwulu (n 9).

6. Conclusion

For better or for worse, AI leaves a lasting mark on energy systems. It reshapes how energy is produced, distributed, and consumed. It enables efficiency, automation, and precision, yet it also introduces new forms of opacity, lack of agency, and risk. So, what does the future hold for AI in blockchain-enabled energy trading? It is impossible to say for sure, but one thing is certain about AI as a technology: it has the potential to revolutionise how we produce, consume, and trade energy, a prospect that should excite us all. AI is not just a support system but a catalyst that drives significant changes in the energy landscape. Its progress through institutional, social, technical, and regulatory strategies and initiatives ensures that the benefits of DESs and DERs are fully realised. While AI presents a promising avenue for peer-to-peer (P2P) energy trading, it faces challenges that hinder its widespread adoption.

In the ongoing race between technological innovation and legal regulation, we are witnessing a modern re-enactment of the tortoise and the hare. The accelerating pace of AI has exposed a growing chasm between innovation and the legal frameworks meant to govern it. Law, traditionally conceived as a stabilising force, now struggles to keep pace with the relentless momentum of technological change. Existing regulatory structures remain mired in bureaucratic inertia, further constrained by paradigms fundamentally unsuited to address the emergent, relational, and often unpredictable nature of AI systems. This widening gap demands urgent attention.

We face two fundamental approaches to bridging this divide: either slowing the pace of technological progress or developing more adaptive, responsive regulatory tools. The first option, although theoretically appealing, proves economically and politically unfeasible given AI's central role in global competitiveness. The second path, developing agile, context-sensitive, and technology-neutral regulatory frameworks, has therefore become not just important but imperative. Such frameworks must evolve in lockstep with the systems they aim to regulate, ensuring the law serves not as a passive observer of technological power but as its essential counterpart.

Overcoming industry-specific and technological barriers to AI adoption in P2P energy trading requires a coordinated, incremental, and context-aware approach. Industry actors must be actively involved in shaping regulatory frameworks through co-regulation, ensuring that policies align with operational realities and reflect the needs of all stakeholders. Technical interoperability standards should be developed collaboratively between parties to enable seamless integration across devices and AI platforms. Importantly, we must retain human oversight in these automated systems, ensuring the tortoise's wisdom guides the hare's speed. The goal should be energy systems that are not just technologically advanced but also equitable, transparent, and resilient, combining the best qualities of both the tortoise and the hare in our energy future.

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