Technology in Society 84 (2026) 103093

Contents lists available at ScienceDirect

Technology in Society

journal homepage: www.elsevier.com/locate/techsoc

Integrating blockchain with virtual power plants: Two-level future roadmaps for enhanced performance

Juwon Hong [a], Eunseong Song [b], Jinwoo Choi [c], Sangkil Song [b], Hakpyeong Kim [d], Hyuna Kang [e], Taehoon Hong [f,*]

[a] Graduate Research Assistant and Ph.D. Student, Department of Architecture and Architectural Engineering, Yonsei University, Seoul, 03722, Republic of Korea
[b] Graduate Research Assistant and Graduate student, Department of Architecture and Architectural Engineering, Yonsei University, Seoul, Republic of Korea
[c] Graduate Research Assistant and Ph.D. Student, Department of Architecture and Architectural Engineering, Yonsei University, Seoul, Republic of Korea
[d] Post-Doctoral Fellow, Department of Architecture and Architectural Engineering, Yonsei University, Seoul, 03722, Republic of Korea
[e] Research professor, Department of Architecture and Architectural Engineering, Yonsei University, Seoul, 03722, Republic of Korea
[f] Professor, Department of Architecture and Architectural Engineering, Yonsei University, Seoul, 03722, Republic of Korea

A R T I C L E I N F O

Keywords:
Virtual power plant
Blockchain
Microgrid
Energy trading
Smart contract

A B S T R A C T

Blockchain is emerging as a major advanced technology to facilitate virtual power plants (VPPs), a means to address global environmental challenges through achieving zero carbon. As the blockchain market in the energy sector grows, the integration of blockchain into VPPs will continue to expand. To this end, this study comprehensively reviewed 129 previous studies integrating blockchain into VPPs to propose ways to enhance the performance of VPPs through blockchain. Based on the quantitative analysis of research trends and interests, it was found that while research trends were on the rise, they were still in the early stages, and research interests were somewhat concentrated on energy trading via smart contracts. In other words, the need to propose comprehensive future roadmaps to revitalize early-stage research in a limited field. Based on the qualitative analysis of research status by VPP components, research limitations that provide direction for future roadmaps were identified. As a result, two-level future roadmaps were proposed, consisting of function-level and integration-level roadmaps. Implementing blockchain in VPPs according to the proposed future roadmaps is expected to result in innovative performance enhancement for VPPs and significantly advance the goal of achieving zero carbon.

NOMENCLATURE

AI	Artificial intelligence
AML	Anti-money laundering
API	Application programming interface
dAPP	Decentralized application
DG	Distributed generation
DLT	Distributed ledger technology
DPoS	Delegated proof of stake
ERC	Ethereum request for comments
ESS	Energy storage system
EV	Electric vehicle
HVAC	Heating, ventilating, and air conditioning
IoTs	Internet of Things
KYC	Know your customer
MILP	Mixed-integer linear programming
NFT	Non-fungible token
P2P	Peer-to-peer
PBFT	Practical Byzantine fault tolerance
PoS	Proof of stake
PoW	Proof of work
PRISMA	Preferred reporting items for systematic reviews and meta-analysis
PV	Photovoltaic
V2G	Vehicle-to-grid
V2V	Vehicle-to-vehicle
VPP	Virtual power plant

* Corresponding author. Yonsei University, 50 Yonsei-ro, Seodaemun-gu, Seoul, 03722, Republic of Korea.
E-mail addresses: juwonae@yonsei.ac.kr (J. Hong), en_s11@yonsei.ac.kr (E. Song), jinwoo818@yonsei.ac.kr (J. Choi), uphillroad_@yonsei.ac.kr (S. Song), ibk1930@yonsei.ac.kr (H. Kim), hyuna_kang@yonsei.ac.kr (H. Kang), hong7@yonsei.ac.kr (T. Hong).

https://doi.org/10.1016/j.techsoc.2025.103093
Received 29 December 2024; Received in revised form 25 September 2025; Accepted 25 September 2025
Available online 26 September 2025
0160-791X/

1. Introduction

To overcome global environmental challenges, it is inevitable to gradually shift energy sources from fossil fuels to renewables (Fankhauser et al., 2022; Xu et al., 2023). Hence, several international organizations are taking the lead in global efforts to increase the share of renewables in energy consumption to achieve zero carbon by 2050 (Sanderson and Wong, 2024). Meanwhile, due to the small-scale distributed generation of renewables, the type of power grid is shifting from a centralized macro grid to a distributed microgrid (Panda et al., 2022). A microgrid, which includes multiple components (e.g., distributed generation (DG), demand, energy storage system (ESS), and energy market), represents an independent local grid that aims to cover total demand through DG, primarily renewables, within the grid. However, intermittent and unpredictable renewables and large and complex demands hinder the efficient microgrid operation (i.e., appropriate power dispatch) and result in problems such as grid instability, energy waste, and shortage. On the other hand, an appropriate power dispatch can result in a win-win strategy that benefits DG and demand as all energy produced can be sold at a low price. Furthermore, microgrids can operate independently through renewables without reliance on fossil fuels (Lee et al., 2018). Therefore, to achieve zero carbon through a successful transition from fossil fuels to renewables, efforts must be made to efficiently operate microgrids.

Meanwhile, a virtual power plant (VPP) has emerged as an advanced energy management system that integrates and optimizes components of one or more microgrids to function as a unified, software-based power plant without physical infrastructure (An et al., 2025; Sonnenschein et al., 2015). The control system of a VPP optimizes the power dispatch of microgrids based on monitoring and prediction of generation and consumption from DG and demand. Optimal power dispatch can produce the effect of generation without the actual generation by reducing energy waste or consumption, especially when used in conjunction with ESS or energy markets (Wang et al., 2023). In addition, VPPs can enhance the safety and flexibility of microgrids and reduce power costs, thereby contributing to the technical and economic advancement of microgrids. In this vein, VPP-related projects have been successfully implemented in several countries (e.g., United States and Australia), and the global VPP market is expected to grow steadily at a compound annual growth rate of about 22.3 % (Rouzbahani et al., 2021; Spherical Insights, 2023). Also, academic communities are interested in VPPs and are actively working to improve them in various aspects for future applications.

Among various advanced technologies, blockchain is regarded as a core technology that enables decarbonization, digitalization, and decentralization (3Ds), serving as the cornerstone of the future energy system (i.e., VPP in this study) (Valdivia and Balcell, 2022). Blockchain is a distributed ledger technology (DLT) that records, verifies, and stores data electronically through blocks, which are linked using a cryptographic hash function (Seven et al., 2020). Various technologies related to blockchain (e.g., consensus algorithms, smart contracts, and cryptographic technologies) ensure transparency in energy data sharing while maintaining security without centralized authentication (Zhang et al., 2022). These features of blockchain could help improve peer-to-peer (P2P) energy trading and establish blockchain-based P2P energy platforms (Lacity, 2018). Like VPPs, blockchain is recognized as a key technology in the energy sector, and the blockchain-related market is projected to grow at a compound annual growth rate of about 34.0 % (Polaris Market Research, 2023). With the prominent role of blockchain in the energy sector, it is expected to be actively integrated into VPPs, where P2P trading between components is common. Integrating blockchain into VPPs to further improve VPPs poses a significant challenge in the energy sector. Despite growing interest in integrating blockchain with VPPs, current research remains at an early stage and is relatively limited in scope. Most existing studies tend to focus narrowly on energy trading applications, particularly those involving smart contracts, while other blockchain technologies and key VPP components such as DG and ESS remain underexplored. This research gap calls for a clear strategic direction to unlock the broader potential of blockchain–VPP integration.

To accelerate the transition to a zero-carbon future, a comprehensive research roadmap is needed to guide the effective and scalable adoption of blockchain in VPPs. Such a roadmap should extend beyond energy trading to include the development and seamless integration of diverse blockchain-based functions. However, review studies on the integration of blockchain into VPPs remain limited, and most of them tend to focus on specific blockchain technologies (e.g., smart contracts and consensus mechanisms) or energy trading aspects (Hua et al., 2022; Ruan et al., 2024; Xia et al., 2023). Likewise, many review studies on the application of blockchain in the energy sector have primarily focused on energy trading (Anandhabalaji et al., 2024; Rodrigues and Garcia, 2023; Uddin et al., 2023; Zhou and Lund, 2023). Therefore, this study proposed two-level future roadmaps for enhancing VPPs based on blockchain through a comprehensive review covering the full spectrum of blockchain technologies and VPP components. In this study, the proposed two-level future roadmap consists of a function-level roadmap, which focuses on developing blockchain systems that perform independent functions within VPP components, and an integration-level roadmap, which aims to interconnect these blockchain systems into a cohesive ecosystem for the VPP.

2. Preliminaries

2.1. Virtual power plant

2.1.1. Components of a virtual power plant

A fundamental distinction from microgrids is that VPPs are not geographically confined to a single, physically bounded distribution network. While microgrids manage local resources within a defined area, VPPs employ ICT-based control, advanced metering, and market participation to aggregate and coordinate geographically dispersed components—often spanning multiple microgrids—as a single power plant. All participating components are physically connected to the central power grid, enabling the VPP to optimize their production, storage, and consumption across multiple locations through integrated power dispatch.

Since the concept of VPPs originated from the "virtual utility" defined by Shimon Awerbuch and Alistair Preston in 1997, much research has been conducted on VPPs; however, a formal definition has not yet been established (Awerbuch and Preston, 1997). Definitions vary across different studies, depending on their intrinsic factors such as operational objectives, strategies, and components, as well as extrinsic factors such as technologies, policies, and regulations (Nosratabadi et al., 2017; Yin and Powers, 2010). Nonetheless, various VPPs share the common goal of "controlling" multiple microgrids to determine the "optimal power dispatch" for operational objectives by "aggregating" the components of microgrids as a single power plant and "integrating" flexibility in DG and demand (U.S department of Energy, 2024). In this study, VPPs were not limited by intrinsic and extrinsic factors, and all possible components capable of directly exchanging energy through the grid were considered (refer to Fig. 1): (i) DG; (ii) demand; (iii) ESS; (iv) energy market; and (v) EV. Furthermore, this study expands the scope of VPPs to include data-driven management in addition to optimal energy dispatch, thereby enhancing performance across multiple operational dimensions.

- *Distributed generation*: DG includes power generation facilities (i.e., DG units) that produce energy at distributed locations based on factors such as resource availability and proximity to demand, and supply energy to microgrids (Ackermann et al., 2001). Under the VPP, the generated energy is either self-consumed by various demand-side loads within microgrids or stored in ESSs and sold to the energy market. DG is classified into renewable and

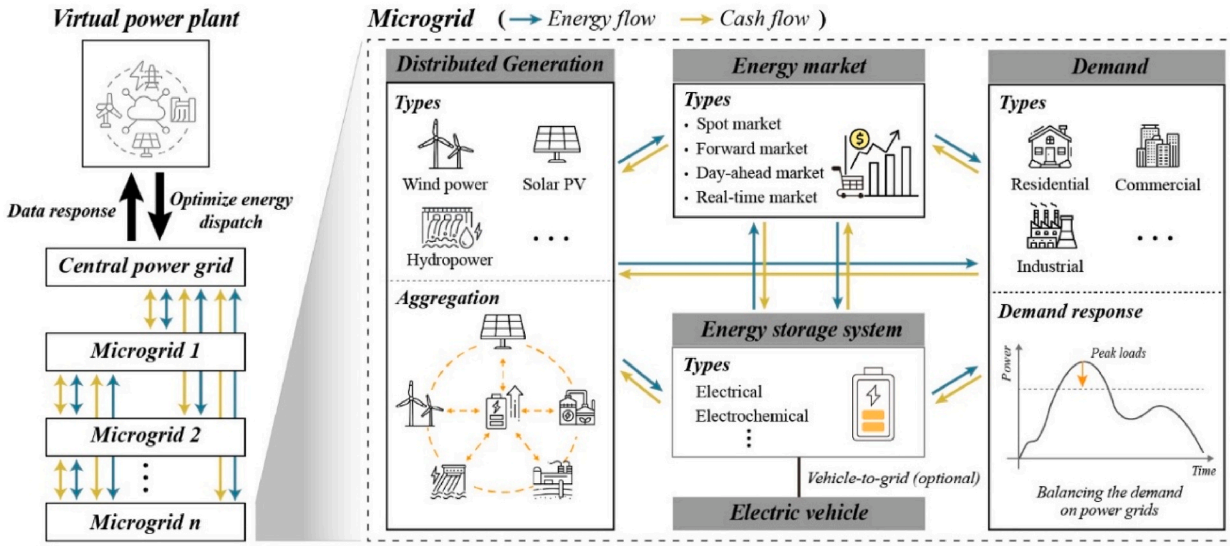

Fig. 1. Example of a virtual power plant configuration.

non-renewable, with renewable DG primary adopted in VPPs for sustainability and carbon reduction (Lee et al., 2016). Although the intermittency of renewable DG undermines microgrid stability, a VPP mitigates this effect by aggregating diverse units (Arar Tahir et al., 2023).

- *Demand*: Demand refers to the energy-consuming equipment (i.e., demand-side loads) used by residential, industrial, and commercial facilities within microgrids (Monie et al., 2021; Pourghaderi et al., 2018). Under the VPP, demand receives energy from DG, ESSs, or energy markets and consume it to ensure smooth operation of facilities (Sipthorpe et al., 2022). Demand is classified into controllable and uncontrollable loads, depending on whether they can be adjusted in response to the VPP's needs. A VPP performs demand response by shifting controllable loads to time zones with more abundant power generation or lower consumption, thereby redistributing peak demand and balancing power generation and consumption within microgrids (Faria et al., 2016; Mnatsakanyan and Kennedy, 2015).
- *Energy storage system*: An ESS is a group of energy storage technologies that can charge from or discharge to microgrids as needed (Kang et al., 2023). Under the VPP, ESSs address imbalances between power generation and consumption while supporting the aggregation of DG units and demand response for peak management, and these functions collectively enhance the stability and resilience of microgrids via frequency regulation and voltage support (Jung et al., 2020). ESSs can improve the profitability of microgrids by purchasing and charging energy when energy prices are low and discharging and selling energy when energy prices are high.
- *Energy market*: An energy market is a type of commodity market where energy is traded to solve energy imbalance problems that cannot be addressed within microgrids (Li et al., 2024). In other words, the energy market is essential for VPPs as it balances power generation and consumption that cannot be managed solely within microgrids while maximizing economic benefits. A VPP sells energy to the energy market when power generation exceeds the microgrids' capacity to absorb energy (i.e., consumption plus ESS charging capacity), and purchases energy from the energy market when power generation falls short of consumption (An et al., 2021). Furthermore, a VPP can improve the profitability of microgrids by trading energy based on energy market prices.
- *Electric vehicle*: An EV is an automobile propelled by an electric motor using energy stored in batteries (Manivannan, 2024). With the advancement of vehicle-to-grid (V2G), a technology that enables EV batteries to interact with microgrids through charging and discharging like ESS, EVs have emerged as vital components in increasing the flexibility and energy capacity of microgrids. In VPPs, EVs are regarded as ESSs that manage the energy flow within microgrids and help balance power generation and consumption, thereby enhancing overall grid stability. EVs are provided with the energy needed for driving from microgrids and can make profits by charging and discharging energy according to energy prices.

2.1.2. *Benefits of a virtual power plant*

VPPs serve as an intelligent energy management system for microgrids, supporting automated and real-time decision-making for optimal power dispatch. By virtue of their inherent characteristics, VPPs contribute to achieving zero carbon emissions, while also providing technological benefits by enhancing the electrical performance of microgrids and economic benefits by ensuring mutual profitability for both VPPs and their participants. Depending on which of these two complementary benefits is prioritized, VPPs can be classified as either technical VPPs (TVPPs) or commercial VPPs (CVPPs) (Esfahani et al., 2025; Gough et al., 2022). In practice, it is important to operate and improve VPPs by appropriately balancing the weight of the following technological and economic benefits.

- *Technological benefit*: VPPs enhance the electric performance of microgrids in various aspects by integrally managing components within local areas through real-time monitoring and optimization. First, VPPs enable prompt responses to frequency fluctuations and voltage instability by coordinating multiple renewable DG units and ESSs in real time and by providing ancillary services (e.g., frequency regulation and voltage support) (Chen et al., 2021; Xiao et al., 2020). Second, VPPs promote both local autonomy and operational stability of microgrids through decentralized management of microgrids enabled by distributed optimization at the local or even more granular level (Dawoud et al., 2018). Specifically, even in emergency situations such as grid failures or blackouts, VPPs enable microgrids to operate autonomously at the local level, thereby enhancing their resilience.
- *Economic benefit*: VPPs generate revenue by enabling the efficient operation of microgrids in various ways. This is achieved through energy savings based on an optimal power dispatch and cost-effective participation in energy markets. The profits generated by VPPs are shared with participants in a transparent and equitable manner through economic models, including optimization-based

approaches that maximize profit and minimize cost, and game theory-based approaches that analyze competitive and cooperative dynamics to regulate market behavior (Wang et al., 2021; Zhou et al., 2024).

2.2. Blockchain

2.2.1. Concepts and types of blockchain

The time-stamping service, which is the concept of blockchain, was proposed by Stuart Haber and W. Scott Stornetta in 1991 to certify the creation and modification times of digital documents and prevent the forgery of information (Haber and Stornetta, 1991). Then, in 2008, Bitcoin, a decentralized cryptocurrency called the first blockchain, was developed by Satoshi Nakamoto (Nakamoto, 2008). Bitcoin enables transactions to be recorded safely and transparently in a decentralized network without going through a centralized financial authority. From this point on, while various blockchains have been and are being developed with tremendous interest, they have a common structure that, as the name suggests, comprises “blocks” where data are stored and “chains” where blocks are linked in succession (refer to Fig. 2). A block is divided into three parts: (i) block hash, a single hash of the block header representing the block; (ii) header, which contains block metadata; and (iii) body, which encompasses the actual transaction data.

As the need for blockchains rises in several fields, the nature of blockchain projects and their participants has become more diverse. Specifically, blockchain exhibits clear differences in decentralization, security, and scalability depending on the configuration of participants in the blockchain network (i.e., network access permission) (Awan et al., 2022). First, public blockchains are permissionless networks that allow anyone to participate, ensuring high transparency and strong security through decentralization (Yang et al., 2020). However, the consensus process among many participants causes scalability issues such as slow transactions and high fees (Rao et al., 2024). Second, private blockchains are permissioned and controlled by a single authority, providing high scalability and strong privacy protection (Yang et al., 2020). Yet, their centralized nature reduces transparency and weakens security against external attacks (Conti et al., 2018). Third, consortium blockchains are permissioned networks jointly managed by multiple groups, combining features of public and private blockchains (Yao et al., 2023). Their transparency, security, and scalability are flexibly determined through intergroup coordination.

2.2.2. Blockchain technologies

The main characteristics of blockchain, stemming from its multiple technologies, have contributed to its adoption in several fields. The four technologies of blockchains are primarily used to operate blockchains: (i) DLT; (ii) cryptographic technologies; (iii) consensus mechanism; and (iv) cryptocurrency.

- *Distributed ledger technology*: DLT is a technology that stores data distributed across all nodes, which are devices of participants in a blockchain network, rather than on a centralized server (Wang and Su, 2020). DLT enables data to be replicated, shared, and synchronized via decision-making between nodes based on a consensus mechanism so that a complete copy of the data (i.e., high transparency) is stored in each node. Even if data manipulation attacks occur on a small number of nodes, a complete copy is kept in the remaining nodes to ensure the integrity and immutability of data stored in the blockchain network (Antal et al., 2021).
- *Cryptographic technologies*: Cryptographic technologies are used in blockchain to comply with the three principles of information protection (i.e., confidentiality, integrity, and availability), which is one of the main purposes of blockchain (El et al., 2024): (i) hash function; (ii) encryption algorithm; and (iii) digital signature. First, a hash function converts data of arbitrary length into a fixed-length value, ensuring data integrity by producing different outputs even for small input changes and enhancing blockchain security as a one-way function that prevents recovery of the original data (Wang and Su, 2020). Second, encryption algorithms are two-way cryptographic technologies using keys to encrypt data and decrypt them as needed. Encryption algorithms ensure data confidentiality and availability because non-participants without keys cannot access the original data, while participants with keys can get the original data after decryption. Third, a digital signature is a cryptographic technology

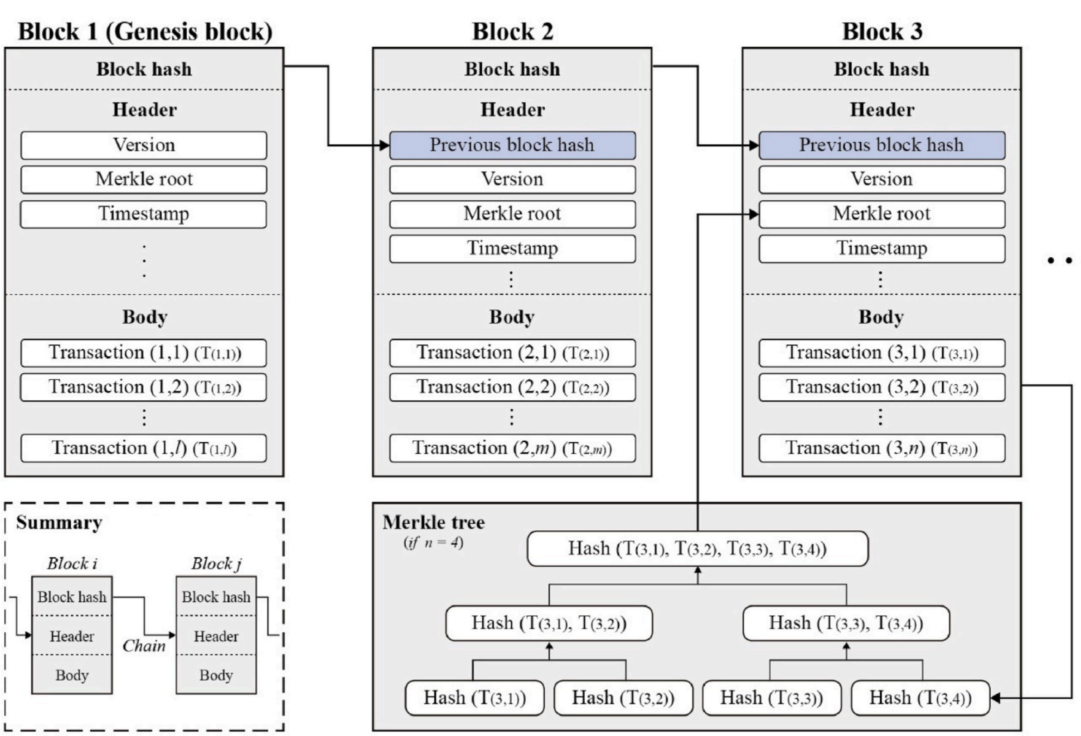

Fig. 2. Basic structure of blockchain.

used to verify the authenticity and source of data or transactions, ensuring that they have not been tampered with during transmission (Johnson et al., 2001). A participant generates a digital signature using a private key to prove that the data originated from them. Then, other participants use a public key to verify the validity of the signature.

- *Consensus mechanism*: A consensus mechanism determines blocks or transactions are to be created in the network to maintain consistency, fault tolerance, and security of the blockchain without relying on a central authority (Carrara et al., 2020). Various consensus mechanisms have been developed and applied to the networks. First, proof of work (PoW) is a consensus mechanism that requires a node to solve a cryptographic puzzle (i.e., work) to create a block and other nodes to verify the block and add a new block to the blockchain (Conti et al., 2018). Second, proof of stake (PoS) is a consensus mechanism in which a selected node among nodes who have staked cryptocurrency (i.e., stakers) creates a block, and other nodes verify the block and add a new block to the blockchain (Fahim et al., 2023). Third, practical Byzantine fault tolerance (PBFT) is a consensus mechanism that allows a highly reliable consensus to be reached even when some nodes called Byzantine nodes in the blockchain network act maliciously or fail (i.e., Byzantine fault) (Zheng et al., 2017). Additionally, other consensus mechanisms are used according to their purposes, such as delegated proof of stake (DPoS), proof of authority (PoA), and proof of importance (PoI).
- *Smart contract*: A smart contract is a computerized contract that is automatically executed when the conditions of agreement written in lines of code are met (Zou et al., 2021). That is, the smart contract ensures efficiency and reliability in transactions because it automates transactions without intermediaries based on accurate smart contract codes. The concluded smart contract is stored on the blockchain, ensuring transparency in transactions. Moreover, it enables the implementation of functions beyond digital asset transactions, thus contributing to the expansion of the blockchain ecosystem (Khan et al., 2021).
- *Cryptocurrency*: Cryptocurrency is a digital or virtual currency created using an encryption algorithm that works as a medium of exchange in a blockchain network without reliance on a central authority such as a bank (Hashemi Joo et al., 2020). Cryptocurrencies are categorized into coins and tokens based on whether they have their own blockchain. Coins are cryptocurrencies that operate on their own blockchain and are mainly used as a means of payment and a store of value (Yao et al., 2023). Tokens are cryptocurrencies that do not have their own blockchain but operate on an existing blockchain network, and are mainly used within blockchain-based services or platforms, or to link with specific assets such as fiat currencies (e.g., the dollar), real assets, and digital assets (Reddi et al., 2024).

2.3. Integration of virtual power plants and blockchain technology

Within the broader framework of VPPs—fundamentally designed to achieve the paramount objective of zero carbon emissions—blockchain technology will be integrated as an instrumental tool for data management. Its diverse capabilities, including decentralization, data integrity, and security, can address structural limitations of existing VPP operations, such as reliance on centralized platforms, lack of transaction transparency, and limited stakeholder trust, while also enhancing current functionalities. By leveraging its decentralized ledger architecture, immutable data recording, and smart contract automation, blockchain enables transparent transaction tracking, faster settlement, and enhanced security, thereby advancing both technological and economic benefits of VPPs (Feng et al., 2025). The following examples demonstrate how blockchain can be integrated into VPPs as a data management tool (refer to Fig. 3). First, blockchain-based decentralized operation has the potential to enable P2P energy trading while maintaining trust, thereby offering economic benefits for participants through the reduction or elimination of intermediary fees. It can also prevent single points of failure in central systems, enhancing the real-time responsiveness and resilience of the power grid (Umar et al.,

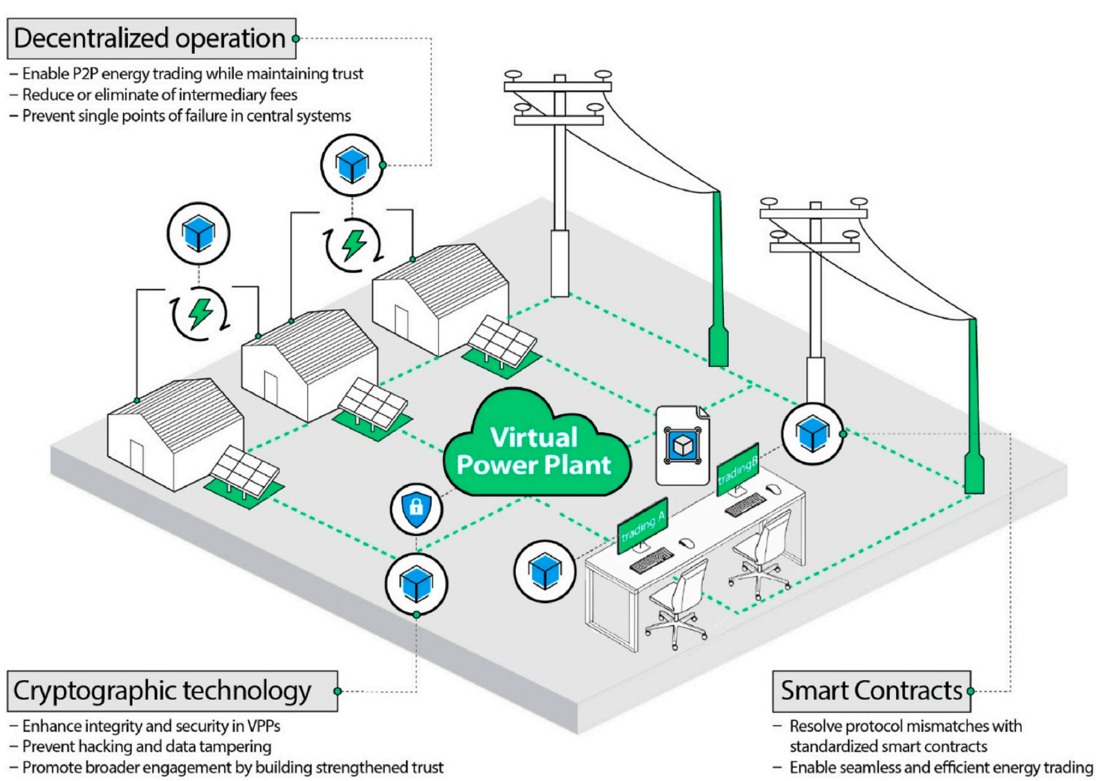

Fig. 3. Blockchain as a data management tool in virtual power plants.

2022). Second, blockchain can enhance integrity and security in VPP operations by leveraging its immutable records and cryptographic technologies to prevent hacking and data tampering during energy trading and settlement processes (Kumar Kasula et al., 2025). This, in turn, can strengthen participants' trust in the VPP and promote broader engagement in its operation. Third, standardized smart contract–based energy trading can overcome limitations of automated transactions caused by protocol or standard mismatches between VPPs and their components, thereby enabling seamless and efficient trading (Kaiss et al., 2025). Beyond these examples, blockchain holds potential as a versatile supporting tool for VPPs across different domains, with integration strategies best informed by a comprehensive review of prior studies.

3. Comprehensive review methodology

To propose future roadmaps for enhancing VPPs based on blockchain, literature that integrates blockchain into VPPs (i.e., target studies) should first be comprehensively reviewed. Prior to analysis, the literature for the comprehensive review was selected in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) framework as follows (refer to Fig. 4) (Hong et al., 2021; Page et al., 2021). First, 1909 documents were identified using specific search terms (i.e., "virtual power plant*" or "VPP*" and "blockchain") from Scopus, which covers a wide range of scientific publications (Wildcard (*) represents any combination of characters that can follow the root term). Second, 442 documents were screened after excluding 1,467 of them based on document type (i.e., research article), language (i.e., English), and research scope (i.e., VPPs with blockchain) using titles, abstracts, and keywords. Third, 129 documents were retained after full-text screening, during which 313 of them were excluded for not meeting the research scope. Finally, 129 documents were included in the comprehensive review as target studies. In this comprehensive review, both quantitative and qualitative reviews were conducted—where the former identified research trends and interests to support the latter, which explored the current research status and its limitations.

Frist, the quantitative review analyzed the research trends and interests in VPPs with blockchain by using metadata from the target studies. The research trends were analyzed based on the number of target studies published by year, indicating the level of interest in the research area on VPPs with blockchain. Then, the research interests were analyzed based on keywords that reflect subjects of interest in the research area. This study carried out a keyword co-occurrence analysis to examine the occurrence of keywords and their relationships (i.e., co-occurrence) in target studies using VOS viewer 1.6.20. A keyword co-occurrence network consists of nodes (i.e., keywords) linked by edges (i.e., co-occurrence between keywords in at least one study), and these edges have a strength as an attribute, which is the frequency of co-

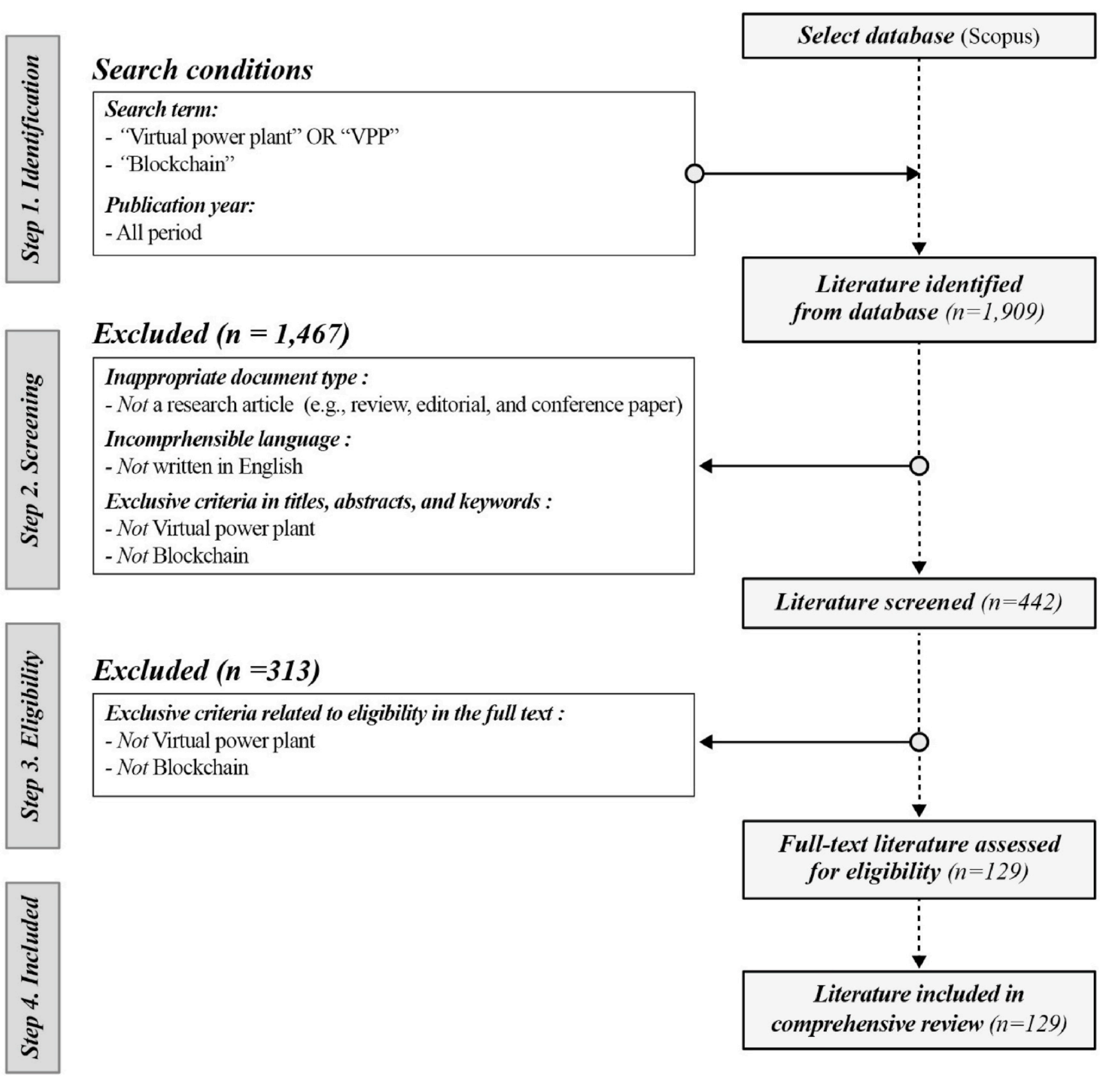

Fig. 4. PRISMA flowchart of literature selection for the comprehensive review.

occurrence between the linked keywords. This network has two criteria to evaluate interest by keyword in the research area: (i) total link strength: sum of the strength of all edges for a keyword; and (ii) number of occurrences: the number of target studies containing a keyword.

Second, the qualitative review analyzed the status of research on VPPs with blockchain by VPP components through an in-depth review of target studies. This analysis was conducted by categorizing blockchain-applied studies according to whether they aimed to achieve the primary objectives for each component of VPPs or to enhance the accessibility of each component to VPPs through associated benefits. Based on this analysis, the limitations were identified in the current research status, serving as the foundation for proposing future roadmaps for enhancing VPPs based on blockchain.

4. Research trends and interests

A quantitative review was conducted on 129 target studies that integrated blockchain into VPPs, focusing on research trends and interests. First, in terms of research trends, target studies began to appear relatively recently—starting in 2018—compared to the earlier onset of research on VPPs in 1997 and blockchain in 2009. The number of target studies from 2018 to 2024 was 4, 7, 15, 21, 35, 35, and 12, respectively. In other words, the number of target studies has steadily increased from 4 in 2018 to 35 in 2023, with an average annual growth rate of 54.31 %. However, the upward trend has slowed in recent years, with the same number (i.e., 35) of target studies were published in 2022 and 2023. Although the number of target studies has increased, it was relatively low compared to related studies. During the same period (from 2018 to 2024), the number of target studies (i.e., 129) constituted only 0.78 % of the research on VPP (i.e., 16,507) and 0.17 % of the research on blockchain (i.e., 77,010), respectively. While many studies that suggested using blockchain as a future technology for improving the performance of VPP, only a few studies were conducted to integrate blockchain into VPP (Brilliantova and Thurner, 2019; Liu and Li, 2022; Nawaz et al., 2022).

Second, in terms of research interests, a keyword co-occurrence network was built based on the top 10 % of keywords (i.e., 31 keywords), excluding the search terms VPP and blockchain, among all keywords (i.e., 319 keywords) of target studies (refer to Table 1 and Fig. 5). The keywords were categorized into VPP-related, blockchain-related, and other keywords.

- *VPP-related keywords*: The most keywords (i.e., 16) were categorized as VPP-related keywords. When compared to keywords in other categories, there were many VPP-related keywords with high total link strength and number of occurrences (i.e., research interest), some of which were ranked 2nd to 12th in research interest. Among the VPP-related keywords, energy trading (or P2P energy trading), one of the key roles of VPP, had the highest research interest. Microgrid (or smart grid) and its components, such as DG, demand, and EV, had similar research interests. Among DGs, there was research interest in renewables (especially PV).
- *Blockchain-related keywords*: Nine keywords were categorized as blockchain-related keywords. Of all the keywords, smart contracts, which are the primary blockchain technology used for P2P energy trading in addition to offering various functions, had the highest research interest. Accordingly, they were also accompanied by research interest in Ethereum, the most representative blockchain network for smart contracts. Among blockchain technologies, consensus mechanism and DLT had similar research interests. In addition, because multiple components (or stakeholders) were included in VPP, there was research interest in consortium blockchain among the types of blockchain.
- *Other keywords*: The least keywords (i.e., 6) were categorized as other keywords. Some of these keywords were about deriving a bidding strategy in game theory (especially, cooperative games) (Ergün, 2024). The rest were interested in technologies (i.e., Internet of Things (IoTs), machine learning, and federated learning) that could be used with blockchain to improve the performance of VPP (Luo and Mahdjoubi, 2024; Saha et al., 2021; Veerasamy et al., 2024).
- *Keyword co-occurrence*: The keyword co-occurrence reflected research focused on improving energy trading, DG, and demand in VPPs, primarily through smart contracts, as visualized in the green, red, and blue clusters, respectively. First, P2P energy trading of distributed energy resources was implemented in local energy markets, where bidding strategies are executed without intermediaries (Soto et al., 2021) and security and privacy were ensured through the integration of DLT and IoT (Muzumdar et al., 2022; Shibu et al., 2024). Second, electricity generated from renewable DG connected

Table 1
Top 10 % keywords determined by keyword co-occurrence analysis.

Keywords	Total link strength	Number of occurrences	Categorization		
			Virtual power plant	Blockchain	Others
Smart contract	37	37		○	
Peer-to-peer energy trading	14	15	○		
Energy trading	14	14	○		
Smart grid	10	10	○		
Distributed energy sources	9	9	○		
Demand response	9	9	○		
Microgrid	9	9	○		
Electric vehicle	9	9	○		
Prosumer	8	8	○		
Photovoltaic	6	6	○		
Peer-to-peer	6	6	○		
Renewables	6	6	○		
Consensus mechanism	5	6		○	
Distributed ledger technology	5	5		○	
Ethereum	4	4		○	
Cooperative game	4	4			○
Internet of Things	4	4			○
Machine learning	4	4			○
Consortium blockchain	3	4		○	
Battery energy storage system	3	3	○		
Bidding strategy	3	3			○
Electricity market	3	3	○		
Energy blockchain	3	3		○	
Federated learning	3	3			○
Integrated energy system	3	3	○		
Local energy market	3	3	○		
Privacy	3	3		○	
Security	3	3		○	
Vehicle-to-grid	3	3	○		
Game theory	2	3			○
Privacy-preserving	2	3		○	

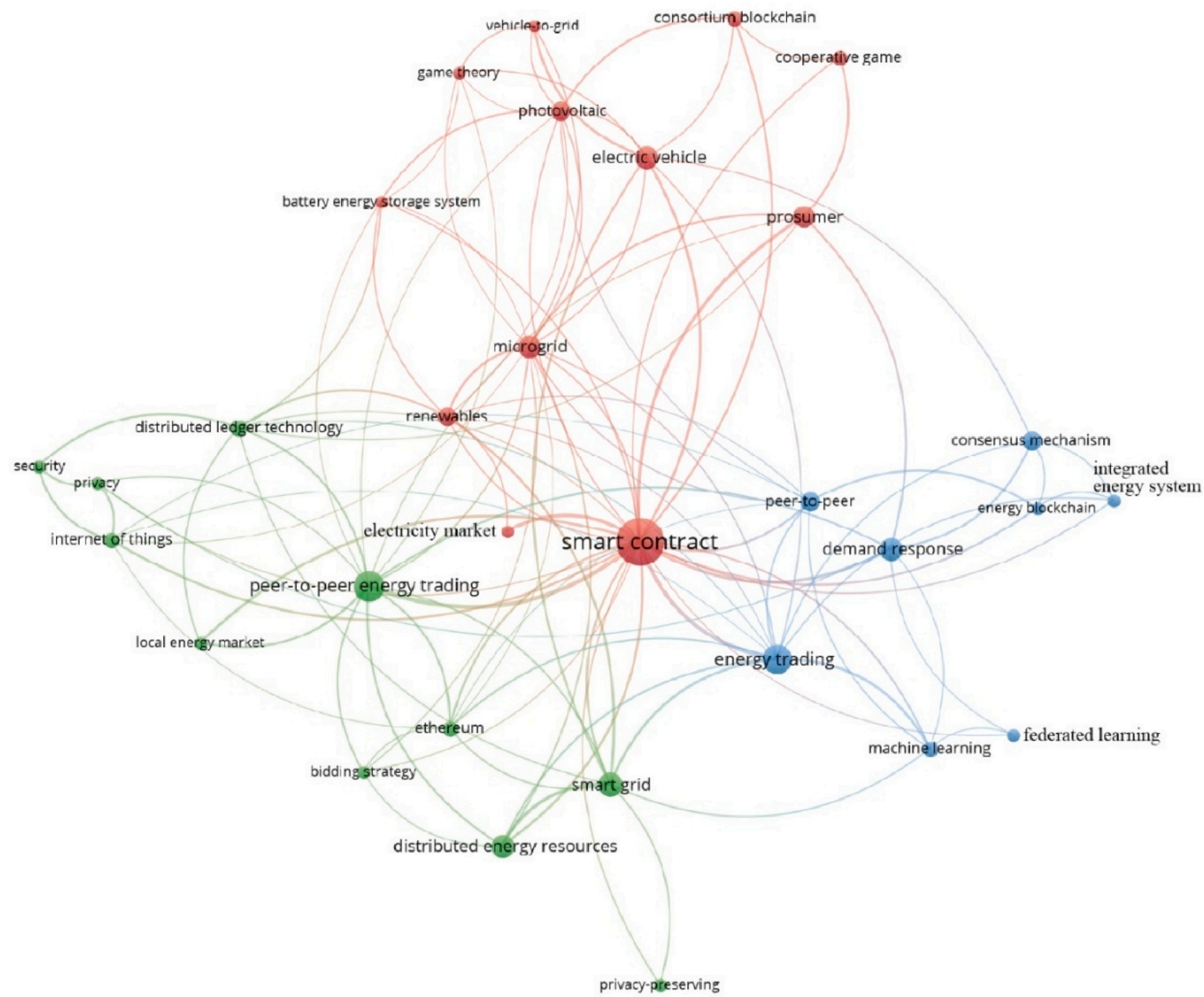

Fig. 5. Keyword co-occurrence network.

to microgrids was efficiently managed using battery ESS and EVs through a consortium blockchain, based on game-theoretical approaches (Chen et al., 2023). Third, demand response in integrated energy systems was improved by applying consensus mechanisms combined with federated learning (Luo and Mahdjoubi, 2024).

In summary, the research area on VPPs with blockchain was in its early stages, showing a gradually increasing trend in interest, with a relatively high focus on energy trading via smart contracts. On the other hand, research interests in other VPP components or blockchain technologies were quite similar. As a result, a quantitative analysis of research trends and interests emphasized the need for comprehensive future roadmaps for integrating blockchain into VPPs to promote early-stage research in a limited field.

5. Research status by virtual power plant components

5.1. Distributed generation

Renewable DG is the primary power source in VPPs, but its intermittency makes generation difficult to predict, reducing microgrid stability and efficiency. Thus, aggregating and controlling more DG units is essential to mitigate these issues. Previous studies used blockchain to improve the energy efficiency of DG (i.e., primary objective) or to improve DG's accessibility to VPPs by providing ancillary benefits (i.e., profitability and security).

First, blockchain improves the energy efficiency of VPPs by aggregating DG units within the network and enabling real-time control of their power generation. Dorri et al. developed a blockchain-based platform to manage the power produced by aggregating DG units (Dorri et al., 2021). This platform integrated DG units with overproduction and underproduction, thereby minimizing energy waste and maximizing profits, while supporting end-to-end automation from energy generation data collection to trading through blockchain-connected smart meters and smart contracts. Mnatsakanyan et al. enabled real-time control of DG through connection with the Ethereum platform and VPP application programming interface (API) (Mnatsakanyan et al., 2022). The smart contract triggers events to control DG based on real-time data, and the control results were verified through a consensus mechanism.

Second, economic motivation and reduction of anxiety about personal information leakage can increase DG's accessibility to VPPs. Blockchain ensures the profitability of DG through transaction automation and token-based incentives and increases security via cryptographic technologies. Samuel et al. ensured the profitability of DG by reducing the energy generation cost (from 2.42 to 1.24 \$/kWh) through smart contracts that automate transaction without an intermediary and token-based incentives for renewable energy sales (Samuel et al., 2020). Tan et al. divided complex optimization problems for power dispatch based on the Lagrangian relaxation technique and effectively controlled the power generation of DG while strengthening security via blockchain (Tan et al., 2019). The DG-related data were not shared because the subproblems were independent of each other and were encrypted using the elliptic curve digital signature algorithm to give an advantage to data privacy protection.

5.2. Demand

Demand predictability and flexibility need to be secured for the stable operation of VPPs. Unexpected spikes in energy consumption (i.e., peak demand) can cause microgrid overloading and imbalance between power generation and consumption, leading to instability (Behzadi et al., 2023; Naraindath et al., 2025). Therefore, previous studies used blockchain to improve demand stability (i.e., primary goal) through demand response, or to encourage participation by providing ancillary benefits (i.e., profitability and security).

First, to maintain microgrid stability in response to power consumption changes, demand responses should be performed rapidly and accurately through a series of data collection, prediction, and control processes, which can be enhanced by blockchain in conjunction with other technologies. Kaif et al. and Ma et al. improved the speed of data collection and training of the demand predictive models (e.g., mixed-integer linear programming (MILP) and Q-learning) by asynchronously training on individual blockchain nodes (Kaif et al., 2024; Ma et al., 2022). Furthermore, the prediction accuracy of the demand predictive model was enhanced by rapidly training demand-related data collected in real time for each node and sharing them in a blockchain. Huang et al. improved the prediction performance of demand predictive models by sharing demand-related data verified for reliability and collected from smart controllers of blockchain nodes, enabling a reduction of cooling load by around 9 % (Huang et al., 2023).

Second, economic motivation and reduction of anxiety about personal information leakage can increase demand's accessibility to VPPs (i.e., demand response) as with DG. Blockchain encourages participation in demand response by improving the profitability of demands in various ways. Saxena et al. introduced a smart contract-based double auction in a blockchain-based residence energy trading system to ensure that demands can purchase energy at the lowest price (Saxena et al., 2021). This trading system also allows demand to voluntarily participate in demand response, reducing peak demand by 62 %. Zhanbolatov et al. proposed a Ethereum-based framework that ensures the profitability of demand by tokenizing the concept of Negawatt, representing the energy saved through demand response, and making it tradable (Zhanbolatov et al., 2022). Next, blockchain has ensured the security of demand in different ways depending on the types of blockchains applied to the VPP. Saxena et al. built a permissioned blockchain system to allow only authorized peers to participate in transactions validation, reducing transaction delays and enhancing privacy (Saxena et al., 2021). On the other hand, Pop et al. demonstrated that in a public blockchain system, an aggregator verifies the activity of new and existing demand-side entities through a smart contract and secures demand-related data using zero-knowledge proof (Pop et al., 2020).

5.3. Energy market for energy trading

Energy flows (i.e., sales) and cash flows (i.e., purchases) that occur between components under optimal power dispatch in a VPP are collectively referred to as energy trading, and the system or platform where these transactions occur is called the energy market. As most of the target studies focused on energy markets for energy trading, the chapter was categorized into the following sub-chapters for a more detailed review: (i) achieving energy trading objectives; (ii) improving accessibility; and (iii) enhancing security. This study referred to VPP components (i.e., players) engaged in buying and selling energy in the energy market as buyers and sellers, respectively, and collectively referred to them as players.

5.3.1. Achieving energy trading objectives

VPPs should determine the optimal power dispatch to achieve their operational objectives as well as the individual objectives of each player, thereby ensuring continued participation in VPPs. Because players trade energy in the energy market with consistent or conflicting objectives, their multiple objectives need to be considered comprehensively. Previous studies used blockchain to achieve the following main objectives through energy trading: (i) maximizing profits; (ii) maximizing self-consumption rate; and (iii) validating energy trading.

First, VPPs aim to maximize players' profits through energy trading by selling energy at high prices and purchasing energy at low prices. Blockchain helps players determine the best bid-offer matching as verified information about energy trading is shared among all players (Gao et al., 2022; Lopez and Zilouchian, 2023; Wang et al., 2022). Zhong et al. incorporated a double auction mechanism that considers energy prices and transaction times into the chain code to improve the profitability of players in VPPs with multiple DG units (Zhong et al., 2022). Through smart contract-based bid-offer matching, the total income of all sellers increased by 24.6 %, while the total cost of all buyers decreased by 31 %. Gough et al. proposed a blockchain-based energy trading platform using smart contracts to perform energy trading with players offering the highest profitability (Gough et al., 2022). The data of the optimal price and quantity of the electricity calculated using MILP was stored on the blockchain. As the profit from energy trading based on the stored data increased, the total operation cost of the VPP was reduced by 4.3 %. Zhao et al. suggested a microgrid trading model based on consortium blockchains to guarantee players' profits despite the intermittency of PV (Zhao et al., 2019). A bid-offer matching mechanism based on Bayesian Nash equilibrium was developed into blockchain code, reducing buyers' energy purchase costs by 5 % and nearly doubling sellers' revenue, thereby improving the profitability for all players.

Second, VPPs aim to maximize the self-consumption rate to achieve a self-sufficient energy community while minimizing carbon emissions within microgrids. Blockchain maintains power generation-consumption balance and improves the self-consumption rate through energy trading by tracking, sharing, and integrating changes in DG and demand in real time. Zhou et al. developed a blockchain-based–double-layer energy trading model to increase the self-consumption rate through energy trading between players and a VPP (Zhou et al., 2024). This model increased energy trading between players or a VPP and reduced energy supply from the external grid, thereby increasing the dependence on the external grid of players and a VPP by up to 10.72 % and 6.72 %, respectively. Yu et al. developed a consortium blockchain-based energy trading mechanism to overcome fluctuating wind power generations and increase the self-consumption rate (Yu et al., 2023). By using blockchain to share fluctuations in power generation and consumption among all players, a VPP increased the self-consumption rate through cooperative gaming-based energy trading among players.

Third, VPPs aim to rapidly and accurately verify the validity of energy trading to enable players to sell or purchase energy consistently with their trading conditions (e.g., energy price, trading time, and trading volume). Blockchain uses a consensus mechanism to validate energy trading and ensures valid transactions with penalties set for malicious or invalid transactions. Lu et al. ensured the validity of 99.38 % of all energy trading by using a POS-based consensus mechanism and setting penalties for failure to meet energy trading conditions (i.e., power generation shortfalls) (Lu et al., 2021). Wang et al. proposed an Ethereum-based blockchain network consensus model to prevent collusion between specific players or malicious energy trading (Wang et al., 2022). This model maintained the security performance of PBFT while reducing the time required for consensus by 3.1 times on average.

5.3.2. Improving accessibility

To balance power generation and consumption in a VPP, multiple players with varying energy profiles should participate in the energy market, offering a wider range of trading options. To do this, efforts are needed to find ways to improve accessibility to the energy market so that both new and existing players can consistently participate in energy trading (Boekelo and Kloppenburg, 2023). Previous studies used blockchain to improve energy market accessibility by automating transactions and utilizing versatile tokens.

First, for energy trading between players, various trading rules, player-specific conditions, and preferences should be considered. Simultaneously, the complex intermediary-based verification process can reduce accessibility to the energy market. To improve energy market accessibility along with the high efficiency of energy trading, blockchain uses smart contracts to codify complex trading considerations and automate verified energy trading without intermediaries (Yao et al., 2021). Yu et al. proposed an Ethereum-based dual blockchain system for validating distributed energy trading (Yu et al., 2022). In this system, the primary blockchain stores energy trading-related data, while the secondary blockchain establishes computation-intensive trading strategies. This system not only automates energy trading but also improves the scalability and efficiency, reducing execution time by up to 87.7 % when compared to the traditional single blockchain system.

Second, blockchain can tokenize both tangible and intangible assets (e.g., energy and engagement level) related to energy trading, assigning quantifiable value and facilitating exchange. Tokens serve multiple purposes, such as transaction currency and incentives, to provide players with ancillary benefits, thus improving energy market accessibility. Toderean et al. used two types of Ethereum-based tokens to perform automated smart contracts for energy trading (Toderean et al., 2023). Lockable Ethereum request for comments (ERC)-20 Tokens were used as payment and incentives between players. In addition, ERC-721 non-fungible tokens (NFTs) were used to ensure the security and traceability of energy trading-related data. Wang et al. implemented a token-based incentive mechanism that rewards players with high participation rates in the energy market, thereby encouraging autonomous energy trading behavior (Wang et al., 2021).

5.3.3. Enhancing security

Security issues related to energy trading should be carefully managed to ensure that players trade energy based on trust in the energy market in a VPP. Manipulation or corruption of energy trading-related data can cause several serious problems (e.g., double payment and fraud) and undermine the credibility of energy markets. In addition, exposure of players' personal information and transaction details can lead to security-related incidents, such as privacy invasions. Therefore, efforts are needed to strengthen security to enable players to actively trade energy without anxiety about security-related incidents. Previous studies used blockchain with derivative ideas to enhance the security of energy trading in terms of credibility and transparency.

First, blockchain provides functions capable of safely processing P2P energy trading while protecting the players' identity. With blockchain, data are encrypted to prevent tampering and are copied, shared, and synchronized to all blocks based on a consensus mechanism to ensure credibility and data integrity for energy trading-related data. Jiang et al. proposed a load resource energy trading system based on a synchronous diffusion mechanism to improve energy trading-related data credibility (Jiang et al., 2023). The synchronization response time and efficiency of blockchain nodes for P2P energy trading were enhanced using a hybrid consensus mechanism and sharing technology. Synchronization to ensure fast responsiveness prevents tampering with data and improves the integrity of stored data. Yu et al. applied a privacy-preserving mechanism to a blockchain, reducing the privacy cost associated with potential cyberattacks (e.g., hash attack, 51 % attack and inference attack) in VPP's P2P energy trading by 75.72 % (Yu et al., 2024).

Second, blockchain uses a decentralized network that allow players to publicly verify all transactions, thereby increasing the transparency of P2P energy trading, building trust between players, and ultimately prevent illegal transactions and fraud. Luo et al. proposed a two-layer distributed P2P energy trading system that ensures transparency and stability of energy trading (Luo et al., 2019). In this system, the upper layer enables transparent energy trading contracts between players through a multi-agent negotiation mechanism while the lower layer helps ensure safe payment through a blockchain-based contract settlement. Khan et al. designed a Hyperledger sawtooth architecture called EPS-ledger (Khan et al., 2021). This architecture provides immutable data records and, by combining hash functions and business rules, detects fraudulent transactions while facilitating the exchange, transmission, tracking, and recording of data.

5.4. Energy storage system and electric vehicles

ESSs and EVs are charged and discharged, reflecting the volatility of DG and demand to maintain a balance between the power generation and consumption of a VPP. However, a complex VPP configuration makes it difficult to determine optimal charge/discharge strategies. Therefore, efforts are needed to improve optimization performance for charge/discharge strategies for ESSs and EVs. The mobility of EVs can also be considered unlike other components. Previous studies used blockchain to improve optimization process for charge/discharge strategies or to activate energy trading between EVs.

First, blockchain enhances the performance of VPPs through the improved optimization process by data sharing and bid-offer matching based on DLT and smart contracts. Lin et al. determined the optimal charge/discharge strategies for multiple ESSs and EVs using MILP and stored them in a distributed ledger in 15-min increments (Lin et al., 2022). Continuous data updates improved the VPP's self-consumption rate, and the predictive accuracy of loads related to ESSs and EVs. Ali et al. proposed a method combining blockchain and multi-agent deep learning that allows a VPP to most efficiently allocate (e.g., consume, store, and sell) surplus energy (Ali et al., 2022). The charging/discharging constraints of ESSs were recorded in smart contracts automating operations and reducing VPP's daily energy costs by up to 21.04 %.

Second, blockchain improves energy trading between EVs in complex situations due to EVs' mobility. Choubey et al. proposed an energy trading model with a consensus mechanism to match valid vehicle-to-vehicle (V2V) energy trading, reflecting the real-time changing energy capacities of EVs (Choubey et al., 2024). This model improved both throughput and latency compared to traditional consensus mechanisms. Bhawana et al. proposed a blockchain enabled energy trading framework that allows EVs to charge their demand from VPPs while maximizing their profitability. This framework reflected traffic conditions (Bhawana et al., 2024).

5.5. Research limitations

The research limitations on VPPs with blockchain, reviewed for each component, were identified. Except for studies about the "energy market for energy trading," research on other components seemed scarce. Most studies focus narrowly on improving energy trading mechanisms rather than leveraging blockchain's diverse capabilities in an integrated manner to achieve comprehensive VPP objectives. Four key limitations were identified:

First, VPPs have different types of individual equipment (e.g., PV, ESS, HVAC system, and EV) for each component. However, target studies discussed linkages and aggregation between components but disregarded using blockchain to manage individual equipment to maintain high performance (e.g., high generation efficiency and charge-discharge efficiency).

Second, VPPs should predict the operation of multiple components to optimize power dispatch. However, there was a lack of research on predicting operations for components other than demand and energy trading, and several variables that could improve predictive performance were not considered.

Third, target studies improved energy trading in VPPs using various blockchain technologies. However, problems related to energy trading that may arise due to the characteristics of blockchain technologies were not considered. These problems include the increased fee, energy, and time required for transactions and the difficulty of changing incorrect energy trading concluded via smart contracts.

Fourth, most target studies focused on small-scale VPPs with limited components. In expanding the blockchain network with VPPs, issues related to network stability, such as security and throughput, were not considered. Accordingly, as the blockchain network expands, personal information leakage is more likely to occur, and real-time energy supply and demand management may become challenging.

6. Two-level futures roadmap for enhancing virtual power plants with blockchain

Based on the identified research limitations in blockchain–VPP integration, this study proposes a two-level future roadmap. The function-level roadmaps outline independent blockchain systems, designed with suitable technologies and tailored to each limitation, aiming to enhance operational efficiency and reliability through data-driven management beyond mere energy dispatch optimization. They also serve to strengthen the technological and economic benefits of VPPs from different perspectives. Furthermore, an integration-level roadmap is proposed to connect these systems into a unified ecosystem. Together, these two-level future roadmaps are expected to overcome current research limitations and fully realize the potential of blockchain–VPP integration.

6.1. Function-level roadmaps

6.1.1. Managing individual equipment with a blockchain-based supply chain system

Before optimizing power dispatch in microgrids, a VPP should ensure that all individual equipment operates at a high performance (Sun and Jin, 2024). Improved performance of individual equipment—such as generating more power with less energy consumption, enables more diverse power dispatch scenarios to meet the operational objectives of the VPP. The supply chain of individual equipment needs to be managed from a life cycle perspective, an area where blockchain offers clear advantages (Ma et al., 2022). Therefore, a blockchain-based supply chain system with three phases based on life cycle was proposed as a function-level roadmap to manage individual equipment within a VPP while maintaining high performance (refer to Fig. 6). Such a system facilitates stable and efficient operation at the individual equipment level, contributing to both grid stability and economic profitability. This future roadmap is expected to be benchmarked against successful cases of blockchain-based supply chain systems in other industries, for example, Walmart's use of Hyperledger Fabric to trace food products, which reduced tracking time from seven days to 2.2 s while ensuring data integrity (LF Decentralized Trust, 2016).

- *Planning and installation phase*: Since individual equipment operates throughout a mid-to long-term life cycle, a VPP should support its participants in planning and installing equipment that best meets operational objectives from the outset. This system can receive the detailed product information (e.g., raw materials, assembly process, performance, and unique identifier) from the manufacturer and store it on a blockchain (Zheng et al., 2017). Additionally, the open and clear disclosure of stored data can allow the participants to purchase high-performance individual equipment from a life cycle perspective with trust.
- *Operation and* maintenance *phase*: A VPP needs to assist participants in operating and managing individual equipment to ensure that performance is maintained as planned in the previous phase. This system uses smart contracts to automatically diagnose faults by comparing real-time IoT sensor data with manufacturer specifications stored on the blockchain. Furthermore, blockchain-based data tracking at the component level supports the creation of optimal repair strategies (e.g., partial repair and full replacement) and clarifies responsibility for defects whether by the manufacturer or the equipment owner (Guo and Zhong, 2023). This means that even if defects occur in individual equipment, this system can automatically identify them and respond rapidly, allowing a VPP to achieve operation objectives as planned without variables. In addition, the continuous accumulation of data on the operation and maintenance of individual equipment is expected to support the development of optimized operational strategies to minimize performance degradation.
- *Decommission and disposal phase*: A VPP should facilitate participants in dismantling and disposing of individual equipment that has reached its end-of-life in an eco-friendly manner. This system can track the dismantling and disposal of individual equipment consisting of high molecular compounds and toxic chemicals. When illegal dismantling and disposal, such as unauthorized dumping, is detected, responsibility can be assigned based on ownership information recorded on the blockchain (Samuel et al., 2020). Furthermore, penalties can be imposed to prevent illegal waste dumping. In addition, this system can increase the recycling rate by automatically selling reusable equipment parts using smart contract-based

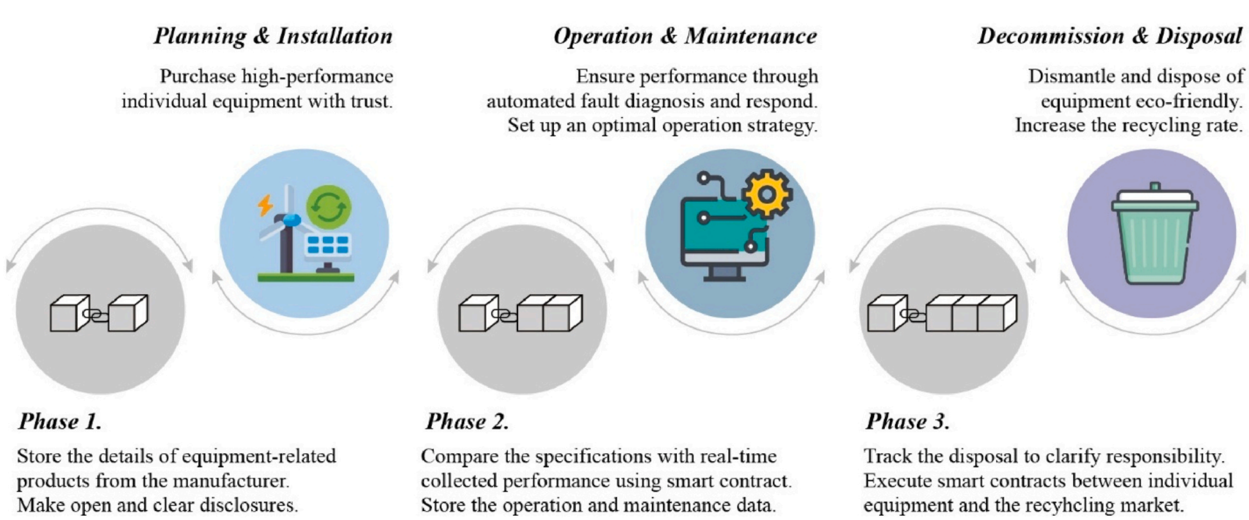

Fig. 6. Blockchain-based supply chain system for individual equipment.

recycling transactions. The sale is triggered when the information on equipment parts matches the purchasing criteria of the recycling market.

6.1.2. Improving predictive performance with blockchain-based big data

Planning and executing the actual optimal power dispatch for a VPP begins with accurate predictions of each component's operation. To improve predictive performance, it is also imperative to enhance the quantity and quality of data used for prediction, over which blockchain has an advantage (Deepa et al., 2022; Tercan and Meisen, 2022). Therefore, building blockchain-based big data with guaranteed quantity and quality by leveraging blockchain's strengths and advanced technologies was proposed as a function-level roadmap to improve the predictive performance of a VPP (refer to Fig. 7). This safeguards the realization of the technological and economic benefits of a VPP envisioned from the outset. Unlike the older generation of blockchain, which focused on cryptocurrency, smart contract, and distributed finance, blockchain 4.0 pursues rapid advancement into a decentralized data management system through linkages with IoTs, AI, and metaverse.

- *Internet of Things*: IoTs are core technologies for real-time monitoring information from various VPP devices. IoTs can be combined with blockchain to create a blockchain assisted-massive wireless network that collects and shares data for systems involving multiple components owned by different users (Zhang et al., 2022). This network can reduce computational overhead by aggregating hierarchical data, distributing data across nodes, and easily adding new nodes while enhancing the scalability of blockchain-based big data (Shen et al., 2020). To this end, it is essential to improve the interoperability between IoT and blockchain to ensure seamless integration and efficient VPP operation.
- *Artificial intelligence*: AI and blockchain mutually reinforce each other's functionality. Blockchain provides trustworthy data to improve the AI performance, whereas AI selects and pre-processes data for storage on the blockchain, forming a virtuous cycle of interaction (Tyagi et al., 2024). In other words, AI can extract relevant data from the diverse formats collected across VPP components, pre-process it for predictive modeling, and simultaneously enhance the conformity and authenticity of blockchain-based big data.
- *Metaverse*: Metaverse, a virtual world where users represented by avatars interact, is expected to present a new paradigm for efficiently collecting data on VPPs in combination with blockchain (Casale-Brunet et al., 2023). Blockchain-based metaverse helps players to voluntarily participate in energy trading and share their trading behavior data through a smart contract-based consensus mechanism in a virtual-real interactive economic system (Zhao et al., 2023). This metaverse can infinitely augment training data for predictive models by simulating diverse VPP operational scenarios using verified real-world data stored on the blockchain, thereby enhancing the effectiveness of blockchain-based big data.
- *Blockchain technologies*: Blockchain technologies can contribute to building big data, depending on their applications. A token economy, which provides fair incentives for data provision, can promote data sharing and collaboration between components and improve the quantity and quality of data (Abou El Houda and Brik, 2023). Cryptographic technologies, which protect sensitive personal information, can encourage components to provide personal attributes (e.g., wage and personality traits) in addition to existing data, based on trust, enhancing the diversity and depth of blockchain-based big data (Shen et al., 2020).

6.1.3. Revitalizing energy markets with a blockchain-based energy trading platform

A VPP should ensure that energy trading is executed as planned, which is one of the most crucial functions in achieving optimal power dispatch. Even a well-planned optimal power dispatch is meaningless without executing actual energy trading. Accordingly, to revitalize energy markets through energy trading, it is essential to develop a user-friendly trading platform offering diverse services. Therefore, a blockchain-based energy trading platform was proposed as a function-level roadmap to revitalize energy markets within a VPP (refer to Fig. 8). This future roadmap is expected to be benchmarked against successful cases of blockchain-based trading platforms in the other sector. For example, in the financial sector, J.P. Morgan launched its own blockchain platform, Onyx, to enable real-time interbank settlements using JPM Coin (Kinexys by J.P. Morgan, 2019). The platform settles over 2 billion USD in transactions daily, with JPM Coin alone accounting for approximately 1 billion USD. These results demonstrate the scalability and reliability of blockchain technology for high-volume, time-sensitive transactions, reinforcing its potential applicability in improving economic profitability as well as facilitating energy trading within a VPP.

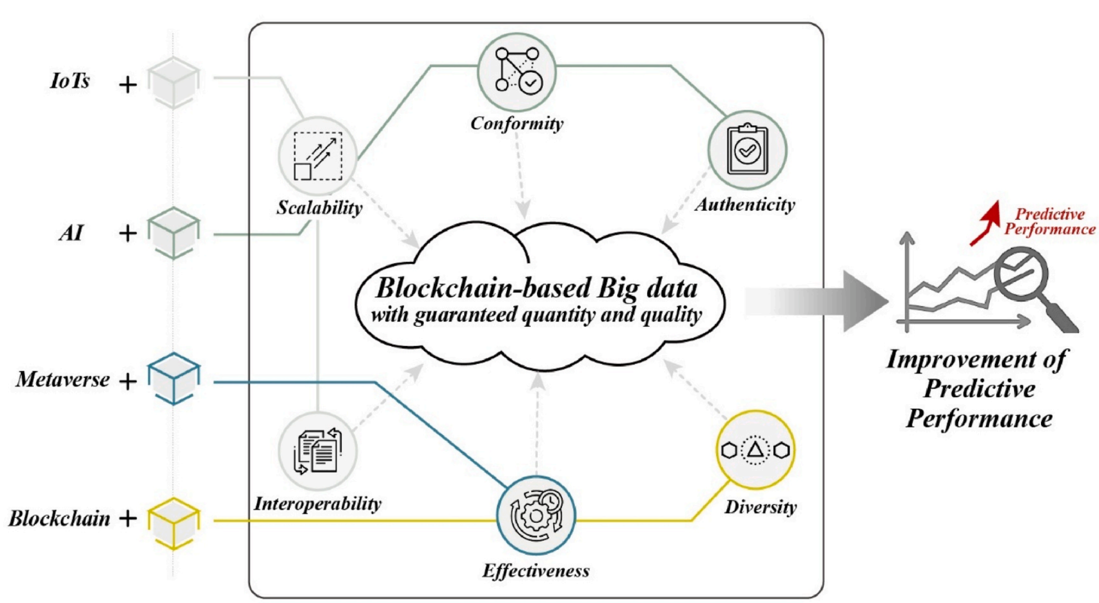

Fig. 7. Blockchain-based big data.

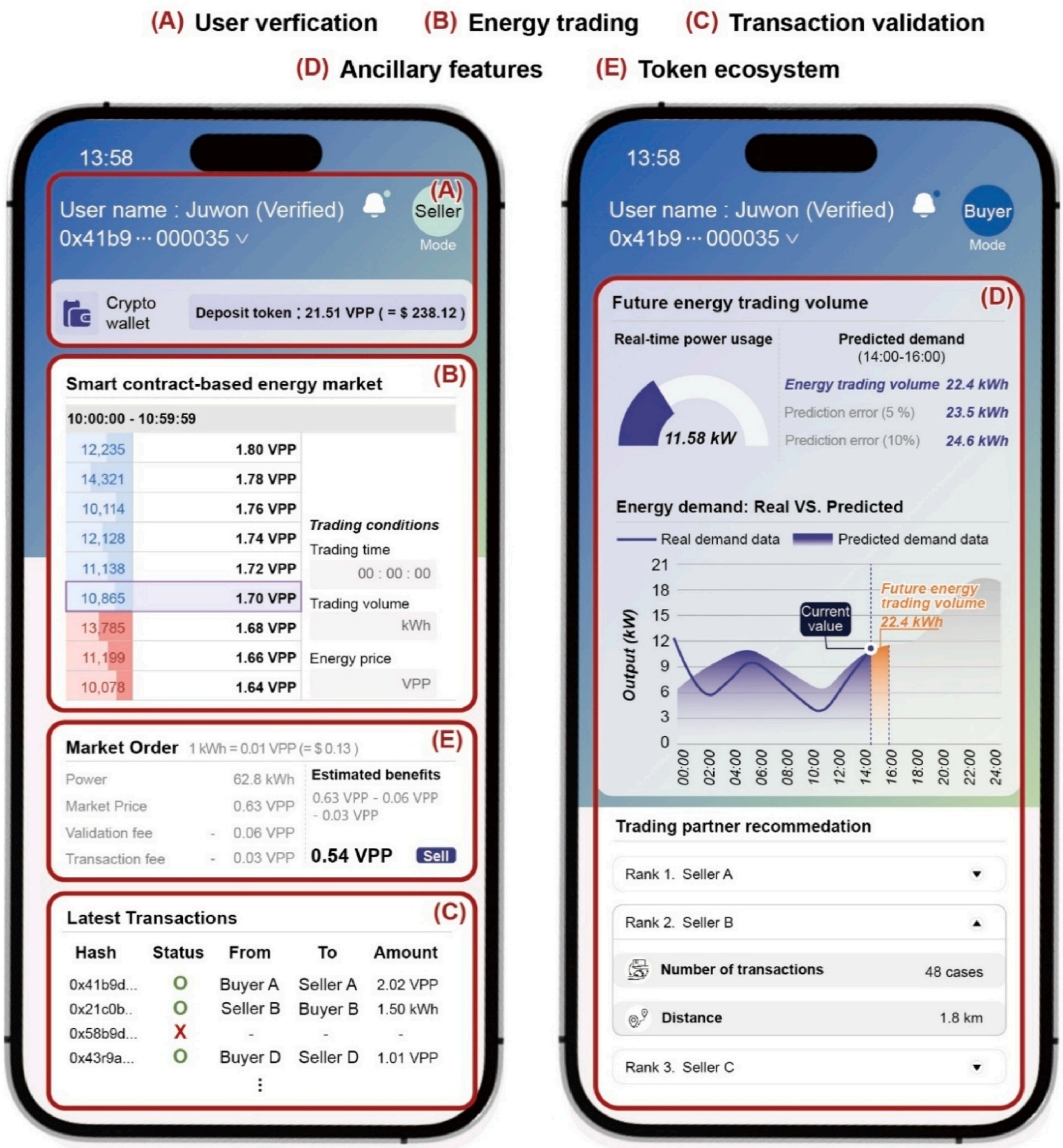

Fig. 8. Blockchain-based energy trading platform.

- *User verification*: New players wishing to participate in this platform should undergo user verification to maintain a trustworthy energy market. New players connect this platform with their cryptocurrency wallets and then go through verification. New players are verified based on their initial platform activities (e.g., reputation system) and the proofs of existing players (e.g., social proof) (de Oliveira et al., 2020). However, since malicious behavior remains possible even after verification, the platform requires new players to put down a token-based deposit as a safeguard (Wang et al., 2022). In the event of malicious behavior, the deposit will be used up in penalties and compensation. In addition, anti-money laundering (AML) and know your customer (KYC) are performed to prevent money laundering through cryptocurrency along with proving of identity.
- *Energy trading*: Smart contracts enable automated and trustless energy trading on the platform without intermediaries. This platform serves to match the most suitable energy trading according to the player's trading conditions. Players enter trading conditions into this platform, and their trading matches other suitable players. However, efforts should be made to make up for the shortcomings of existing smart contracts. The irreversibility of smart contracts that enhance security makes it difficult to cancel or change the contract when incorrect energy trading is executed. Moreover, the smart contract code contains complex conditions, posing difficulties in maintenance required when an error occurs, or additional conditions are added to the contract. Smart contracts, such as upgradable or modularized, can be used to address these shortcomings of smart contracts (Khan et al., 2021).

- *Transaction validation*: This platform performs diverse functions, in addition to energy trading, and transactions occur for various items (e.g., energy, token, and data). The transactions are validated using various consensus mechanisms, depending on the type and purpose of each transaction, and the validation process is shared with players. For instance, consensus mechanism like proof of comprehensive energy ratio (PoCER) and proof of energy consumption (PoEC) can be applied to grant greater authority to players who make higher environmental contributions (Moniruzzaman et al., 2019; Yu et al., 2024).
- *Ancillary features*: This platform offers ancillary features beyond energy trading to offer additional services to users. Ancillary features should be implemented off-chain to avoid transaction delays caused by blockchain network congestion. Ancillary features can be configured based on data stored off-chain. This platform shares data (e.g., energy-related data, historical transaction-related data, and distance) from anonymous trading partners and recommends suitable trading partners based on the shared data. This platform also provides predictive models for energy generation and demand, which can suggest future energy trading volumes to players. These predictive models are expected to demonstrate high predictive performance, supported by data collected from multiple players.
- *Token ecosystem*: A token ecosystem is built to support the economic independence of this platform. Tokens can be used for multiple purposes, such as a currency and incentives for energy trading within the platform. When energy trading is executed in the energy market, the buyer pays the seller the tokens of the same value as the traded energy, some of which are used as incentives for transaction validation and transaction fees for platform use. This platform should incorporate a real-time algorithm that calculates the number of tokens required per unit energy traded, based on current energy and token prices. Additionally, players should be able to convert tokens into fiat currency at any time through integration with the cryptocurrency market. To address price volatility which can affect players' profitability, appropriate token management mechanisms (e.g., token burn and token buyback mechanisms) must be developed and applied to the platform (Cong et al., 2022).

6.1.4. *Ensuring the stability of the network with blockchain-based integrated scaling technology*

A VPP needs to retain technology that ensures network stability (i.e., throughput and security) due to the expansion of VPPs and blockchain networks in preparation for the participation of new components. As the network size (i.e., the number of nodes) increases, the number and complexity of transactions increase exponentially, reducing the stability of the network. That is, the performance of the blockchain network, which was high in small VPPs, can decrease sharply with the addition of nodes. Therefore, blockchain-based integrated scaling technologies were proposed as a functional-level roadmap. It combines on-chain and off-chain approaches to ensure network stability as the number of nodes increases. In the meantime, off-chain and on-chain scaling technologies are selected and integrated depending on the characteristics of the blockchain network.

- *On-chain scaling technology*: Sharding is an on-chain scaling technology that enables blockchain to simultaneously process transactions by dividing the network into small independent units (i.e., shard) as it scales (Vitalik Buterin's website, 2017). In addition, shards process different transactions in parallel, thereby improving throughput and ensuring network stability even during expansion. In addition, sharding ensures stability in terms of security against cyberattacks (e.g., 51 % attack) toward small-scale shards as committees for transaction validation are randomly formed among all nodes at regular intervals. Sharding can be applied to various types of blockchain networks, such as those with high transaction volumes, a large number of nodes, or complex smart contracts, enhancing the performance of VPPs that operate with diverse blockchain functions comprehensively (Liu et al., 2022).
- *Off-chain scaling technology*: Off-chain scaling technologies are tools used to process some transactions in a chain (i.e., off-chain) outside the main chain to reduce the data processing volume of the main chain when the network expands. Off-chain scaling technologies are classified into child chains and side chains depending on whether the external chain depends on the main chain. The child chain, an external chain dependent on the main chain, processes some transactions of the main chain and periodically records the processed transactions on the main chain (Rao et al., 2024). In addition, the child chain inherits the security properties of the main chain but may be slightly vulnerable to cyberattacks due to its small number of nodes. On the other hand, the side chain independently processes specific assets or functions of the main chain and has its own consensus mechanism and model, as needed. In summary, off-chain scaling technologies ensure stability in terms of throughput even if the network expands. While the side chain ensures stability in terms of security, the child chain needs to introduce an additional security model to guarantee security. Currently, off-chain scaling technologies process transactions for bid-offer matching in the blockchain networks of VPPs, and they are expected to support the entire process of smart contracts, except for payment approval (Vionis and Kotsilieris, 2024; Yin et al., 2022).

6.2. *Integration-level roadmap*

6.2.1. *Building a blockchain ecosystem for a virtual power plant*

With the advancement of blockchain-related technologies, it is expected that more function-level blockchain systems (including the function-level roadmaps) will be developed to contribute to achieving the operational objectives of a VPP. Although each function-level blockchain system performs independent functions, it has common goals and shares some data with each other. That is, the integration of function-level blockchain systems can create a synergistic effect in achieving the operational objectives of a VPP. Therefore, a blockchain for a VPP that integrates function-level blockchain systems was proposed as an integration-level roadmap to enhance the performance of a VPP (refer to Fig. 9). This blockchain ecosystem is expected to ultimately become a major means of achieving zero carbon, and the main features of blockchain need to be considered in building the system.

- *Interoperability*: Independent function-level blockchain systems should be able to smoothly interact (i.e., sharing data and assets) with one another. Based on the flow of data and assets, the types of data and assets shared between different systems should be defined and their formats unified. In addition, technologies (e.g., API and blockchain bridge) that support safe data and asset exchange and transfer between systems should be implemented in the blockchain ecosystem.
- *Integrity*: The integrity of the data shared through interaction should be guaranteed for function-level blockchain systems, which belong to the same VPP and are thus exposed to the same situations. Hence, the blockchain ecosystem should implement an optimal data synchronization mechanism to maintain data consistency and further validate the data through a consensus mechanism (Wang et al., 2023).
- *Security*: The security should be ensured at the function-level blockchain system and blockchain ecosystem levels. Because each system involves different components, the blockchain ecosystem must ensure security by restricting access (Miglani et al., 2025). This includes blocking non-participating components and external entities. In addition, the blockchain ecosystem should also ensure its security using strong encryption technologies when data are shared between the systems (Singh et al., 2021).

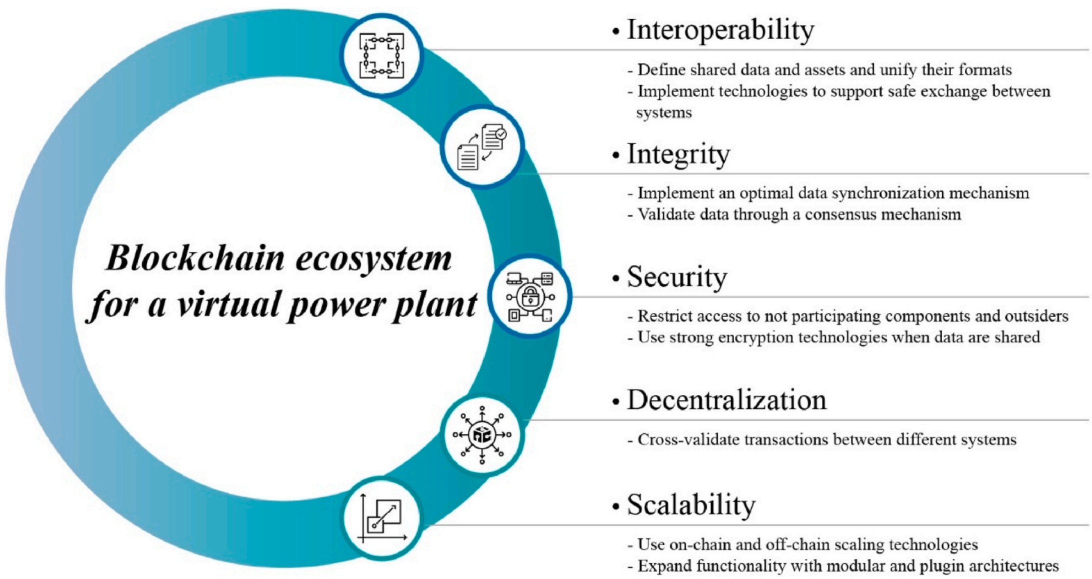

Fig. 9. Considerations of a blockchain ecosystem for a VPP.

- *Decentralization*: A small function-level blockchain system with core functions assigned to it can hinder the overall decentralization of the blockchain ecosystem. Different systems should cross-validate each other's transactions to ensure the decentralization of both individual system and the blockchain ecosystem (Pillai et al., 2020).
- *Scalability*: The scalability of the blockchain ecosystem should be ensured in preparation for VPP activation and expansion. On-chain and off-chain scaling technologies can effectively handle the increased data and transaction volumes. Modular and plugin architectures allow for functional expansion of the blockchain ecosystem.

7. Conclusions

This study offers one of the first comprehensive reviews of blockchain-enabled virtual power plants (VPPs), broadening the perspective beyond energy trading to encompass the full spectrum of blockchain functions across VPP components. Synthesizing 129 studies, the review shows that blockchain-VPP integration is still in its early stages, with research largely concentrated on trading rather than the wider set of blockchain applications. At the component level, studies addressing functions other than trading remain scarce, leaving the full potential of blockchain for comprehensive VPP objectives largely untapped. These gaps indicate the need for targeted development of diverse blockchain functions and their effective integration into a unified operation system.

To address this, the study proposes two level-future roadmaps. At the function level, the focus is on developing blockchain systems that perform independent functions within a VPP: (i) blockchain-based supply chain system to oversee individual equipment within a VPP and maintain high performance throughout its life cycle; (ii) blockchain-based big data to enhance the predictive capabilities of a VPP; (iii) blockchain-based energy trading platform to simulate and expand energy markets within a VPP; and (iv) blockchain-based integrated scaling technology to ensure network stability as VPP and blockchain networks expand to accommodate new components. At the integration level, these functions should be orchestrated within a unified blockchain ecosystem, which can significantly enhance the operational performance of VPPs and accelerate progress toward zero carbon emissions.

While the proposed roadmaps offer strategic insights, further research is required to implement and validate them through practical applications or simulations. The limited availability of real-world cases and operational datasets highlights the need for stepwise pilot studies and benchmark-driven evaluations that can confirm the feasibility and effectiveness of blockchain-enabled VPPs.

CRediT authorship contribution statement

Juwon Hong: Writing – original draft, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Eunseong Song:** Writing – original draft, Visualization, Resources, Data curation. **Jinwoo Choi:** Writing – original draft, Software, Formal analysis, Data curation. **Sangkil Song:** Writing – original draft, Visualization, Data curation. **Hakpyeong Kim:** Writing – review & editing, Resources, Formal analysis, Data curation. **Hyuna Kang:** Writing – review & editing, Visualization, Validation, Software. **Taehoon Hong:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of ethics in publishing

The authors declare that we have read and agree with Elsevier's publishing ethics and confirm that there are no related issues.

Declaration of generative AI in scientific writing

The authors declare that generative artificial intelligence (AI) and AI-enabled technologies were used only to improve the readability and language of the creation process.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT; Ministry of Science and ICT) (NRF-2021R1A3B1076769).

Data availability

Data will be made available on request.

References

Abou El Houda, Z., & Brik, B. (2023). Next-power: Next-generation framework for secure and sustainable energy trading in the metaverse. *Ad Hoc Networks, 149*(June), Article 103243. https://doi.org/10.1016/j.adhoc.2023.103243

Ackermann, T., Andersson, G., & Söder, L. (2001). Distributed generation: A definition. *Electric Power Systems Research, 57*(3), 195–204. https://doi.org/10.1016/S0378-7796(01)00101-8

Ali, L., Azim, M. I., Peters, J., Bhandari, V., Menon, A., Tiwari, V., Green, J., & Muyeen, S. M. (2022). Blockchain-based local energy market enabling P2P trading: An Australian collated case study on energy users, retailers and utilities. *IEEE Access, 10*(December), 124429–124447. https://doi.org/10.1109/ACCESS.2022.3224936

An, J., Hong, J., Kang, H., Yeom, S., Jung, D., Hong, T., Jeong, K., & Lee, J. (2025). The first step towards energy self-sufficiency in smart cities: The present and future of virtual power plant technology. *Building and Environment, 277*(March), Article 112920. https://doi.org/10.1016/j.buildenv.2025.112920

An, J., Hong, T., & Lee, M. (2021). Development of the business feasibility evaluation model for a profitable P2P electricity trading by estimating the optimal trading price. *Journal of Cleaner Production, 295*, Article 126138. https://doi.org/10.1016/j.jclepro.2021.126138

Anandhabalaji, V., Babu, M., & Brintha, R. (2024). Energy consumption by cryptocurrency: A bibliometric analysis revealing research trends and insights. *Energy Nexus, 13*(February), Article 100274. https://doi.org/10.1016/j.nexus.2024.100274

Antal, C., Cioara, T., Anghel, I., Antal, M., & Salomie, I. (2021). Distributed ledger technology review and decentralized applications development guidelines. *Future Internet, 13*(3), 1–32. https://doi.org/10.3390/fi13030062

Arar Tahir, K., Zamorano, M., & Ordóñez García, J. (2023). Scientific mapping of optimisation applied to microgrids integrated with renewable energy systems. *International Journal of Electrical Power & Energy Systems, 145*(September 2022), Article 108698. https://doi.org/10.1016/j.ijepes.2022.108698

Awan, I., Benbernou, S., Younas, M., & Aleksy, M. (2022). In I. Awan, S. Benbernou, M. Younas, & M. Aleksy (Eds.), *The international conference on deep learning, big data and blockchain (Deep-BDB 2021)* (Vol 309). Springer International Publishing. https://doi.org/10.1007/978-3-030-84337-3.

Awerbuch, S., & Preston, A. (Eds.). (1997). *The virtual utility: Accounting, technology & competitive aspects of the emerging Industry*. Springer US. https://doi.org/10.1007/978-1-4615-6167-5.

Behzadi, A., Mojtaba, S., Yu, H., & Sadrizadeh, S. (2023). An efficient renewable hybridization based on hydrogen storage for peak demand reduction : A rule-based energy control and optimization using machine learning techniques. *Journal of Energy Storage, 57*(December 2022), Article 106168. https://doi.org/10.1016/j.est.2022.106168

Bhawana, Kumar, S., Rathore, R. S., Dohare, U., Kaiwartya, O., Lloret, J., & Kumar, N. (2024). BEET: Blockchain enabled energy trading for E-mobility Oriented electric vehicles. *IEEE Transactions on Mobile Computing, 23*(4), 3018–3034. https://doi.org/10.1109/TMC.2023.3267565

Boekelo, M., & Kloppenburg, S. (2023). Energy platforms and the future of energy citizenship. *Energy Research & Social Science, 102*(408), Article 103165. https://doi.org/10.1016/j.erss.2023.103165

Brilliantova, V., & Thurner, T. W. (2019). Blockchain and the future of energy. *Technology in Society, 57*(November 2018), 38–45. https://doi.org/10.1016/j.techsoc.2018.11.001

Carrara, G. R., Burle, L. M., Medeiros, D. S. V., de Albuquerque, C. V. N., & Mattos, D. M. F. (2020). Consistency, availability, and partition tolerance in blockchain: A survey on the consensus mechanism over peer-to-peer networking. *Annales Des Telecommunications/Annals of Telecommunications, 75*(3–4), 163–174. https://doi.org/10.1007/s12243-020-00751-w

Casale-Brunet, S., Mattavelli, M., & Chiariglione, L. (2023). Exploring blockchain-based metaverses: Data collection and valuation of virtual lands using machine learning techniques. *Digital Business, 3*(2), Article 100068. https://doi.org/10.1016/j.digbus.2023.100068

Chen, Y., Li, Y., Chen, Q., Wang, X., Li, T., & Tan, C. (2023). Computer Standards & Interfaces Energy trading scheme based on consortium blockchain and game theory. *Computer Standards & Interfaces, 84*(September 2022), Article 103699. https://doi.org/10.1016/j.csi.2022.103699

Chen, J., Liu, M., & Milano, F. (2021). Aggregated model of virtual power plants for transient frequency and voltage stability analysis. *IEEE Transactions on Power Systems, 36*(5), 4366–4375. https://doi.org/10.1109/TPWRS.2021.3063280

Choubey, A., Sikarwar, A., Asoba, S., & Misra, R. (2024). Towards an IPFS-based highly scalable blockchain for PEV charging and achieve near super-stability in a V2V environment. In *Cluster computing*. Springer, Article 0123456789. https://doi.org/10.1007/s10586-023-04227-z. US.

Cong, L. W., Li, Y., & Wang, N. (2022). Token-based platform finance. *Journal of Financial Economics, 144*(3), 972–991. https://doi.org/10.1016/j.jfineco.2021.10.002

Conti, M., Sandeep, K. E., Lal, C., & Ruj, S. (2018). A survey on security and privacy issues of bitcoin. *IEEE Communications Surveys and Tutorials, 20*(4), 3416–3452. https://doi.org/10.1109/COMST.2018.2842460

Dawoud, S. M., Lin, X., & Okba, M. I. (2018). Hybrid renewable microgrid optimization techniques : A review. *Renewable and Sustainable Energy Reviews, 82*(April 2016), 2039–2052. https://doi.org/10.1016/j.rser.2017.08.007

de Oliveira, M. T., Reis, L. H. A., Medeiros, D. S. V., Carrano, R. C., Olabarriaga, S. D., & Mattos, D. M. F. (2020). Blockchain reputation-based consensus: A scalable and resilient mechanism for distributed mistrusting applications. *Computer Networks, 179* (May), Article 107367. https://doi.org/10.1016/j.comnet.2020.107367

Deepa, N., Pham, Q. V., Nguyen, D. C., Bhattacharya, S., Prabadevi, B., Gadekallu, T. R., Maddikunta, P. K. R., Fang, F., & Pathirana, P. N. (2022). A survey on blockchain for big data: Approaches, opportunities, and future directions. *Future Generation Computer Systems, 131*, 209–226. https://doi.org/10.1016/j.future.2022.01.017

Dorri, A., Luo, F., Karumba, S., Kanhere, S., Jurdak, R., & Dong, Z. Y. (2021). Temporary immutability: A removable blockchain solution for prosumer-side energy trading. *Journal of Network and Computer Applications, 180*(January), Article 103018. https://doi.org/10.1016/j.jnca.2021.103018

El, N., Ioanna, M., & Emmanuel, D. (2024). Blockchain and smart-contract technologies for innovative applications. In N. El Madhoun, I. Dionysiou, & E. Bertin (Eds.), *Blockchain and smart-contract technologies for innovative applications*. Nature Switzerland: Springer. https://doi.org/10.1007/978-3-031-50028-2.

Ergün, S. (2024). Trading excess consumption certificates on the blockchain using the cooperative game theory. *Kybernetes, 53*(2), 645–668. https://doi.org/10.1108/K-01-2023-0022

Esfahani, M., Alizadeh, A., Cao, B., Kamwa, I., & Xu, M. (2025). Bridging theory and practice: A comprehensive review of virtual power plant technologies and their real-world applications. *Renewable and Sustainable Energy Reviews, 222*(June), Article 115929. https://doi.org/10.1016/j.rser.2025.115929

Fahim, S., Katibur Rahman, S., & Mahmood, S. (2023). Blockchain: A Comparative study of consensus algorithms PoW, PoS, PoA, PoV. *International Journal of Mathematics and Soft Computing, 9*(3), 46–57. https://doi.org/10.5815/ijmsc.2023.03.04

Fankhauser, S., Smith, S. M., Allen, M., Axelsson, K., Hale, T., Hepburn, C., Kendall, J. M., Khosla, R., Lezaun, J., Mitchell-Larson, E., Obersteiner, M., Rajamani, L., Rickaby, R., Seddon, N., & Wetzer, T. (2022). The meaning of net zero and how to get it right. *Nature Climate Change, 12*(1), 15–21. https://doi.org/10.1038/s41558-021-01245-w

Faria, P., Spínola, J., & Vale, Z. (2016). Aggregation and Remuneration of electricity Consumers and Producers for the definition of demand-response Programs. *IEEE Transactions on Industrial Informatics, 12*(3), 952–961. https://doi.org/10.1109/TII.2016.2541542

Feng, C., Cheng, J., Li, Z., Yan, Y., Ma, L., An, L., & Zhang, Y. (2025). Blockchain-based transaction mechanism in virtual power plant: Considering users' privacy and reputation. *Electric Power Systems Research, 249*(February), Article 111988. https://doi.org/10.1016/j.epsr.2025.111988

Gao, G., Song, C., Thusitha Asela Bandara, T. G., Shen, M., Yang, F., Posdorfer, W., Tao, D., & Wen, Y. (2022). FogChain: A blockchain-based peer-to-peer solar power trading system powered by fog AI. *IEEE Internet of Things Journal, 9*(7), 5200–5215. https://doi.org/10.1109/JIOT.2021.3109057

Gough, M., Santos, S. F., Almeida, A., Lotfi, M., Javadi, M. S., Fitiwi, D. Z., Osorio, G. J., Castro, R., & Catalao, J. P. S. (2022). Blockchain-based transactive energy framework for connected virtual power plants. *IEEE Transactions on Industry Applications, 58*(1), 986–995. https://doi.org/10.1109/TIA.2021.3131537

Gough, M., Santos, S. F., Lotfi, M., Javadi, M. S., Osorio, G. J., Ashraf, P., Castro, R., & Catalao, J. P. S. (2022). Operation of a technical virtual power plant considering diverse distributed energy resources. *IEEE Transactions on Industry Applications, 58* (2), 2547–2558. https://doi.org/10.1109/TIA.2022.3143479

Guo, R., & Zhong, Z. (2023). A customer-centric IoT-based novel closed-loop supply chain model for WEEE management. *Advanced Engineering Informatics, 55*(July 2022), Article 101899. https://doi.org/10.1016/j.aei.2023.101899

Haber, S., & Stornetta, W. S. (1991). How to time-Stamp a digital document. In *Advances in Cryptology-CRYPTO' 90* (pp. 437–455). Springer Berlin Heidelberg. https://doi.org/10.1007/3-540-38424-3_32.

Hashemi Joo, M., Nishikawa, Y., & Dandapani, K. (2020). Cryptocurrency, a successful application of blockchain technology. *Managerial Finance, 46*(6), 715–733. https://doi.org/10.1108/MF-09-2018-0451

Hong, J., Kang, H., An, J., Choi, J., Hong, T., Park, H. S., & Lee, D. E. (2021). Towards environmental sustainability in the local community: Future insights for managing the hazardous pollutants at construction sites. *Journal of Hazardous Materials, 403* (September 2020), Article 123804. https://doi.org/10.1016/j.jhazmat.2020.123804

Hua, W., Chen, Y., Qadrdan, M., Jiang, J., Sun, H., & Wu, J. (2022). Applications of blockchain and artificial intelligence technologies for enabling prosumers in smart grids: A review. *Renewable and Sustainable Energy Reviews, 161*(December 2021), Article 112308. https://doi.org/10.1016/j.rser.2022.112308

Huang, Z. F., Soh, K. Y., Islam, M. R., & Chua, K. J. (2023). Development of a novel grid-free district cooling system considering blockchain-based demand response management. *Applied Energy, 342*(May), Article 121152. https://doi.org/10.1016/j.apenergy.2023.121152

Jiang, W., Lin, X., Yang, Z., Xiao, Y., Zhang, K., Zhou, M., & Qian, B. (2023). A credible and adjustable load resource trading system based on blockchain networks. *Frontiers in Physics, 11*(February), 1–14. https://doi.org/10.3389/fphy.2023.1145361

Johnson, D., Menezes, A., & Vanstone, S. (2001). The elliptic curve digital signature algorithm (ECDSA). *International Journal of Information Security, 1*(1), 36–63. https://doi.org/10.1007/s102070100002

Jung, S., Kang, H., Lee, M., & Hong, T. (2020). An optimal scheduling model of an energy storage system with a photovoltaic system in residential buildings considering the economic and environmental aspects. *Energy and Buildings*. https://doi.org/10.1016/j.enbuild.2019.109701

Kaif, A. M. A. D., Alam, K. S., & Das, S. K. (2024). Blockchain based sustainable energy transition of a Virtual Power Plant: Conceptual framework design & experimental implementation. *Energy Reports, 11*(November 2023), 261–275. https://doi.org/10.1016/j.egyr.2023.11.061

Kaiss, M., Wan, Y., Gebbran, D., Vila, C. U., & Dragičević, T. (2025). Review on virtual power plants/virtual aggregators: Concepts, applications, prospects and operation strategies. *Renewable and Sustainable Energy Reviews, 211*, Article 115242. https://doi.org/10.1016/j.rser.2024.115242 (August 2024).

Kang, H., Jung, S., Kim, H., Hong, J., Jeoung, J., & Hong, T. (2023). Multi-objective sizing and real-time scheduling of battery energy storage in energy-sharing community based on reinforcement learning. *Renewable and Sustainable Energy Reviews, 185*(July), Article 113655. https://doi.org/10.1016/j.rser.2023.113655

Khan, A. A., Laghari, A. A., Liu, D. S., Shaikh, A. A., Ma, D. A., Wang, C. Y., & Wagan, A. A. (2021). EPS-ledger: Blockchain hyperledger sawtooth-enabled distributed power systems chain of operation and control node privacy and security. *Electronics (Switzerland), 10*(19), 1–22. https://doi.org/10.3390/electronics10192395

Khan, S. N., Loukil, F., Ghedira-Guegan, C., Benkhelifa, E., & Bani-Hani, A. (2021). Blockchain smart contracts: Applications, challenges, and future trends. *Peer-to-Peer Networking and Applications, 14*(5), 2901–2925. https://doi.org/10.1007/s12083-021-01127-0

Kinexys by J.P. Morgan. (2019). Digital payments. https://www.jpmorgan.com/kinexys/digital-payments. (Accessed 10 August 2025).

Kumar Kasula, V., Babu Rakki, S., & Banoth, R. (2025). Enhancing hyperledger fabric security with Lightweight Post-Quantum Cryptography and National cryptographic algorithms. In *Conference of open innovation association, FRUCT* (pp. 93–99). https://doi.org/10.23919/FRUCT65909.2025.11008110

Lacity, M. C. (2018). Addressing key challenges to make enterprise blockchain a reality. *Growing Business Interest in Blockchain Technology, 12*(September), 201–222. https://angel.co/blockchains.

Lee, M., Hong, T., & Koo, C. (2016). An economic impact analysis of state solar incentives for improving fi nancial performance of residential solar photovoltaic systems in the United States. *Renewable and Sustainable Energy Reviews, 58*, 590–607. https://doi.org/10.1016/j.rser.2015.12.297

Lee, M., Hong, T., Koo, C., & Kim, C. J. (2018). A break-even analysis and impact analysis of residential solar photovoltaic systems considering state solar incentives. *Technological and Economic Development of Economy, 24*(2), 358–382. https://doi.org/10.3846/20294913.2016.1212745

LF Decentralized Trust. (2016). How walmart brought unprecedented transparency to the food supply chain with hyperledger fabric. https://www.lfdecentralizedtrust.org/case-studies/walmart-case-study. (Accessed 10 August 2025).

Li, Q., Chen, Z., Min, J., Xu, M., Zhan, Y., Zhang, W., & Sun, C. (2024). Hybrid transaction model for optimizing the distributed power trading market. *Humanities and Social Sciences Communications, 11*(1), 1–13. https://doi.org/10.1057/s41599-024-04012-2

Lin, Y. J., Chen, Y. C., Zheng, J. Y., Shao, D. W., Chu, D., & Yang, H. T. (2022). Blockchain-based intelligent charging station management system platform. *IEEE Access, 10*(September), 101936–101956. https://doi.org/10.1109/ACCESS.2022.3208894

Liu, C., & Li, Z. (2022). Comparison of centralized and peer-to-peer decentralized market Designs for. *IEEE Transactions on Industry Applications, 58*(1), 67–77. https://doi.org/10.1109/TIA.2021.3119559

Liu, Y., Liu, J., Vaz Salles, M. A., Zhang, Z., Li, T., Hu, B., Henglein, F., & Lu, R. (2022). Building blocks of sharding blockchain systems: Concepts, approaches, and open problems. *Computer Science Review, 46*, Article 100513. https://doi.org/10.1016/j.cosrev.2022.100513

Lopez, H. K., & Zilouchian, A. (2023). Peer-to-peer energy trading for photo-voltaic prosumers. *Energy, 263*(PA), Article 125563. https://doi.org/10.1016/j.energy.2022.125563

Lu, J., Wu, S., Cheng, H., & Xiang, Z. (2021). Smart contract for distributed energy trading in virtual power plants based on blockchain. *Computational Intelligence, 37*(3), 1445–1455. https://doi.org/10.1111/coin.12388

Luo, F., Dong, Z. Y., Liang, G., Murata, J., & Xu, Z. (2019). A distributed electricity trading system in active distribution networks based on multi-agent Coalition and blockchain. *IEEE Transactions on Power Systems, 34*(5), 4097–4108. https://doi.org/10.1109/TPWRS.2018.2876612

Luo, X., & Mahdjoubi, L. (2024). Towards a blockchain and machine learning-based framework for decentralised energy management. *Energy and Buildings*, (July 2023), 303. https://doi.org/10.1016/j.enbuild.2023.113757

Ma, D., Qin, H., & Hu, J. (2022). Achieving triple sustainability in closed-loop supply chain: The optimal combination of online platform sales format and blockchain-enabled recycling. *Computers & Industrial Engineering, 174*(October), Article 108763. https://doi.org/10.1016/j.cie.2022.108763

Ma, R., Yi, Z., Xiang, Y., Shi, D., Xu, C., & Wu, H. (2022). A blockchain-enabled demand management and control framework driven by deep reinforcement learning. *IEEE Transactions on Industrial Electronics, 70*(1), 430–440. https://doi.org/10.1109/TIE.2022.3146631

Manivannan, R. (2024). Research on IoT-based hybrid electrical vehicles energy management systems using machine learning-based algorithm. *Sustainable Computing: Informatics and Systems, 41*(October 2023), Article 100943. https://doi.org/10.1016/j.suscom.2023.100943

Miglani, A., Patel, K., Modi, M., Gadhvi, Y., & Shah, M. (2025). A comprehensive study on energy trading and finance using blockchain technology. *Unconventional Resources, 6*(November 2024), Article 100160. https://doi.org/10.1016/j.uncres.2025.100160

Mnatsakanyan, A., Albeshr, H., Almarzooqi, A., Iraklis, C., & Bilbao, E. (2022). Blockchain mediated virtual power plant: From concept to demonstration. *Journal of Engineering, 2022*(7), 732–738. https://doi.org/10.1049/tje2.12158

Mnatsakanyan, A., & Kennedy, S. W. (2015). A novel demand response model with an application for a virtual power plant. *IEEE Transactions on Smart Grid, 6*(1), 230–237. https://doi.org/10.1109/TSG.2014.2339213

Monie, S., Nilsson, A. M., Widén, J., & Åberg, M. (2021). A residential community-level virtual power plant to balance variable renewable power generation in Sweden. *Energy Conversion and Management, 228*. https://doi.org/10.1016/j.enconman.2020.113597

Moniruzzaman, M., Yassine, A., & Benlamri, R. (2019). Blockchain-based mechanisms for local energy trading in smart grids. In *HONET-ICT 2019 - IEEE 16th international Conference on smart Cities: Improving quality of life using ICT, IoT and AI* (pp. 110–114). https://doi.org/10.1109/HONET.2019.8908024

Muzumdar, A., Modi, C., & Vyjayanthi, C. (2022). Designing a blockchain-enabled privacy-preserving energy theft detection system for smart grid neighborhood area network. *Electric Power Systems Research, 207*(October 2021), Article 107884. https://doi.org/10.1016/j.epsr.2022.107884

Nakamoto, S. (2008). Bitcoin: A peer-to-peer electronic cash system. www.bitcoin.org.

Naraindath, N. R., Naidoo, R. M., & Bansal, R. C. (2025). Adaptive optimization and dynamic pricing in decentralized energy markets using blockchain technology and consensus-based verification. *Sustainable Energy, Grids and Networks, 42*(January), Article 101630. https://doi.org/10.1016/j.segan.2025.101630

Nawaz, A., Zhou, M., Wu, J., & Long, C. (2022). A comprehensive review on energy management, demand response, and coordination schemes utilization in multi-microgrids network. *Applied Energy, 323*(May), Article 119596. https://doi.org/10.1016/j.apenergy.2022.119596

Nosratabadi, S. M., Hooshmand, R. A., & Gholipour, E. (2017). A comprehensive review on microgrid and virtual power plant concepts employed for distributed energy resources scheduling in power systems. *Renewable and Sustainable Energy Reviews, 67*, 341–363. https://doi.org/10.1016/j.rser.2016.09.025

Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., McDonald, S., … Moher, D. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *The BMJ, 372*. https://doi.org/10.1136/bmj.n71

Panda, S., Mohanty, S., Rout, P. K., & Sahu, B. K. (2022). A conceptual review on transformation of micro-grid to virtual power plant: Issues, modeling, solutions, and future prospects. *International Journal of Energy Research, 46*(6), 7021–7054. https://doi.org/10.1002/er.7671

Pillai, B., Biswas, K., & Muthukkumarasamy, V. (2020). Cross-chain interoperability among blockchain-based systems using transactions. *The Knowledge Engineering Review, 35*, e23. https://doi.org/10.1017/S0269888920000314

Polaris Market Research. (2023). Blockchain technology in the energy sector market share, size, trends, industry analysis Report, by type (public, private), by component, by end-user, by application, by region, Segments & Forecast, 2024 – 2032. https://www.polarismarketresearch.com/industry-analysis/blockchain-technology-in-the-energy-sector-market. (Accessed 10 August 2025).

Pop, C. D., Antal, M., Cioara, T., Anghel, I., & Salomie, I. (2020). Blockchain and demand response: Zero-knowledge proofs for energy transactions privacy. *Sensors, 20*(19), 1–21. https://doi.org/10.3390/s20195678

Pourghaderi, N., Fotuhi-Firuzabad, M., Moeini-Aghtaie, M., & Kabirifar, M. (2018). Commercial demand response Programs in bidding of a technical virtual power plant. *IEEE Transactions on Industrial Informatics, 14*(11), 5100–5111. https://doi.org/10.1109/TII.2018.2828039

Rao, I. S., Kiah, M. L. M., Hameed, M. M., & Memon, Z. A. (2024). *Scalability of blockchain: A comprehensive review and future research direction* (Vol. 7). Cluster Computing. https://doi.org/10.1007/s10586-023-04257-7

Reddi, R., Onur, D. J. S., & Manisa, E. (2024). Cybersecure and scalable , token-based renewable energy certificate framework using blockchain-enabled trading platform. *Electrical Engineering, 106*(2), 1841–1852. https://doi.org/10.1007/s00202-022-01688-0

Rodrigues, S. D., & Garcia, V. J. (2023). Transactive energy in microgrid communities: A systematic review. *Renewable and Sustainable Energy Reviews, 171*(October 2022), Article 112999. https://doi.org/10.1016/j.rser.2022.112999

Rouzbahani, H. M., Karimipour, H., & Lei, L. (2021). A review on virtual power plant for energy management. *Sustainable Energy Technologies and Assessments, 47*(November 2020), Article 101370. https://doi.org/10.1016/j.seta.2021.101370

Ruan, G., Qiu, D., Sivaranjani, S., Awad, A. S. A., & Strbac, G. (2024). Data-driven energy management of virtual power plants: A review. *Advances in Applied Energy, 14*(February), Article 100170. https://doi.org/10.1016/j.adapen.2024.100170

Saha, R., Kumar, G., Geetha, G., Tai-Hoon-Kim, Alazab, M., Thomas, R., Rai, M. K., & Rodrigues, J. J. P. C. (2021). The blockchain solution for the security of internet of energy and electric vehicle interface. *IEEE Transactions on Vehicular Technology, 70*(8), 7495–7508. https://doi.org/10.1109/TVT.2021.3094907

Samuel, O., Almogren, A., Javaid, A., Zuair, M., Ullah, I., & Javaid, N. (2020). Leveraging blockchain technology for secure energy trading and least-cost evaluation of decentralized contributions to electrification in sub-Saharan Africa. *Entropy, 22*(2). https://doi.org/10.3390/e22020226

Sanderson, K., & Wong, C. (2024). EU unveils controversial climate target: What scientists think. *Nature, 626*(7999), 467. https://doi.org/10.1038/d41586-024-00361-9, 467.

Saxena, S., Farag, H. E. Z., Brookson, A., Turesson, H., & Kim, H. (2021). A permissioned blockchain system to reduce peak demand in residential communities via energy trading: A real-world case study. *IEEE Access, 9*, 5517–5530. https://doi.org/10.1109/ACCESS.2020.3047885

Seven, S., Yao, G., Soran, A., Onen, A., & Muyeen, S. M. (2020). Peer-to-peer energy trading in virtual power plant based on blockchain smart contracts. *IEEE Access, 8*, 175713–175726. https://doi.org/10.1109/ACCESS.2020.3026180

Shen, M., Lu, Y., Harn, K., & Cui, Q. (2020). Prediction of household electricity consumption and effectiveness of concerted intervention strategies based on occupant behaviour and personality traits. *Renewable and Sustainable Energy Reviews, 127*(March), Article 109839. https://doi.org/10.1016/j.rser.2020.109839

Shen, X., Zhu, L., Xu, C., Sharif, K., & Lu, R. (2020). A privacy-preserving data aggregation scheme for dynamic groups in fog computing. *Information Sciences, 514*, 118–130. https://doi.org/10.1016/j.ins.2019.12.007

Shibu, N. B. S., Devidas, A. R., Balamurugan, S., Ponnekanti, S., & Ramesh, M. V. (2024). Optimizing microgrid resilience: Integrating IoT, blockchain, and smart contracts for power outage management. *IEEE Access, 12*, 18782–18803. https://doi.org/10.1109/ACCESS.2024.3360696

Singh, P., Masud, M., Hossain, M. S., & Kaur, A. (2021). Blockchain and homomorphic encryption-based privacy-preserving data aggregation model in smart grid. *Computers & Electrical Engineering, 93*(May), Article 107209. https://doi.org/10.1016/j.compeleceng.2021.107209

Sipthorpe, A., Brink, S., Van Leeuwen, T., & Staffell, I. (2022). Blockchain solutions for carbon markets are nearing maturity. *One Earth, 5*(7), 779–791. https://doi.org/10.1016/j.oneear.2022.06.004

Sonnenschein, M., Lünsdorf, O., Bremer, J., & Tröschel, M. (2015). Decentralized control of units in smart grids for the support of renewable energy supply. *Environmental Impact Assessment Review, 52*, 40–52. https://doi.org/10.1016/j.eiar.2014.08.004

Soto, E. A., Bosman, L. B., Wollega, E., & Leon-Salas, W. D. (2021). Peer-to-peer energy trading: A review of the literature. *Applied Energy, 283*(October 2020), Article 116268. https://doi.org/10.1016/j.apenergy.2020.116268

Spherical Insights. (2023). *Global virtual power plant market size Worth USD 13* (Vol. 65). *Billion by 2032* https://www.sphericalinsights.com/press-release/virtual-power-plant-market. (Accessed 10 August 2025).

Sun, F., & Jin, T. (2024). Integrating virtual power plants for sustainable supply chain operations in production-climate nexus. *Journal of Industrial and Production Engineering, 00*(00), 1–17. https://doi.org/10.1080/21681015.2024.2364643

Tan, S., Wang, X., & Jiang, C. (2019). Privacy-preserving energy scheduling for ESCOs based on energy blockchain network. *Energies, 12*(8). https://doi.org/10.3390/en12081530

Tercan, H., & Meisen, T. (2022). Machine learning and deep learning based predictive quality in manufacturing: A systematic review. *Journal of Intelligent Manufacturing, 33*(7), 1879–1905. https://doi.org/10.1007/s10845-022-01963-8

Toderean, L., Chifu, V. R., Cioara, T., Anghel, I., & Pop, C. B. (2023). Cooperative Games over blockchain and smart contracts for self-sufficient energy communities. *IEEE Access, 11*(July), 73982–73999. https://doi.org/10.1109/ACCESS.2023.3296258

Tyagi, P., Shrivastava, N., Sakshi, & Jain, V. (2024). Synergizing artificial intelligence and blockchain, 83–97 https://doi.org/10.1007/978-981-97-1249-6_4.

Uddin, S. S., Joysoyal, R., Sarker, S. K., Muyeen, S. M., Ali, M. F., Hasan, M. M., Abhi, S. H., Islam, M. R., Ahamed, M. H., Islam, M. M., Das, S. K., Badal, M. F. R., Das, P., & Tasneem, Z. (2023). Next-generation blockchain enabled smart grid: Conceptual framework, key technologies and industry practices review. *Energy and AI, 12*(December 2022), Article 100228. https://doi.org/10.1016/j.egyai.2022.100228

Umar, A., Kumar, D., & Ghose, T. (2022). Blockchain-based decentralized energy intra-trading with battery storage flexibility in a community microgrid system. *Applied Energy, 322*(March), Article 119544. https://doi.org/10.1016/j.apenergy.2022.119544

U.S department of Energy. (2024). Virtual power plants. https://www.energy.gov/lpo/virtual-power-plants. (Accessed 10 August 2025).

Valdivia, A. D., & Balcell, M. P. (2022). Connecting the grids: A review of blockchain governance in distributed energy transitions. *Energy Research & Social Science, 84* (November 2021), Article 102383. https://doi.org/10.1016/j.erss.2021.102383

Veerasamy, V., Sampath, L. P. M. I., Singh, S., Nguyen, H. D., & Gooi, H. B. (2024). Blockchain-based decentralized frequency control of microgrids using federated learning Fractional-Order Recurrent Neural network. *IEEE Transactions on Smart Grid, 15*(1), 1089–1102. https://doi.org/10.1109/TSG.2023.3267503

Vionis, P., & Kotsilieris, T. (2024). The potential of blockchain technology and smart contracts in the energy sector: A review. *Applied Sciences (Switzerland), 14*(1). https://doi.org/10.3390/app14010253

Vitalik Buterin's website. (2017). Sharding FAQ. https://vitalik.eth.limo/general/2017/12/31/sharding_faq.html.

Wang, Y., Gao, W., Qian, F., & Li, Y. (2021). Evaluation of economic benefits of virtual power plant between demand and plant sides based on cooperative game theory. *Energy Conversion and Management, 238*(April), Article 114180. https://doi.org/10.1016/j.enconman.2021.114180

Wang, T., Hua, H., Wei, Z., & Cao, J. (2022). Challenges of blockchain in new generation energy systems and future outlooks. *International Journal of Electrical Power & Energy Systems, 135*(May 2021), Article 107499. https://doi.org/10.1016/j.ijepes.2021.107499

Wang, H., Jia, Y., Shi, M., Lai, C. S., & Li, K. (2023). A mutually Beneficial operation framework for virtual power plants and electric vehicle charging stations. *IEEE Transactions on Smart Grid, 14*(6), 4634–4648. https://doi.org/10.1109/TSG.2023.3273856

Wang, L., Jiao, S., Xie, Y., Xia, S., Zhang, D., Zhang, Y., & Li, M. (2022). Two-way dynamic pricing mechanism of hydrogen filling stations in electric-hydrogen coupling system enhanced by blockchain. *Energy, 239*, Article 122194. https://doi.org/10.1016/j.energy.2021.122194

Wang, X., Liu, P., & Ji, Z. (2021). Trading platform for cooperation and sharing based on blockchain within multi-agent energy internet. *Global Energy Interconnection, 4*(4), 384–393. https://doi.org/10.1016/j.gloei.2021.09.009

Wang, Q., & Su, M. (2020). Integrating blockchain technology into the energy sector - from theory of blockchain to research and application of energy blockchain. *Computer Science Review, 37*, Article 100275. https://doi.org/10.1016/j.cosrev.2020.100275

Wang, K., Tu, Z., Ji, Z., & He, S. (2023). Multi-stage data synchronization for public blockchain in complex network environment. *Computer Networks, 235*(July), Article 109952. https://doi.org/10.1016/j.comnet.2023.109952

Wang, D., Wang, Z., & Lian, X. (2022). Research on distributed energy consensus mechanism based on blockchain in virtual power plant. *Sensors, 22*(5), 1–19. https://doi.org/10.3390/s22051783

Xia, Y., Xu, Q., Li, S., Tang, R., & Du, P. (2023). Reviewing the peer-to-peer transactive energy market: Trading environment, optimization methodology, and relevant resources. *Journal of Cleaner Production, 383*(October 2022), Article 135441. https://doi.org/10.1016/j.jclepro.2022.135441

Xiao, C., Sutanto, D., Muttaqi, K. M., & Zhang, M. (2020). Multi-period data driven control strategy for real-time management of energy storages in virtual power plants integrated with power grid. *International Journal of Electrical Power & Energy Systems, 118*(December 2019), Article 105747. https://doi.org/10.1016/j.ijepes.2019.105747

Xu, D., Abbas, S., Rafique, K., & Ali, N. (2023). The race to net-zero emissions: Can green technological innovation and environmental regulation be the potential pathway to net-zero emissions? *Technology in Society, 75*(August), Article 102364. https://doi.org/10.1016/j.techsoc.2023.102364

Yang, R., Wakefield, R., Lyu, S., Jayasuriya, S., Han, F., Yi, X., Yang, X., Amarasinghe, G., & Chen, S. (2020). Public and private blockchain in construction business process and information integration. *Automation in Construction, 118*(February), Article 103276. https://doi.org/10.1016/j.autcon.2020.103276

Yao, W., Deek, F. P., Murimi, R., & Wang, G. (2023). SoK: A Taxonomy for Critical analysis of consensus mechanisms in consortium blockchain. *IEEE Access, 11*, 79572–79587. https://doi.org/10.1109/ACCESS.2023.3298675

Yao, Y., Gao, C., Chen, T., Yang, J., & Chen, S. (2021). Distributed electric energy trading model and strategy analysis based on prospect theory. *International Journal of Electrical Power & Energy Systems, 131*(December 2020), Article 106865. https://doi.org/10.1016/j.ijepes.2021.106865

Yin, S., Ai, Q., Li, J., Li, D., & Guo, Q. (2022). Trading mode design for a virtual power plant based on main-side consortium blockchains. *Applied Energy, 325*(February). https://doi.org/10.1016/j.apenergy.2022.119932

Yin, H., & Powers, N. (2010). Do state renewable portfolio standards promote in-state renewable generation{glottal stop. *Energy Policy, 38*(2), 1140–1149. https://doi.org/10.1016/j.enpol.2009.10.067

Yu, T., Luo, F., Pu, C., Zhao, Z., & Ranzi, G. (2022). Dual-blockchain-based P2P energy trading system with an improved optimistic rollup mechanism. *IET Smart Grid, 5*(4), 246–259. https://doi.org/10.1049/stg2.12074

Yu, Z., Qiu, Z., Cai, Y., Tao, W., Ai, Q., & Wang, D. (2023). *Hybrid Game trading mechanism for virtual power plant based on main-side consortium blockchains*.

Yu, S., Wei, Z., Sun, G., Zhou, Y., & Zang, H. (2024). A double auction mechanism for virtual power plants based on blockchain sharding consensus and privacy preservation. *Journal of Cleaner Production, 436*, Article 140285. https://doi.org/10.1016/j.jclepro.2023.140285 (August 2023).

Zhanbolatov, A., Zhakiyeva, S., Zhakiyev, N., & Kayisli, K. (2022). Blockchain-based decentralized peer-to-peer Negawatt trading in demand-side flexibility driven transactive energy system. *International Journal of Renewable Energy Research, Vol12i3, 12*(3), 1475–1483. https://doi.org/10.20508/ijrer.v12i3.13195.g8530

Zhang, L., Li, F., Wang, P., Su, R., & Chi, Z. (2022). A blockchain-assisted massive IoT data collection intelligent framework. *IEEE Internet of Things Journal, 9*(16), 14708–14722. https://doi.org/10.1109/JIOT.2021.3049674

Zhang, X., Song, Z., & Moshayedi, A. J. (2022). Security scheduling and transaction mechanism of virtual power plants based on dual blockchains. *Journal of Cloud Computing, 11*(1). https://doi.org/10.1186/s13677-021-00273-3

Zhao, W., Lv, J., Yao, X., Zhao, J., Jin, Z., Qiang, Y., Che, Z., & Wei, C. (2019). Consortium blockchain-based microgrid market transaction research. *Energies, 12* (20), 3812. https://doi.org/10.3390/en12203812

Zhao, H., Zhao, J., Liu, W., Yan, Y., Huang, J., & Wen, F. (2023). Metaverse-based decentralised autonomous organisation in energy systems. *Energy Conversion and Economics, 4*(6), 379–386. https://doi.org/10.1049/enc2.12104

Zheng, Z., Xie, S., Dai, H., Chen, X., & Wang, H. (2017). An Overview of blockchain technology: Architecture, consensus, and future trends. In *Proceedings - 2017 IEEE 6th international Congress on big data, BigData Congress 2017* (pp. 557–564). https://doi.org/10.1109/BigDataCongress.2017.85

Zhong, X., Yu, S., Zheng, J., Chen, A., Wei, T., Liu, J., & Zhou, J. (2022). Research on trusted power transaction strategy in virtual power plant. In *2022 IEEE 3rd China international Youth Conference on electrical Engineering, CIYCEE 2022* (pp. 1–7). https://doi.org/10.1109/CIYCEE55749.2022.9957125

Zhou, K., Chu, Y., & Yin, H. (2024). Peer-to-peer electricity trading model for urban virtual power plants considering prosumer preferences and power demand heterogeneity. *Sustainable Cities and Society, 107*(December 2023), Article 105465. https://doi.org/10.1016/j.scs.2024.105465

Zhou, Y., & Lund, P. D. (2023). Peer-to-peer energy sharing and trading of renewable energy in smart communities — trading pricing models, decision-making and agent-based collaboration. *Renewable Energy, 207*(February), 177–193. https://doi.org/10.1016/j.renene.2023.02.125

Zhou, K., Xing, H., & Ding, T. (2024). Sustainable Energy , Grids and Networks P2P electricity trading model for urban multi-virtual power plants based on double-layer energy blockchain. *Sustainable Energy, Grids and Networks, 39*(January), Article 101444. https://doi.org/10.1016/j.segan.2024.101444

Zou, W., Lo, D., Kochhar, P. S., Le, X. B. D., Xia, X., Feng, Y., Chen, Z., & Xu, B. (2021). Smart contract development: Challenges and opportunities. *IEEE Transactions on Software Engineering, 47*(10), 2084–2106. https://doi.org/10.1109/TSE.2019.2942301