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Transactive energy and peer-to-peer energy trading based on blockchain: A comprehensive review and a generalized cyber-physical framework

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ABSTRACT

This research comprehensively reviews blockchain-based transactive and peer-to-peer energy trading systems, highlighting their challenges, benefits, and limitations. These systems can revolutionize the energy industry by facilitating decentralized energy transactions and enhancing energy efficiency. The research proposes a general pattern for establishing and operating blockchain-based transactive and peer-to-peer energy trading platforms. It considers critical aspects such as smart contracts, consensus mechanisms, data privacy, and system interoperability. Furthermore, it proposes a generalized framework to serve as a basis for designing and implementing blockchain-based platforms for transactive energy and peer-to-peer energy trading. The framework comprises critical components, including smart contracts, consensus mechanisms, data privacy, and system interoperability. This research provides valuable insights for researchers, policymakers, and industry professionals seeking to understand and develop blockchain-based solutions for transactive and peer-to-peer energy trading.

Nomenclature

Abbreviation			
AI	Artificial intelligence	V2G	Vehicle-to-grid
IoT	Internet of Things	G2V	Grid-to-vehicle
P2P	Peer-to-peer	V2X	vehicle-to-everything
TE	Transactive energy	V2H	Vehicle-to-Home
PoS	Proof of stack	V2B	Vehicle-to-Building
SC	Smart contract	V2L	Vehicle-to-Load
CPS	Cyber-physical systems	V2V	Vehicle-to-Vehicle
SG	Smart grid	TSS	Thermal storage systems
MG	Microgrid	GHG	Greenhouse gas
VPPs	Virtual power plants	SHSS	Sensible heat storage system
TDN	Traditional distribution network	LHSS	Latent heat storage system
ADN	Active distribution network	THSS	Thermochemical heat storage system
DER	Distributed energy resource	IoM	Internet of microgrid
SCADA	Supervisory control and data acquisition	CPPS	Cyber-physical power system
RES	Renewable energy source	CPSoS	Cyber-physical systems of systems
SM	Smart meter	CPDS	cyber-physical distribution systems
PV	Photovoltaic system	DISL	Decision-making intelligent subsystem layer
WT	Wind turbine	CCSL	Communication and coupling the subsystem layer
DR	Demand response	RTU	Remote terminal units
ESS	Energy storage system	PPSL	Physical power subsystem layer
HDCS	Hierarchical and distributed control systems	CPSS	Cyber-physical-social power systems
MPC	Model predictive control	CPHS	Cyber-Physical-Human System
EV	Electric vehicles	HCPS	Human-Cyber-Physical System
DG	Distributed generation	HiL-CPS	Human-in-the-Loop Cyber-Physical System
ICT	Information communication technology	SIoT	Social Internet of Things
AMI	Advanced metering infrastructure	SCPS	Social Cyber-Physical System

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(*continued*)

AC	Alternating current	HCPPS	Human Cyber-Physical Production System
DS	Distributed storage	CIoT	Cognitive Internet of Things
ES	Energy storage	HitM	Human in the Mesh
PCC	Point of common coupling	PKI	Public-key infrastructure
DC	Direct current	CPHMS	Cyber-physical human-machine Systems
ISO	Independent system operator	PCSC	Physical-Cyber-Social Computing
IoE	Internet of energy	ZKOracle	Zero-knowledge Oracle
CL	Controllable load	ZKP	Zero-knowledge proof
FBES	Flow battery energy storage	DAG	Directed acyclic graphs
EMS	Energy management systems	NFT	Non-fungible token
DSM	Demand-side management	DL	Distributed ledger
AMR	Automatic meter reading	SaaS	Software as a Service
MDMS	Meter data management system	PaaS	Platform as a Service
PHEV	Plug-in hybrid electric vehicle	IaaS	Infrastructure as a Service
DTS	Decentralized Transaction System	UTXO	Unspent Transaction Output
MMG	Multi-microgrid	TSO	Transmission system operators
DoS	denial-of-service	DSO	Distribution system operator
FDI	False data injection	IDS	intrusion detection systems
PoW	Proof of work	dApp	decentralized application
BFT	Byzantine fault tolerance	TRL	Technology readiness level
PBFT	Practical Byzantine fault tolerance	IBC	Inter-Blockchain communication
DPoS	Delegated Proof of Stake	DID	decentralized identifiers
PoA	Proof of authority	LMP	Locational marginal price
PoC	Proof of capacity	IPFS	InterPlanetary File System

1. Introduction

In recent years, the rapid advancements in digitalization technologies, such as artificial intelligence (AI), blockchain, and the internet of things (IoT), have had a significant impact on energy systems worldwide. However, while numerous studies have explored specific technologies, there is a lack of comprehensive reviews that assess their collective impact on energy strategy and digital transformation. In addition to presenting an overview of the current advancements in blockchain-based energy trading, the review also provides insights into the future directions of this field. Emerging technologies, such as AI, machine learning, and quantum computing, are expected to play a crucial role in optimizing energy systems. These technologies could enable enhanced decision-making processes, predictive analytics, and further decentralization of energy trading systems. However, challenges related to scalability, security, and integrating these technologies into existing infrastructure must be addressed to realize their potential fully. While previous reviews have predominantly focused on the technological components of blockchain for energy trading, they have often overlooked critical aspects such as regulatory frameworks, privacy concerns, and the social implications of peer-to-peer (P2P) energy markets. This review addresses these gaps by providing a comprehensive analysis that integrates technological, economic, social, and regulatory perspectives. The integration of emerging technologies, such as AI and IoT, in decentralized energy systems is also explored.

1.1. Historical evolution of blockchain in energy systems

The concept of transactive energy (TE) emerged in the late 20th century as part of efforts to decentralize the power grid. Early works, such as the GridWise Architecture Council's frameworks (2003), set the stage for decentralized energy systems. Blockchain technology, introduced in 2009 with Bitcoin by Satoshi Nakamoto, soon found a natural application in decentralized energy systems due to its immutable, transparent, and secure nature.

In the mid-2010s, initial pilot projects, such as the Brooklyn Microgrid (2016), demonstrated blockchain's ability to facilitate secure P2P energy trading. These early experiments demonstrated blockchain's potential to revolutionize energy markets by providing a digital ledger that ensures the transparency and security of transactions without the need for intermediaries.

Over the past decade, technological advancements, including smart contracts (SCs), consensus algorithms like Proof of Stake (PoS), and the integration of IoT and AI, have enabled the scalability of blockchain-based energy trading systems. Key research contributions during this period have focused on scalability, data privacy, and enhancing the reliability of these decentralized systems in real-world energy networks.

The growing significance of P2P energy trading is reflected in measurable trends. For example, the number of related publications has increased from fewer than 15 papers in 2018 to over 40 in 2024, indicating a rapid rise in both academic and industrial interest. Pilot projects report transaction throughput ranging from hundreds to thousands of transactions per second in permissioned blockchain networks, with latency in the order of milliseconds to seconds, depending on the consensus protocol. Market forecasts predict that blockchain-enabled energy platforms may reach a global market size of several hundred million USD by 2030. These quantifiable indicators underscore the urgency and importance of conducting a comprehensive review of the field.

1.2. The principal theme and organization of this paper

This article aims to fill this gap by providing an integrated overview of emerging digital technologies in the energy sector, highlighting their applications, challenges, and opportunities for future growth. In recent years, blockchain and TE systems have been widely explored within the academic community. However, many existing reviews fall short in addressing the evolving nature of these technologies. While early research has predominantly focused on the theoretical aspects of blockchain, recent developments emphasize the importance of integrating blockchain with emerging technologies, such as AI, digital twins, and IoT, to enhance the flexibility, security, and scalability of energy systems. Previous reviews have not fully captured the latest case studies or the technical challenges associated with integrating these technologies into real-world energy systems, particularly in the context of smart grids. Furthermore, as energy systems continue to become more complex, the need for resilience and real-time adaptability has grown; however, this has not been adequately addressed in the existing literature. This review fills these gaps by exploring how blockchain, combined with AI and digital twins, can address the critical issues of security, efficiency, and real-time decision-making in TE systems.

The contemporary centralized energy system is undergoing a transformation towards decentralization and sustainability, propelled by advancements in renewable energy technologies, ES, and intelligent grid infrastructure [1]. Utilizing blockchain technology in transactive and P2P energy trading has enabled transparency, immutability, and decentralization [2–4]. While previous reviews have primarily focused on the technological components, they have overlooked the emerging need to integrate blockchain with evolving regulatory frameworks, economic models, and the societal implications of decentralized energy markets. The rapid advancements in blockchain scalability and regulatory requirements have rendered many previous reviews outdated. This paper fills these gaps by offering a comprehensive analysis that includes both technical and socio-economic perspectives. This paper presents a thorough assessment of blockchain-based systems for TE and P2P energy trading. The discussion encompasses system architectures, transaction models, market mechanisms, and regulatory considerations, while considering challenges such as scalability, data privacy, grid integration, and the impact of regulatory frameworks. The concept of TE began to

take shape in the late 20th century as energy systems began to embrace decentralization and increased use of renewable energy sources (RESs). Early work, such as that by the GridWise Architecture Council [5,6], outlined the foundations of a TE system, emphasizing the dynamic balance between energy supply and demand through decentralized control mechanisms. In parallel, blockchain technology emerged in 2009 with the publication of Satoshi Nakamoto's Bitcoin white paper, which introduced a decentralized digital ledger as a means of securing P2P transactions. Over time, blockchain's inherent characteristics, including immutability and transparency, were recognized as essential for energy transactions in decentralized systems. As the fields evolved, blockchain technology began to gain traction in energy markets, particularly for P2P energy trading. Early experiments, such as the Brooklyn Microgrid project, demonstrated blockchain's potential to facilitate transparent and secure transactions among prosumers. Furthermore, the integration of blockchain with other emerging technologies, such as IoT and SCs, sets the stage for the future of TE systems that aim to revolutionize energy trading.

A generalized framework is suggested, outlining pivotal components, including SCs, consensus mechanisms, data privacy, and system interoperability. The subsequent portions of this manuscript are arranged in the following manner. In recent years, the integration of blockchain technology into TE and P2P trading systems has witnessed significant advancements. Driven by the need for decentralized energy transactions, enhanced efficiency, and the potential for more resilient energy markets, these systems are poised to transform the energy industry. Despite the progress, a crucial need remains to synthesize the existing body of knowledge to better understand the broader implications, emerging trends, and gaps in current methodologies. The increasing interdisciplinary nature of digital transformation in energy systems highlights the convergence of multiple advanced fields. This review uniquely integrates perspectives from blockchain technology, energy economics, cybersecurity, and control systems, providing a comprehensive understanding of how these elements contribute to the optimization of energy systems. The integration of blockchain enhances data security and transparency, while cybersecurity ensures the resilience of digital systems against growing cyber threats.

Furthermore, the evolving role of energy economics facilitates the modeling of cost-effective solutions for implementing these technologies. Together, these disciplines play a crucial role in navigating the complexities of modern energy systems, making this integrated approach essential for advancing the digital transformation of the energy sector. This review aims to provide an in-depth analysis of blockchain-based transactive and P2P energy trading systems, highlighting their challenges, benefits, and limitations. It serves as a comprehensive resource for researchers, practitioners, and policymakers interested in designing and implementing blockchain-based solutions for energy trading.

The review will assess key developments, including SCs, consensus mechanisms, data privacy, and system interoperability, and propose a comprehensive cyber-physical framework that can serve as a foundation for future research and innovation in this evolving field. This review distinguishes itself by adopting an interdisciplinary approach that integrates perspectives from blockchain technology, energy economics, cybersecurity, and control systems. This integrated framework is crucial for understanding the full scope of challenges and opportunities that blockchain presents for TE systems and P2P energy trading, particularly as these markets evolve towards decentralization. This review provides significant insights tailored to three key audiences:

Researchers will gain a comprehensive understanding of the research gaps in blockchain scalability, interoperability, and its integration with energy systems.

- **Policymakers** will find valuable guidance on the regulatory challenges and frameworks necessary to facilitate the adoption of blockchain-based P2P energy trading.
- **Industry professionals** will benefit from practical recommendations on implementing blockchain solutions, addressing cybersecurity concerns, and navigating the complexities of decentralized energy markets.

Previous reviews have predominantly focused on the technological aspects of blockchain for energy trading. Still, they have largely overlooked the crucial integration of cyber-physical systems (CPS), market design, and regulatory frameworks. This review addresses these gaps by offering a comprehensive analysis that bridges these key areas. To further contextualize this study within broader academic and policy-driven ecosystems, Interdisciplinary studies examining the governance and market design aspects of blockchain-enabled energy systems have been considered, as outlined by Refs. [5,7–10]. Unlike previous reviews, which primarily focus on the technical aspects of blockchain in energy systems, this paper integrates considerations of regulatory frameworks, business models, and cyber-physical integration, offering a more holistic view of the evolving landscape [7–9]. To further contextualize this study within broader academic and policy-driven ecosystems, Interdisciplinary studies exploring the governance and market design aspects of blockchain-enabled energy systems have been considered, such as those outlined by Refs. [5,11–16].

The remainder of this paper is organized as follows. Section 2 outlines the methodology adopted for the literature review, detailing the search strategy, inclusion criteria, and data analysis techniques. Section 3 traces the evolution of energy distribution systems, from traditional networks to emerging cyber-physical-social power systems (CPSS). Section 4 explores Blockchain technology, focusing on its architecture, applications, and critical analysis of consensus mechanisms in the energy sector. Section 5 presents the modern power market frameworks and the integration of Blockchain in P2P and TE models. Section 6 presents a proposed framework for Blockchain-based energy trading, along with its future outlook and practical use cases. Section 7 highlights the key challenges, research opportunities, and emerging trends in the field. Finally, Section 8 concludes the study by summarizing the main contributions and situating them within the context of existing literature. The overall structure of the paper is illustrated in Fig. 1.

2. Methods

2.1. Search strategy

A systematic search was conducted across Scopus, Web of Science, IEEE Xplore, and ScienceDirect. The review covered the period 2015–2025, capturing both early developments and recent advances in blockchain-enabled P2P and TE research.

The following keywords and Boolean operators were applied: "P2P energy trading" OR "P2P energy market" OR "TE" AND "blockchain" AND ("privacy" OR "security" OR "market clearing"). Additional filters included English language and peer-reviewed publications only.

Search strings combined controlled vocabulary and free-text terms:

"smart grid (SG)" OR "microgrid (MG)" OR "virtual power plant (VPP)" AND "tokenomics" OR "digital governance"

Key review article reference lists were manually searched in addition to database queries. To find further pertinent works, the reference lists of a few chosen publications were also searched.

2.2. Inclusion and exclusion criteria

Studies were included if they: (i) addressed P2P or transactive energy trading, (ii) examined blockchain or related digital platforms as enablers, and (iii) provided sufficient technical, economic, or regulatory detail to contribute to the analysis:

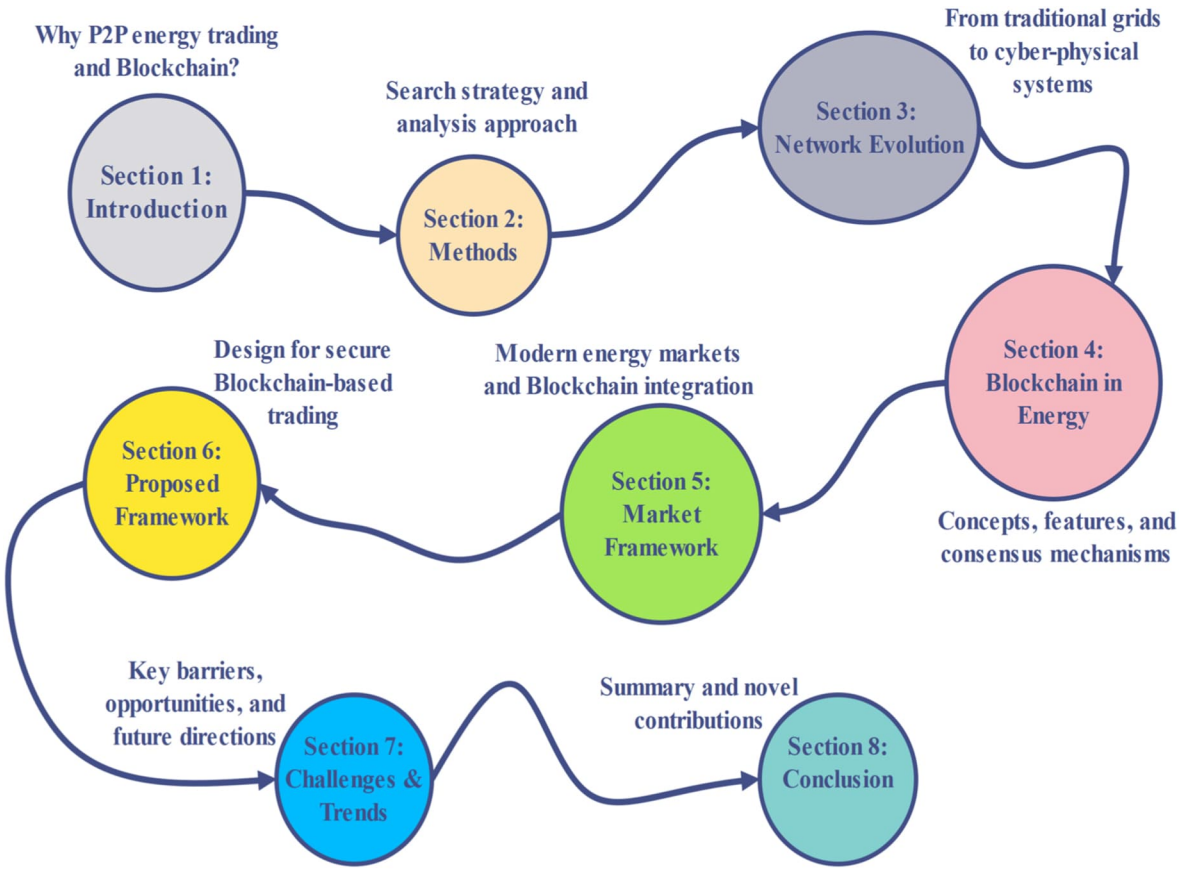


Fig. 1. Overall procedure of the paper.

- Addressed distribution-level energy systems (traditional distribution networks (TDNs), active distribution networks (ADNs), MGs, VPPs, SGs)
- Discussed blockchain- or token-based digital platforms
- Presented original data, frameworks, or case studies

We excluded: (i) articles not written in English, (ii) non-peer-reviewed sources such as blogs or news items, (iii) papers unrelated to the energy domain, and (iv) works lacking substantive technical or methodological depth:

2.3. Risk-of-bias assessment

Each included study was assessed independently by two authors using a modified AMSTAR-2 checklist tailored for technology reviews. Methodological transparency, data completeness, and conflict-of-interest disclosures were evaluated. Discrepancies were resolved by consensus.

2.4. Data extraction and summary methods

From each article, the following information was extracted: author (s), year, technology platform, application domain, key findings, and reported performance metrics (e.g., throughput, latency, efficiency). Results were synthesized qualitatively, with studies grouped by system type (MG, VPP, SG) and thematic focus (governance, scalability, tokenomics).

This review primarily uses bibliometric analysis and quantitative indicators (e.g., publication counts, adoption trends, transaction throughput, latency, and market forecasts) to summarize developments in the field. Due to the heterogeneity of study designs, metrics, and reporting standards across the reviewed literature, a formal meta-analysis or meta-regression was not feasible. The statistical approaches applied here are therefore limited to descriptive statistics (counts, percentages, and trend analysis), which were verified in consultation with a statistician to ensure appropriateness for this type of review article.

2.5. Keyword Co-occurrence and publication trends

To quantify thematic emphasis and publication growth, a bibliometric co-occurrence analysis was performed on 150 peer-reviewed articles published between 2018 and 2024 using VOSviewer. Three major keyword clusters emerged:

- Consensus Mechanisms (e.g., Proof of Authority (PoA), hybrid PoS)
- Tokenization & Asset Modeling (e.g., kWh-backed tokens)
- Governance Frameworks (e.g., zero-knowledge privacy layers)

Annual publication volume grew from 12 papers in 2018 to 42 in 2024, reflecting a compound annual growth rate of 22 %. Fig. 2 visualizes the co-occurrence network and yearly output.

More details are provided in Table 1.

3. From traditional distribution network to smart microgrid

The transition from the TDN to the contemporary network within the power system represents a significant advancement in electricity production, distribution, and consumption. The modern network incorporates sophisticated technologies such as SGs and dispersed energy resources. The current network in the power system, which includes SGs and distributed energy resources (DERs), represents a noteworthy advancement in the production, distribution, and consumption of electricity. It facilitates the incorporation of RESs at the local level,

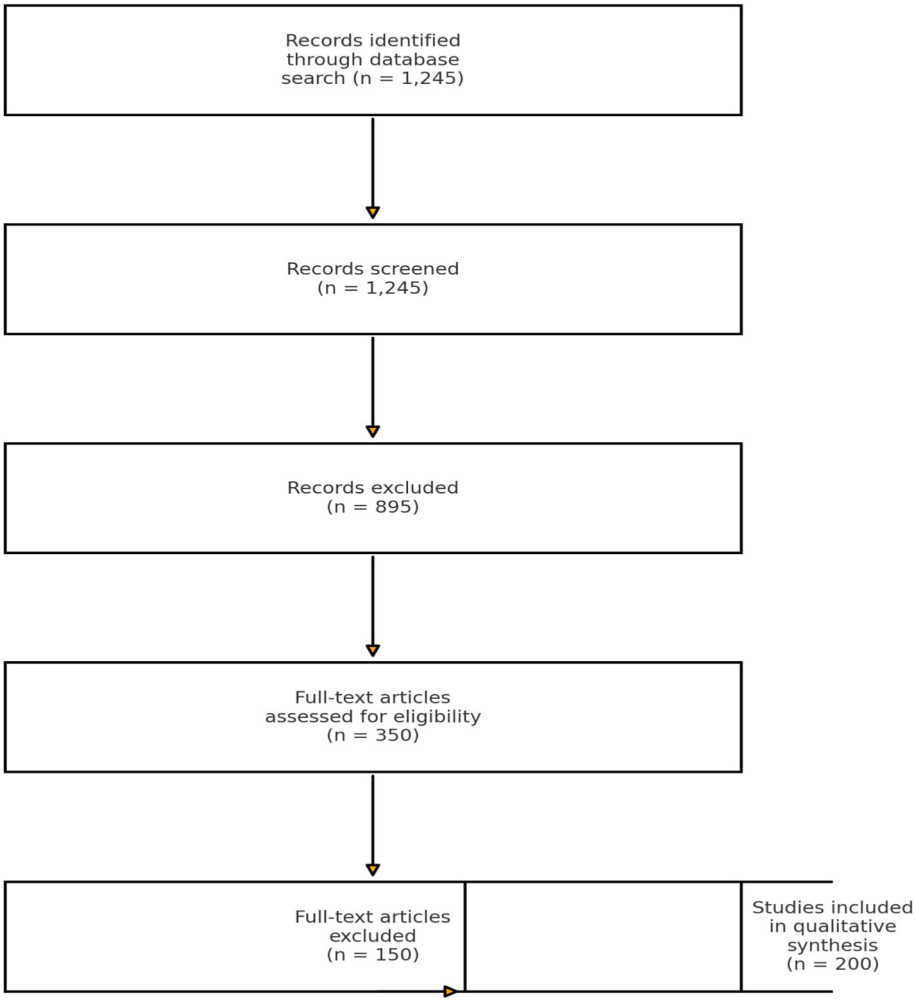


Fig. 2. PRISMA flow diagram of literature search and selection process.

Table 1
Characteristics of included studies (n = 120) by publication year, research method, geographic scope, and primary topic.

Publication Year	Num. Studies	Empirical	Simulation	Review	Europe	North America	Asia	Other Regions	Scalability	Governance	Privacy/ Security	Market Mechanisms
2000–2009	20	5	10	5	8	6	4	2	6	4	4	6
2010–2019	50	20	20	10	16	14	12	8	15	12	11	12
2020–2025	50	15	20	15	16	15	14	5	14	14	10	12
Total (n = 120)	120	40	50	30	40	35	30	15	35	30	25	30

establishes two-way communication between the grid and consumers, and enables consumers to manage their energy consumption actively. Furthermore, the modern network fortifies the power system's resilience through decentralized energy production and storage, ensuring dependable and autonomous functionality during emergencies. The contemporary network generally advocates for sustainability, efficiency, consumer empowerment, and system resilience in the power sector.

The TDN and ADN, along with MGs and VPPs, have progressively paved the way for the adoption of decentralized control and energy trading systems. Blockchain's potential to enhance transparency, security, and data integrity in such systems can be seen as a natural extension of these evolving technologies. The following sections will explore advancements in energy systems and demonstrate how blockchain can address the challenges inherent in these existing frameworks, leading to more efficient, secure, and decentralized energy markets.

3.1. Traditional distribution network

The TDN has been the cornerstone of electricity distribution for decades. This vast network of power lines, transformers, and substations is crucial in delivering electricity from power plants to end-users.

3.1.1. Enhanced Renewable Energy Integration network

The TDN comprises three main components Fig. 3:

- Power generation: Electricity is produced at power plants, which can be powered by various resources, including coal, natural gas, nuclear energy, and sustainable sources such as solar and wind. These power plants generate electricity at elevated voltages.
- Transmission: High-voltage transmission cables facilitate the conveyance of electrical energy across vast spans, from electricity generation facilities to intermediate distribution points. These

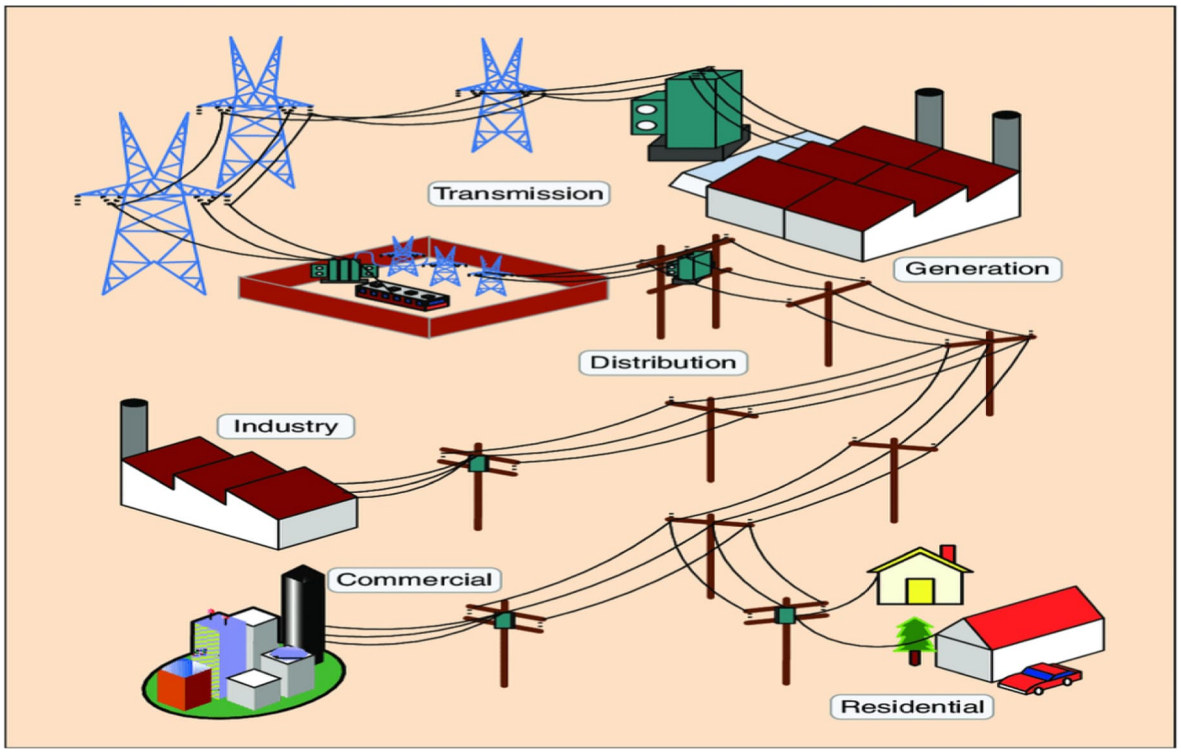


Fig. 3. Traditional electric grid.

conduits, customarily made from conductive alloys such as aluminum or copper, are supported by tall structures or poles.
- Distribution: The voltage is reduced to suitable levels for distributing electricity to end-users at electric substations. These lines (commonly known as power lines or feeders) transport electric power to residential households, commercial establishments, and other types of consumers. To ensure consumer safety, transformers are used to further reduce the voltage level.

3.1.2. Improved network flexibility via active demand management

While vertically integrated utility models governed early distribution grids, the economic and technical underpinnings of modern grid management were laid decades before blockchain emerged. Hotelling's seminal work on marginal cost pricing [17] and the regulatory regimes formalized by Joskow & Schmalensee [18] established the economic framework for wholesale electricity markets. On the operational side, Schweppe et al. [19] introduced static state-estimation techniques that remain central to real-time grid monitoring. At the same time, Carpentier's optimal power-flow algorithm [20] provided the mathematical basis for cost-effective dispatch. Wood & Wollenberg's integrated analysis of power generation, operation, and control [21] further consolidated these developments, laying the groundwork for subsequent advances in distribution automation and smart-grid architectures. The TDN utilizes multiple technologies to guarantee the efficient and reliable delivery of electricity:

- Transformers: These devices step up or down the voltage as needed for transmission and distribution.
- Switchgear: Switches, circuit breakers, and other protective mechanisms are employed to regulate and ensure the integrity of electrical current.
- Meters: Analog or digital meters are implemented at consumers' sites to assess electrical energy consumption.
- SCADA Systems: Supervisory Control and Data Acquisition (SCADA) systems oversee and regulate the grid's operations, enabling operators to effectively and promptly govern power transmission and address any faults or interruptions.

3.1.3. Attributes

The TDN possesses several key attributes:

- Reliability: The grid has been strategically designed to provide dependable electrical power to end-users, featuring redundancies and auxiliary systems in place, thereby mitigating any potential interruptions.
- Scalability: The electricity grid possesses the capacity to effectively cater to the rising demand for energy by augmenting its generation capability and extending its transmission and distribution infrastructure.
- Centralized Generation: Power stations are commonly situated in regions distant from densely populated areas, facilitating the concentration of power generation and effective energy transmission.
- Established Infrastructure: The conventional grid possesses a comprehensive infrastructure that is currently established, thereby facilitating easy accessibility for electricity allocation.

3.1.4. Limitations and challenges of this network

Despite its extensive history of achievement, the TDN for distributing energy encounters numerous limitations and challenges:

- Deteriorating Infrastructure: A significant portion of the grid consists of outdated systems that require substantial capital investment for modernization and routine maintenance.
- Limited Resilience: The grid is vulnerable to disturbances caused by severe weather phenomena, environmental calamities, or physical damage to infrastructure.
- Lack of Flexibility: The traditional grid has constrained functionalities in incorporating and administering dispersed energy assets, including sustainable energy sources and storage mechanisms.

- Cybersecurity Risks: As the grid is digitized, it becomes increasingly susceptible to potential cyber threats, necessitating comprehensive security measures.

The TDN has effectively catered to our needs for an extensive period, providing dependable access to electricity for end-users. Nevertheless, with the continuous advancement of technology and the emergence of new challenges, there is an increasing need to modernize and transform the grid into a more intelligent and resilient system. The path toward a more sustainable and efficient energy future can be paved by confronting constraints and embracing ingenious technologies.

3.2. Active distribution network

The evolution towards ADNs is being propelled by the pressing necessity for a power system that is more sustainable, efficient, and adaptable. The TDNs, which are largely reliant on centralized generation and one-way power transmission, are undergoing a transformation to accommodate DERs, advanced communication and control systems, and energy management methods that prioritize customer needs. This transition is necessary for the integration of RES, enhancing grid resilience, and empowering consumers.

3.2.1. Role of MGs in maintaining reliability during outages

These essential keys are:

- Renewable Energy Integration: The progression in sustainable energy sources, particularly solar and wind, necessitates a shift towards ADNs. Previously, TDNs were structured to manage power flow from centralized generation sources, primarily power plants dependent on fossil fuels. ADNs facilitate the uninterrupted assimilation of DERs, comprising solar Photovoltaic (PV) systems, wind turbines (WTs), and energy storage (ES), by permitting bidirectional power flow and regulating the sporadic nature of renewable energy generation [22].
- Decentralization of Power Generation: ADNs offer a promising solution in the quest for decentralizing power generation, thereby enabling energy production closer to the point of consumption. Such an approach effectively curbs transmission losses, promotes energy efficiency, and bolsters system resilience. By seamlessly integrating DERs at diverse scales, ranging from individual residential rooftop solar panels to entire community-based wind farms, ADNs unlock the potential for a more varied and widely distributed energy mix.
- Technological Advancements: SG technologies, communication systems, and data analytics have made ADNs more practical and cost-effective. Real-time monitoring, control, and optimization of distribution networks are now possible through the use of advanced sensors, smart meters (SMs), and innovative devices. Intelligent devices enable grid operators to collect data, respond to changes, and enhance operational efficiency. Sophisticated algorithms optimize the management of DERs like solar PV systems and ES, enhancing grid performance. ADNs improve reliability, reduce downtime, enhance resilience, integrate RESs, and reduce greenhouse gas (GHG) emissions. In summary, ADNs have been revolutionized by intelligent technologies, enabling real-time monitoring, efficient DER management, and a sustainable energy future.
- Grid Resilience and Reliability: ADNs strengthen grid resilience by diversifying power generation through DERs. This decentralized approach minimizes the impact of localized failures and disruptions, ensuring a more reliable and stable power supply. Integrating energy storage systems (ESSs) further enhances resilience by providing backup power during outages. With ADNs, our power systems become more robust, adaptable, and capable of withstanding challenges, ultimately benefiting consumers and society.
- Demand Response (DR) and Consumer Empowerment: ADNs enable us to transition from passive energy consumers to active participants in the grid. Through DR programs, time-of-use pricing, and the availability of real-time energy data, conscious choices can reduce peak demand, improve system efficiency, and contribute to grid stability. ADNs provide us with the tools to be more engaged and responsible energy users, ultimately benefiting the grid and our energy bills.
- Environmental Sustainability: ADNs play a crucial role in our endeavor towards environmental sustainability by facilitating the amalgamation of RESs. This reduces our reliance on non-RESs, which in turn decreases the emission of GHGs. ADNs facilitate the acceptance of clean energy within communities, propelling us towards a more environmentally conscious future. This technique creates a pathway to address climate change and establish a sustainable world for the present and future generations.
- Regulatory Support and Policy Initiatives: Governments and regulatory bodies are actively supporting the growth of ADNs by developing policies and regulations. By providing incentives, subsidies, and feed-in tariffs, they encourage investment and adoption of ADNs. Additionally, establishing grid codes and standards ensures the seamless integration of DERs into the grid. These efforts pave the way for a thriving and sustainable ADN ecosystem, benefiting both the environment and energy consumers.

[23] has developed a power-flow algorithm for modeling ADNs in Egypt, evaluates its effectiveness through case studies, and examines the current and future state of the Egyptian electricity market. The findings have emphasized the benefits of ADNs in terms of network asset preservation, system performance improvement, and power loss reduction compared to TDNs. Also [24], has introduced a hybrid system-based CPS model for ADN, which accurately represents primary devices and hierarchical and distributed control systems (HDCS). To optimize energy and information processes and enable the smooth integration of energy and information flows in ADN, the model uses the model predictive control (MPC) technique. The study aims to showcase the model's ability to accurately capture the features of HDCS and effectively achieve operational targets for primary devices despite any challenges posed by HDCS [25]. has proposed a decentralized and collaborative scheduling approach for ADNs with multiple VPPs. The aim is to optimize the integration of DERs and large-scale electric vehicles (EVs), ensure energy autonomy management, and minimize operating costs. It has also addressed the stochastic uncertainty of renewable energy output through a two-stage stochastic optimization method. The proposed model is validated using a real-world ADNs scenario with multiple VPPs. Additionally [24], has proposed a technique to minimize costs and risks in network reconfiguration, addressing the challenges of loss reduction, reliability improvement, and financial risk management. The study employs scenario theory and particle swarm optimization to model and solve the risk-based reconfiguration problem, providing a practical and effective solution for ADNs [26]. has critically reviewed the current state of ADN planning, considering the influence of DERs. It overviews ADN planning characteristics and objectives, highlighting recent models and research in load and distributed generation (DG) forecasting, mathematical modeling, and solution algorithms [27]. has presented a novel approach for constructing a preventive control policy in ADNs using reinforcement learning techniques. The proposed preventive control policy construction method, based on a deep deterministic method, utilizes historical data and reinforcement learning to optimize the control policy, thereby addressing the challenges associated with traditional analysis and experimentation methods. An experimental case study demonstrates the method's effectiveness, highlighting its advantages in reducing failure nodes and managing state space explosion. Additionally [27], has explored the use of ADN elements to optimize the operation of a time-discrete network. The proposed procedure proves effective by minimizing power losses and maintaining operational constraints, such as voltage profiles and line currents. The tests on a medium-voltage distribution network model validate the approach's ability to reduce power losses while maintaining voltage profiles within acceptable

limits. Additionally, the paper emphasizes the potential for long-term optimization by conducting successive optimization procedures over extended periods. Fig. 4 presents a representative structure of ADN.

3.2.2. Optimization algorithms for MG scheduling

ADN planning and TDN planning are contrasted in Fig. 5. To ensure seamless load transfer during faults, conventional planning includes a safety buffer between the peak load and the maximum substation capacity. The load rate impacts this margin, referred to as the capacity-load ratio in China. However, most of the time, the loads in the system are lower than the peak load, resulting in underutilization of the facilities throughout the year.

ADNs, on the other hand, incorporate diverse energy sources and controllable mechanisms such as DR, DG, ESS, and on-load tap changers. ADNs also leverage information and communication technology (ICT) and advanced metering infrastructure (AMI). These advancements enable planners to consider active management during the network planning stage, thereby improving asset utilization and reducing overall planning costs. Fig. 5(b) shows that peak loads are supported by installing DGs/ESS and active network management as the maximum substation capacity decreases. In such cases, a synthetic optimization minimizes the total cost while meeting system constraints. However, practical load profiles introduce uncertainties and complicate the problem, resulting in many constraint formulas and decision variables. The paper employs a clustering methodology to address this complexity, which is explained in the next section [28].

3.3. Microgrid

The United States Department of Energy defines MGs as follows: "*A MG is a group of interconnected loads DER within clearly defined electrical boundaries that acts as a single controllable entity concerning the grid, and that connects and disconnects from such grid to enable it to operate in both grid-connected or island mode*" [29]. MGs are an essential and distinct component of the SG, functioning at the distribution system level. They can bring together power generation and storage sources close to the loads, giving customers complete control over each component. This empowers MGs to meet a significant portion of power requirements effectively. To provide a more straightforward explanation, it's worth noting that the United States Department of Energy MG Exchange Group defines an MG as a collection of distributed power sources and end-users interconnected within a specific electrical board. It is a controllable system that can operate independently or in conjunction with the main power grid. Fig. 6 illustrates the structural layout and interconnections of an MG. These smaller-scale grids offer improved reliability, security, and resilience in delivering energy, making them a desirable solution for communities and businesses.

Additionally, MGs provide a high degree of flexibility in selecting the amount and type of renewable power sources that can be integrated into the system. This capability allows MGs to efficiently incorporate various distributed power generation sources, with a particular emphasis on renewable energy. In doing so, MGs play a significant role in advancing the development of a sustainable energy future [30].

Drawing on the insights from Ref. [31], future trends in MGs are poised to be significantly shaped by the convergence of blockchain technology and renewable energy innovations. The bibliometric analysis reveals that research is increasingly focusing on energy system optimization, secure decentralized platforms, and the integration of digital technologies such as SCs and IoT. These trends suggest that MGs will not only serve as isolated energy systems but will also evolve into dynamic, self-managed networks, where blockchain facilitates transparent, P2P trading and robust energy management. Moreover, as regulatory frameworks and technical standards mature, MGs are expected to leverage advanced digital solutions to enhance resilience, improve load balancing, and integrate diverse DERs more effectively. Such developments will be critical in ensuring that future MGs can meet the demands of a rapidly digitalizing and decentralized energy landscape.

3.3.1. MG benefits

MGs play a crucial role in transforming power generation and distribution. They facilitate a shift from centralized power systems to a decentralized approach. One intriguing aspect of MGs is their self-sufficiency, allowing them to operate independently and possess extraordinary resilience. These systems can operate in two modes, depending on the circumstances. While in grid-connected mode, they work in unison with the larger grid and contribute to the overall energy supply. However, their true potential is revealed when they transition to islanded mode. In this mode, MGs function as autonomous powerhouses, assuming responsibility for power generation, energy demand management, and seamless system operation [30].

Integrating MGs into the system yields a wide range of significant benefits. It offers remarkable flexibility and achieves high efficiency at

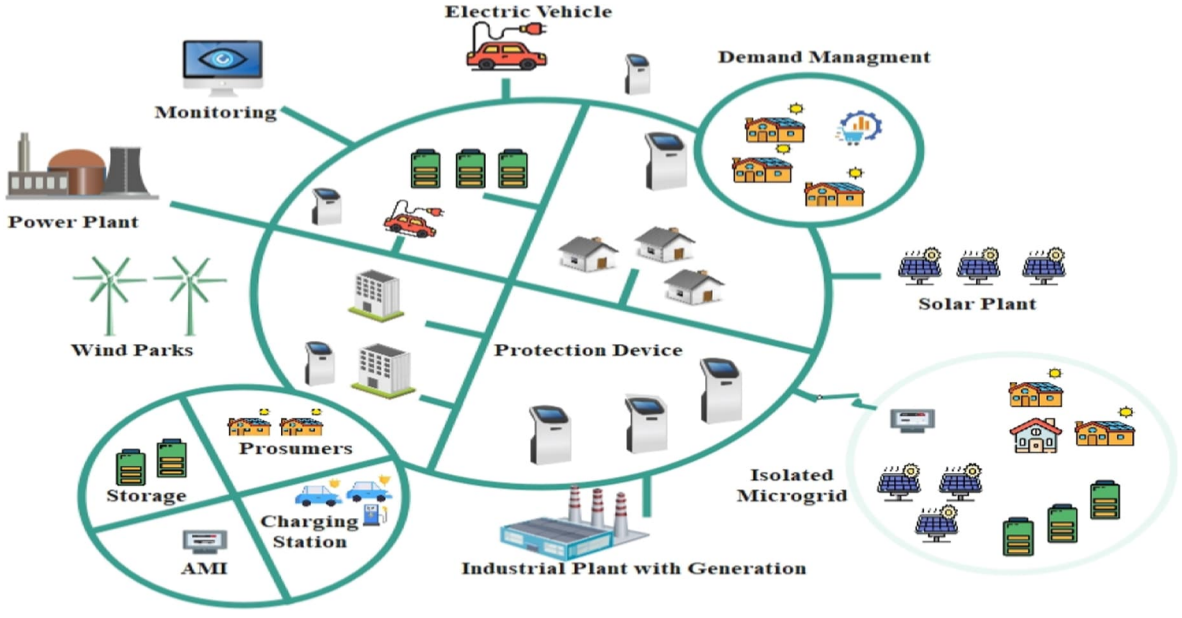


Fig. 4. Representative structure of ADN.

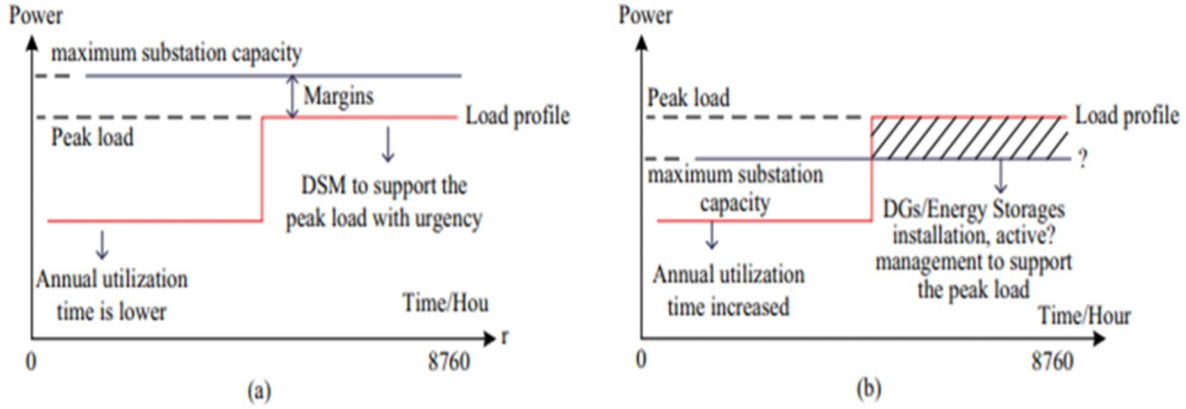


Fig. 5. Two types of distribution system planning: (a) TDN planning, and (b) ADN planning.

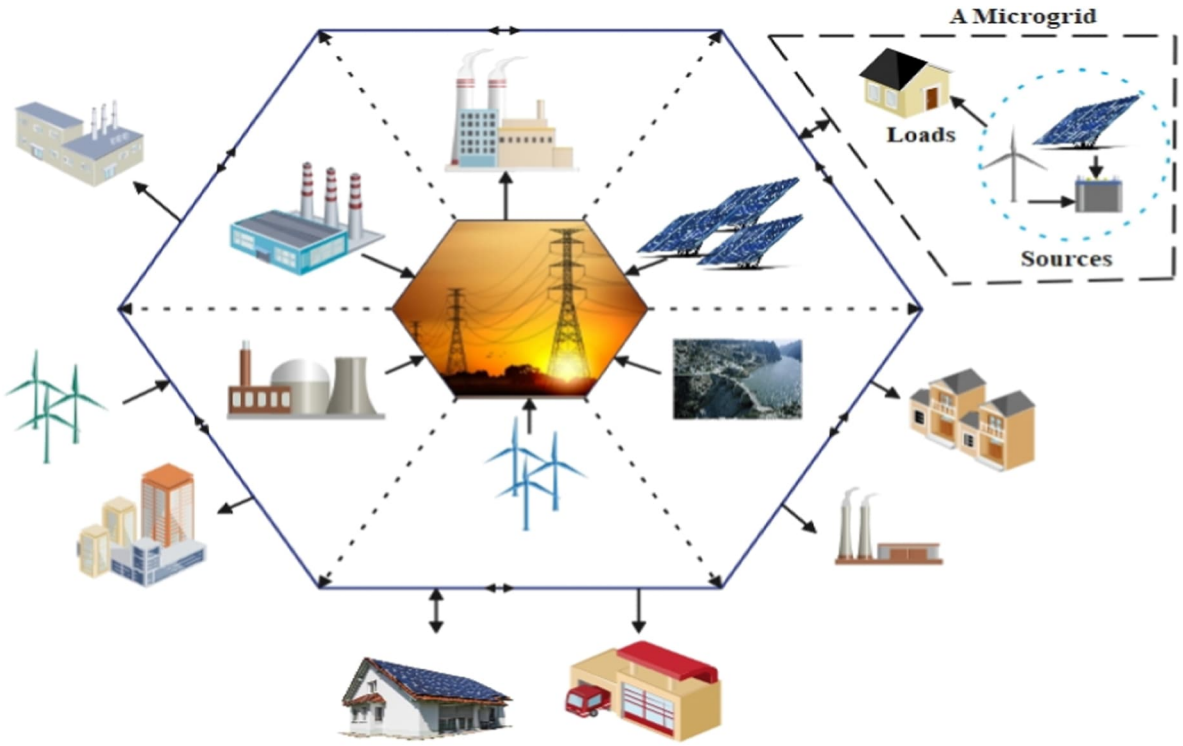


Fig. 6. Integration of MG into the existing power system.

reduced costs while providing a dynamic response as an energy resource. The system is designed to adapt to climatic variations and seamlessly incorporate a diverse array of power sources. Moreover, it contributes to job creation and fosters local economic growth, thereby serving as an additional source of income. The integration also minimizes transmission losses, enhances power reliability, and reduces electric bills and grid congestion. Further benefits include straightforward installation, enhanced cybersecurity, and diversified risk management.

3.3.2. *Basic components of MG*

3.3.2.1. Distributed generation. One of the crucial components of an MG is undoubtedly DG. DG plays a vital role, particularly in islanding mode, which involves generating electricity locally. In simple terms, DG occurs near the area where power is needed. These DG systems are not centrally planned and are typically operated by local energy producers or users. It's essential to note that the capacity of a DG system is normally less than 50 MW and is connected to the local electricity distribution network, which can vary depending on the region. This usually refers to the part of the system that operates at voltages ranging from 240/400 V up to 110 kV.

Regarding traditional energy sources, alternating current (AC) generators and synchronous generators are commonly used as DGs. However, it's worth mentioning that many renewable energy projects also function as DG systems. Through renewable energy networks, these energy sources can be effectively harnessed. Various environmentally friendly energy sources, such as hydropower, biomass, wind, nuclear, geothermal, wave, and tidal energy, are feasible as DG in MGs. Besides the environmental advantages, incorporating DG systems into MGs can bring technological and economic benefits.

3.3.2.2. Distributed storage (DS). Deploying MG storage systems for energy transmission uses batteries, flywheels, and capacitors. ES performs several functions in the MG, including maintaining power efficiency, regulating voltage, and more. In MGs with varying capacities

and multiple ESs available, their loading and discharge coordination is essential to avoid the faster release of smaller power storage than that of those with greater capacity. Additionally, smaller-capacity storage is susceptible to needing to be fully charged, which can be addressed through centralized management of energy storage based on its charging position. Efficient operation can be ensured by utilizing a single monitoring device to manage multiple ESSs, which are built on a master-slave structure, especially in autonomous mode.

3.3.2.3. Interconnection switch. The juncture at which an MG establishes linkage with the primary grid represents a pivotal phase in its functioning. In remote locations, it is often observed that MGs are not connected to the central grid. This can be attributed to technological constraints or financial limitations that impede the assimilation of the MG with the principal grid. Consequently, these MGs operate autonomously and lack a point of common coupling (PCC) where they interface with the primary grid [32].

3.3.3. Classification of the MGs

An MG can be classified into AC, direct current (DC), Hybrid, Community, Virtual MGs, etc. AC MGs operate on AC power and work in grid-connected and islanded modes, providing reliable and sustainable energy to local communities [32]. By being capable of working in both grid-connected and islanded modes, these solutions can address challenges related to electricity demand and transmission. Protection schemes ensure their safe operation, and connection to the distribution network is possible through a PCC [33]. DC MGs are independent systems that operate in DC mode, even during grid failures. They offer numerous benefits, including affordability, dependability, security, ease of use, and energy efficiency. In particular, DC MGs are characterized by superior efficiency, enhanced reliability, and compatibility, rendering them well-suited for various applications, such as shipboard power systems and aircraft technology.

In contrast to their AC counterparts, DC MGs provide superior power density, efficient power flow between RESs, and reduced power loss [34]. Hybrid MGs integrate the advantages of both AC and DC systems and are commonly referred to as hybrid AC-DC microgrids. By circumventing conventional and expensive components, such as rectifiers and inverters, in either the AC or DC segments, the AC-DC MG has become a more financially viable alternative to existing power systems. Integration, synchronization, voltage transformation, economic viability, protection, and reliability are the key benefits of hybrid MGs [35].

3.3.4. Challenges of MGs

MGs encounter several obstacles that demand resolution for their triumphant execution and adoption. These hindrances encompass regulatory impediments, intricate technological aspects, interconnection challenges, economic feasibility, cybersecurity threats, integration of renewable energy, reliability, societal acceptance, and environmental impact. Overcoming these challenges necessitates innovative solutions and collaboration among stakeholders. Nonetheless, despite the impediments, efforts are underway to overcome these challenges and fully harness the potential of MGs in delivering dependable, sustainable, and resilient power solutions.

3.4. Virtual power plant

In [36], VPP is defined as "*a cloud-based platform that aggregates DERs, loads (i.e., fixed, shiftable, and controllable loads), fixed storage, and EVs, providing real-time monitoring* via *a bidirectional communication system, aiming to establish a distributed and decentralized power plant enhancing energy management and trading across the power system*.". According to Fig. 7, the VPP communication layer facilitates data exchange between different layers, such as generation, consumption, state of charge, and transmission information.

The infrastructure layer encompasses flexible loads, DERs, fixed storage units, EVs, and charging stations, submits pricing proposals to a centralized decision hub, and, in turn, receives operational commands that regulate energy distribution. Energy trading occurs in both internal and external market settings, directed by these control signals. This decision-making tier is organized into technical, economic, and processing sub-layers. Moreover, together with the external market, it supplies load forecasting data and bidding strategies to the independent system operator (ISO) to ensure regulatory compliance and achieve optimal outcomes. VPP is a highly adaptable entity that operates regardless of distance, capacity, or resource type. It leverages a collaborative framework known as the Internet of Energy (IoE), comprising elements such as ICT and AMIs, to aggregate and manage a diverse array of energy resources, regardless of their location or scale.

3.4.1. VPP components

The VPP in this subsection comprises present and next-generation components: present VPPs, in their entirety, encompass four essential constituents that enable power flow operations.

3.4.1.1. Distributed energy resources. DERs are power-producing devices

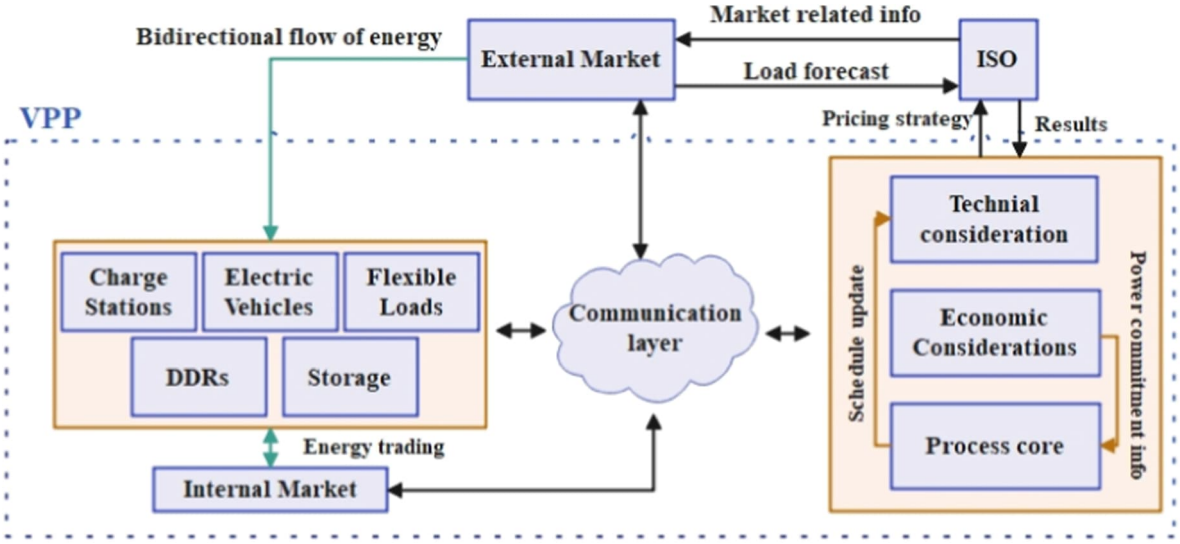


Fig. 7. Layout of a system with VPP.

that utilize various energy sources to varying capacities, providing consumers with a more efficient, highly dependable, and less expensive energy supply [37]. DERs can be categorized from various perspectives. One standard classification differentiates between renewable and non-renewable energy sources (RESs). Renewable sources encompass technologies such as photovoltaic arrays, solar-thermal systems, wind turbines, hydroelectric generators, tidal power plants, and geothermal plants. In contrast, non-renewable sources include nuclear reactors, biomass, biogas systems, gas turbines, and fuel cell installations. Additionally, DERs are often classified by capacity, ranging from small to large-scale units, based on criteria such as installation size, support power, peak shaving capabilities, and cogeneration potential. Ownership of DERs also varies and may include public, domestic, cooperative, and industrial entities [38].

3.4.1.2. Energy storage systems. ESSs are critical in optimizing energy distribution by capturing and supplying energy during off-peak periods and periods of peak demand. They stabilize frequency and voltage levels within VPPs, benefiting both micro and macro applications. ESSs can be centralized or decentralized, providing power support to municipalities while enhancing system durability, safety, and efficiency [39]. During power grid blackouts, distributed ESSs effectively function as a central power supply, offering high-level power support for minutes to several hours. Various types of ESSs exist, including pumped hydro storage, battery energy storage, hydrogen-based energy storage, and flow battery energy storage (FBES). FBES is a promising, scalable technology consisting of zinc-bromine flow batteries, vanadium-redox flow batteries, and polysulfide-bromide flow batteries. However, the size and placement of ESSs remain essential considerations due to associated risks and market uncertainties [40].

3.4.1.3. Controllable loads. Controllable loads (CLs) refer to commercial, residential, or municipal consumers who can adjust their electricity usage in response to price fluctuations and specific periods under authorized control [41]. Prosumers, including EVs, are also part of VPPs and can consume and provide electrical power. In medium-sized electrical networks, the variability of CLs is likely higher compared to utility systems, emphasizing the significant contribution of load control and ESSs to VPPs. Time-varying rates can incentivize consumers to make policy choices quickly, such as shifting energy consumption from peak to off-peak periods. Consequently, controlling loads associated with VPPs becomes increasingly crucial as loads rise [42].

3.4.1.4. Information and communication technologies. Embedded ICT has revolutionized value chains and revenue streams in various industries, including the energy sector. VPPs exemplify the integration of ICT systems in the energy domain. ICT-based systems extensively monitor power production, distribution, transmission, consumption, storage, retail, and value-added services, facilitating the consistent exchange of information. Through an energy management control system, communication technologies enable bidirectional control of DERs, ESSs, and loads. This system receives real-time data on component status, coordinates energy flow, facilitates energy trading, enables condition monitoring and predictive maintenance, provides asset analytics, and forecasts inputs and outputs. The relevant information is stored in cloud or fog computing platforms. However, latencies within VPPs can significantly impact ICT performance. Wireless time-variant latency, disruption effects, information dropout in secondary control layers, and delays in load frequency regulation in DERs and MGs are some challenges faced [43,44]. The components required for the current VPPs are also essential for the foundation of the next-generation VPPs. In addition, the next generation of VPPs will incorporate further technologies to enhance their functionality and capitalize on advancements in the field.

3.4.1.5. Intelligent control. AI techniques and algorithms have extensive applications across diverse fields. In VPPs, AI efficiently manages a wide range of participants such as power plants, consumers, prosumers, ESs, MGs, and SGs. By processing large volumes of data, AI enables autonomous operations, supports network maintenance, and facilitates decentralized control. It is pivotal in swiftly and accurately evaluating power generation, distribution, and consumption. Moreover, AI enhances energy trading by employing machine learning, deep learning [45], and reinforcement learning methods [46] that incorporate weather forecasts, demand patterns, market conditions, historical data, and participant behaviors. This approach is often referred to as algorithmic trading. Furthermore, AI can be applied to optimize power reduction in VPPs.

3.4.1.6. Edge computing. Current VPPs face challenges related to security and complexity in cloud data storage, primarily due to the large volume of real-time data transmission. Operational hurdles, such as transmission interference, exceeding storage limits, and the absence of standardized protocols, can hinder effective economic dispatch. To address these issues, edge computing offers a more efficient computational framework by leveraging autonomous edge devices linked to each participant. These devices perform local operations and enable direct communication with one another, thereby reducing data transmission by processing data on-site. The central cloud platform can then be utilized for big data analytics [47].

3.4.1.7. Smart inverters. Smart inverters are becoming increasingly crucial in VPPs to enhance resilience. In addition to power conversion, smart inverters offer benefits such as battery charging, circuit breaker functionality, and maximum power point tracking. They possess advanced features such as automatic fault diagnosis, fault tolerance, self-adaptability, and the ability to switch operating modes automatically under different conditions. Research conducted in recent years has focused on smart inverters in PV systems, exploring their potential and advancing their capabilities [48,49].

3.4.1.8. Advanced communication protocols. Communication protocols for next-generation VPPs can be engineered by employing system layering techniques, object-oriented design methodologies, and abstract service communication interfaces. To further develop VPPs, it is crucial to enhance solutions related to multimedia transmission, routing, and mobility. Upgrades in these areas are necessary to support the evolving needs and requirements of VPPs [44].

3.4.1.9. P2P energy trading. P2P energy trading is a method that facilitates direct market transactions to encourage local consumption of DERs. It has become a significant focus in energy research, with studies highlighting the process of transmitting power directly to other participants through peer-to-peer (P2P) energy trading [50]. Existing P2P trading methods have been extensively reviewed, and more recently, blockchain technology has gained widespread adoption in P2P energy trading due to its enhanced traceability and decentralized nature [51].

3.4.2. VPP vs. MG and conventional power plant

An MG is a small-scale system that combines micro-sources and loads to produce heat and electricity. Simultaneously, a larger-scale concept, a VPP, encompasses energy storage technologies and functions as a single dispatchable power system unit, meeting the needs of wholesale markets and operations. While VPPs provide flexibility and controllability through dispersed generation, controlled loads, and ES, conventional power plants generally rely on stable thermal units for grid stability [52]. Table 2 compares VPP with MG and traditional power plans.

3.5. Smart grid

SG is a modernized electrical network that harnesses advanced

Table 2
VPP VS MG and conventional power plant.

Aspect	VPP	MG	Conventional power plant
Design focus	Focuses on participation and aggregation of DGs, energy storage, and adjustable loads	Focuses on self-management and local applications of DGs and loads.	Focuses on stable and controllable output, frequency regulation, and peak shaving.
Interface	Connected to the grid through an open protocol, enabling participation in power system operations and markets.	Connected to the grid through a coupling switch, limiting its interaction with power system operations.	Connected to the grid through stable and direct connections, allowing for stable and controllable output.
Area	Depends on technology and communication networks.	Depends on power lines connecting DGs and loads, making it strongly related to geographical location.	Not limited by geographical area, but depends on the availability of fossil energy resources.
Functions	Provides capacity, ancillary services, and power sales to wholesale markets.	Provides power and heat to the local area, with basic functional requirements such as power quality and security.	Provides stable and controllable output, frequency regulation, and peak shaving.
Environmental Impact	It is composed of renewable resources, contributing to clean and low-carbon power systems.	Depending on the type of generation used, it can contribute to environmental pollution.	The type of fuel used can contribute to environmental pollution.

technologies and sophisticated communication systems to enhance the efficiency, reliability, and sustainability of power generation, distribution, and consumption. It unites renewable energy resources with ES technologies, including sporadic renewable power supply, and improves grid stability. The SG enables decentralized power generation and delivery by integrating the embedded MGs with the main grid. It gathers information from SMs on energy production and consumption to improve grid management. DR programs, integration of electric cars, energy management systems (EMS), and other smart gadgets are all made possible by the SG, encouraging the effective and sustainable use of energy [53]. A schematic of a typical SG is shown in Fig. 8.

3.5.1. Components of SG

Three components of the interconnection of communication, computational, and newly emerging gadgets make up the SG, which functions as a whole to deliver reliable and efficient electricity. The electric power grid has been further upgraded thanks to technological advancements and improved monitoring methods [54].

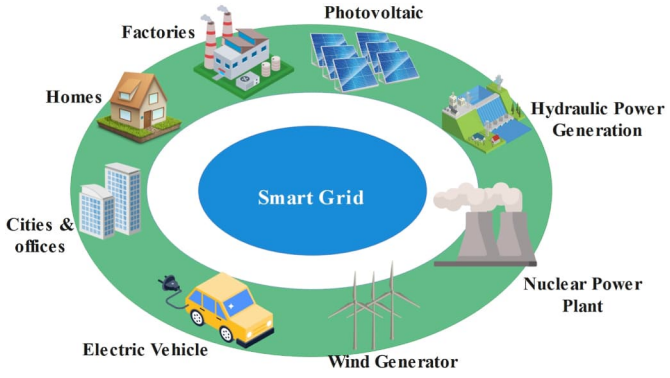


Fig. 8. SG schematic.

3.5.1.1. Smart devices. Smart devices are electronic gadgets that connect wirelessly to networks or other devices, enabling interactive and autonomous operation. They are pivotal for real-time data processing in power generation and for managing system components. Integrating these devices seamlessly into both DERs and centrally managed systems is essential. Common examples include smart vehicles, doorbells, refrigerators, thermostats, locks, tablets, watches, phones, speakers, and similar devices.

3.5.1.2. Storage. Due to the inconsistency between RESs and the disparity between usage and availability peaks, it is essential to explore methods for capturing and storing energy for later use. Storage components enhance dependability and ada ptability for the utility grid and electricity consumers. Lithium-ion batteries, hydrogen fuel cells, flywheels, pumped-hydro storage, and compressed air are ES technologies.

3.5.1.3. Transmission. Transmission systems serve as the backbone of an integrated power network by interconnecting all major substations and load centers. The primary goal for transmission operators and planners is to ensure both reliability and efficiency at a reasonable cost. These transmission lines are engineered to endure unexpected contingencies and dynamic load variations without interrupting service. Moreover, adherence to specific standards is crucial to maintaining performance, supply quality, and overall system reliability. Strategies for achieving optimal performance of the SG in the transmission domain entail the development and implementation of cutting-edge technological innovations and analytical tools. To comprehensively evaluate performance, sophisticated technologies incorporating intelligent features are leveraged, including real-time stability evaluation, simulation tools for reliability and market assessment, resilient state estimation, and dynamic optimal power flow analysis.

3.5.1.4. Monitoring and control technology. The technological framework for monitoring and control integrates a range of devices that enable autonomous diagnostics, self-healing capabilities, predictive insights, and adaptive responses within power generation systems. Furthermore, it features an intelligent network capable of addressing concerns related to reliability, instability, and congestion. For the recently implemented flexible grid to be deemed effective, it must possess the capacity to withstand unexpected disruptions, ensure dependability and longevity, and offer real-time modifications in its utilization. Additionally, integrating intelligent and energy-efficient devices, along with distributed DERs that possess inherent monitoring and control capabilities, can significantly enhance the grid's reliability. These devices exhibit self-awareness and can autonomously act based on situational awareness.

3.5.1.5. Intelligent grid distribution. The distribution network serves as the final stage of power delivery, channeling electricity to end-users through primary and secondary feeders that support small-scale industrial, commercial, and residential customers. At this level, advanced support systems incorporate monitoring and automation capabilities, facilitated by robust communication links connecting utility control centers, consumers, smart meters, AMI, and EMS. The automation framework is equipped with self-learning features that encompass functions such as automated billing, fault detection, system restoration, feeder reconfiguration, voltage optimization, load transfer, and real-time pricing.

3.5.1.6. Demand-side management. Advances in demand-side management (DSM) and energy efficiency measures offer a unique opportunity

to adjust consumer demand and lower operating costs by reducing reliance on high-cost generators and deferring capacity expansion. These DSM strategies not only enhance generation reliability but also reduce emissions, thereby influencing the utility load profile. Moreover, establishing a standardized protocol based on two-way communication technologies is crucial for streamlining consumer engagement. Additionally, deploying smart energy infrastructures such as energy-efficient buildings and homes, plug-and-play systems, clean air standards, demand-side metering, and interactive consumer interfaces further boosts overall energy efficiency.

3.5.2. Benefits of SG

The smart grid offers several notable advantages. It features self-healing capabilities that enhance system resilience, while its design actively engages consumers. Additionally, it delivers high power quality and accommodates a diverse range of generation and storage options. The system also facilitates market participation, optimizes asset management, and operates with superior efficiency [55].

3.5.3. Challenges of SG

SGs face several significant challenges as they evolve. For example, SGs must learn to handle unpredictable RESs, such as wind and solar, that don't always produce a steady amount of power. This means that existing power systems need to be upgraded with new digital communication and control tools, improved ES, and more advanced algorithms. Additionally, these modern grids must be secure against cyberattacks, interoperable with various technologies, and accepted by regular users [56].

3.5.4. SG technologies

Combining a restricted assortment of technologies makes converting the conventional electrical grid into an SG possible. The ensuing sections will elaborate on the SG technologies that facilitate the transition [57].

3.5.4.1. Smart meters. An SM is an integrated device that performs both metering and communication functions. It continuously records energy consumption and can either display this data on a local in-home device or securely transmit it to a central system. Moreover, the SM is designed to receive remote instructions, such as switching from a credit-based mode to prepayment or updating tariff details. Its dual primary roles are to supply consumers with real-time energy usage information for better consumption control and cost management and to relay consumption data to utilities for managing peak loads, adjusting load factors, and tailoring pricing strategies. Fundamental features of the SM include automated data collection and robust two-way communication between utilities and consumers. Originally developed to measure electricity, gas, and water usage, the SM is a critical component of the SG, providing users with detailed insights into their power consumption and cost per kilowatt-hour. This futuristic approach leads to more precise billing, enhanced pricing transparency, and accelerated outage detection and restoration by utility providers. Additional functionalities include tariff options, integration of tax credits, DR rates, compatibility with smart thermostats, prepaid metering capabilities, load switching, advanced grid monitoring, remote connect/disconnect features, appliance control and tracking, and participation in incentive programs designed to reduce consumption. Data outputs from the SM also contribute to assessments of voltage stability and overall system security.

3.5.4.2. Automatic meter reading. Automatic meter reading (AMR) devices enable utilities to remotely collect meter data, eliminating the need for personnel to manually read each meter. While these devices provide a limited form of bidirectional communication, their functionality remains confined, suggesting that enhancements could further boost the efficiency and reliability of the grid. Moreover, the absence of integrated home displays means that consumers do not receive direct feedback about their energy consumption, hindering their ability to adjust usage during peak hours for energy conservation. In the distribution network, AMR technology permits utilities to remotely obtain status reports, alarms, and consumption records from customer premises. However, due to its primarily one-way communication architecture, AMR is restricted to merely reading meter data, which prevents utilities from taking corrective action based solely on the received information. As a result, a full transition to an SG is unfeasible with AMR systems alone because pervasive control across all levels cannot be achieved. Essentially, AMR technology involves remotely gathering consumption data from both traditional electric meters and smart meters using telephony, radio frequency, power-line, or satellite communications, followed by processing this data to generate bills. Fig. 9 presents a block diagram of an AMR system.

3.5.4.3. Advanced metering infrastructure. AMI is a pivotal aspect of the SG infrastructure. The two fundamental constituents of AMI encompass the SM and the meter data management system (MDMS). The SMs consist of a communication board and a meter board connected through a serial port. The communication board communicates with external nodes and performs necessary computations, while the meter board measures power consumption. Critical information is stored in tables on the main board for secure communication. The communications board employs an interrupt-driven mechanism to retrieve data from the meter board and transmit it to the utility.

Meanwhile, the MDMS functions as a long-term repository for data storage and management. In addition, AMI facilitates bidirectional communication between meters and distribution system operators, enabling quicker outage detection and more comprehensive power quality reporting. SMs also allow detailed monitoring of power flows within the distribution system, facilitating prompt responses to fluctuations in consumption. Power flow monitoring is helpful for real-time pricing through DSM. Recent advancements in SM technologies have led to the implementation of time-based pricing initiatives by utilities and states [58]. Fig. 10 shows elements of AMI.

3.5.4.4. Vehicle-to-grid. Vehicle-to-grid (V2G) power is used to supply electricity to specific markets using electric vehicles with drive systems. The vehicle's energy is stored using fuel cells, batteries, or a combination. There are three versions of the V2G concept: hybrid or fuel cell vehicles, battery-powered or plug-in hybrid vehicles, and solar vehicles, all of which have onboard batteries. The advantages of V2G include providing storage for renewable energy generation and stabilizing large-scale wind generation. Plug-in hybrid electric vehicles (PHEVs) help mitigate local air pollution issues and provide an alternative to petroleum-based energy sources, thereby reducing overall emissions [59]. EVs allow for two-way flow. Two types of power interactions are possible: Grid-to-Vehicle (G2V), where the utility grid supplies energy to the vehicle, and V2G, where the vehicle can return power to the grid. There are two primary V2G architectures: deterministic and aggregative. In the deterministic approach, the grid system operator directly delivers services to plug-in vehicles, with each vehicle acting as a discrete resource that can bid and supply services at the charging station. Although this model is straightforward to implement, it faces challenges in delivering high-power services and meeting energy thresholds.

To facilitate a clear, side-by-side comparison of the various vehicle-to-everything (V2X) modalities discussed above, Table 3 summarizes each mode's core characteristics, primary benefits, and inherent limitations. By collating Vehicle-to-Grid (V2G), Vehicle-to-Home (V2H), Vehicle-to-Building (V2B), Vehicle-to-Load (V2L), and Vehicle-to-Vehicle (V2V) technologies in one place, readers can more easily discern the trade-offs and identify the most suitable applications for different grid and end-use scenarios.

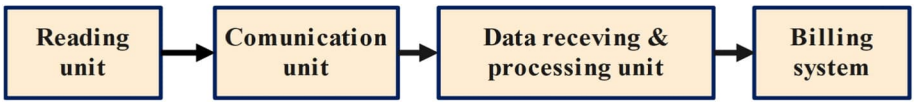


Fig. 9. Block diagram of an AMR system.

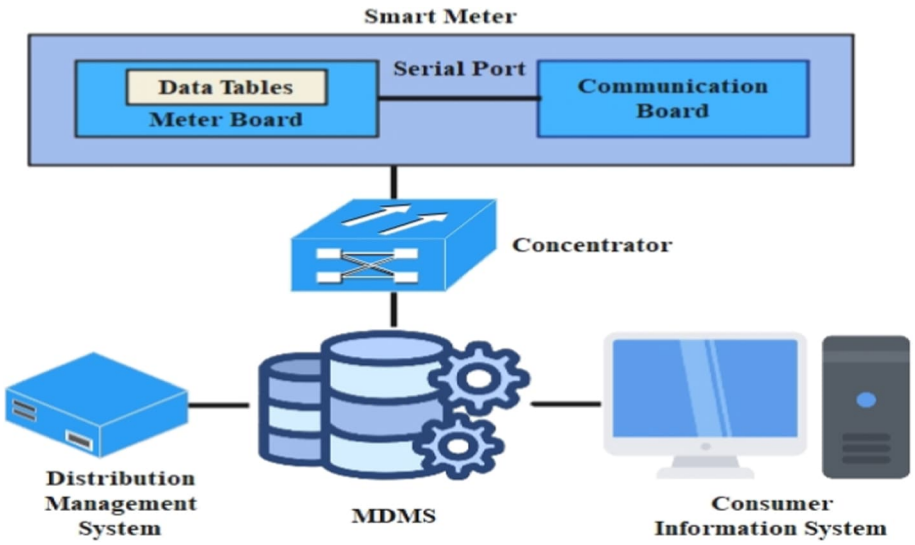


Fig. 10. Ami.

Table 3
Comparison of V2X modalities.

Modality	Description	Key Advantages	Key Disadvantages
V2G	Bidirectional energy flow between EV and grid.	Grid stabilization, ancillary services revenue.	Battery degradation, complex aggregation.
V2H	EV powers home loads during outages or peak pricing.	Backup power, reduced home electricity costs.	Requires smart home integration; limited duration.
V2B	EV supplies energy to commercial or industrial buildings.	Demand-charge management; peak shaving.	High-capacity bi-directional chargers are needed.
V2L	EV directly powers small appliances or tools.	Portable power source; emergency use.	Very low power; niche applications only.
V2V	P2P energy exchange between two EVs.	Local trading, emergency support.	Very short range; coordination overhead.

3.5.4.5. Smart sensor. Smart sensors are advanced devices integrating processing components to provide additional functions beyond accurate measurements. They utilize communication technology for activities such as telemetry and remote operation. The objectives of smart sensors include integrating distributed sensor systems, achieving cost-effectiveness, and interfacing with different sensor types. They offer a more precise and automated method for collecting environmental data, reducing noise, and providing actionable insights. Smart sensors find applications in the SG, battlefield monitoring, exploration, and scientific research. In the SG, they play a crucial role in monitoring and diagnosing equipment, such as transformers and circuit breakers. Smart sensors detect parameter changes, convert analog signals to digital, process data, and communicate with both local and remote users. They are categorized into local, station/feeder, and centralized control room levels. Local sensors have embedded intelligence, station/feeder sensors monitor distributed systems, and centralized sensors handle overall monitoring and diagnostics. Smart sensors enhance data collection, monitoring, and diagnostics in various applications [60].

3.6. Evolution Roadmap and Policy Milestones (1980–2035)

Fig. 11 presents an integrated, seven-point timeline that couples each major distribution-level technology epoch (TDN → ADN → MG → VPP → SG) with its enabling policy or market reform:

- 1980–1993: First SCADA-driven automation under vertically integrated monopolies, establishing the TDN baseline.
- 1997–2005: EU feed-in tariff directives trigger early ADN pilot projects, accelerating the integration of DERs.
- 2008: NIST Smart Grid Interoperability Framework codifies MG standards, enabling the MG transition.
- 2011: FERC Order 755 monetizes fast frequency response, incentivizing storage-rich MGs.
- 2016: Brooklyn Microgrid launches P2P energy trading, proving VPP concepts.
- 2019–2024: Regulatory sandboxes in the UK, NL, and AUS validate blockchain-settled VPP trials [61,62].
- 2025–2035 (Projected): Convergence of cross-chain settlement layers (e.g., IBC, Hyperledger Cacti) and mainstream V2G services at scale.

Quantitative analysis of CAPEX per GWh and DER-integration elasticity (sourced from IEA, ENTSO-E, and NREL) reveals that each policy impulse reduces marginal integration costs by approximately 18–35 %, underscoring the co-evolution of technology and regulation.

Early regulatory and policy initiatives have significantly influenced the evolution of peer-to-peer (P2P) energy trading. The NIST Smart Grid Interoperability Framework (2008) established standards for information exchange and interoperability, while FERC Order 755 (2011) introduced compensation mechanisms for frequency regulation, incentivizing the participation of distributed energy resources in ancillary services. These regulatory milestones created the foundation for integrating distributed resources into electricity markets. At the same time, pioneering pilot projects, such as the Brooklyn Microgrid (2016), provided practical demonstrations of how blockchain-based peer-to-peer

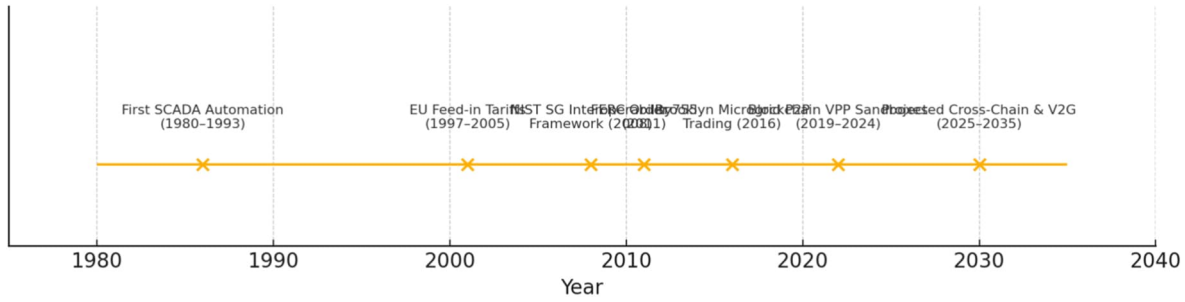


Fig. 11. Evolution roadmap and policy milestones (1980–2035).

(P2P) trading could operate within local communities. Together, these regulatory frameworks and pilot initiatives provided the technical, economic, and social groundwork for the subsequent development of decentralized energy markets [63].

Several foundational studies have shaped the intellectual basis for P2P and TE systems. Carpentier (1962) introduced optimization models for power system operation, establishing a mathematical foundation still used in modern market-clearing algorithms. Schweppe et al. (1988) proposed the concept of spot pricing of electricity, which directly influenced transactive control strategies. Wood and Wollenberg (1996) formalized power system economics, creating a bridge between engineering optimization and electricity market design. In addition, the GridWise TE Framework (2013–2015) outlined architectures for integrating demand response and distributed generation into wholesale markets. These seminal works provided the theoretical and practical foundations for blockchain-enabled peer-to-peer (P2P) trading in smart grids [64].

3.7. The IoE

IoE combines the capabilities of SG with those of IoT. The IoT, built on an internet-based framework, enables the seamless exchange of services, information, and data among billions of connected smart devices. Its applications are extensive, spanning areas such as smart grid monitoring, power distribution, telemetry services, military operations, and weather forecasting. Meanwhile, smart grids support two-way communication between the grid and EMS, facilitating the supervision and control of power generation units. As a result, IoE technology is increasingly adopted across buildings, electric vehicles, distributed energy sources, and both residential and industrial sectors. Just as routing information on the Internet directs data from source to destination, energy is transferred from source to load as needed [16]. Fig. 12 illustrates the comprehensive architecture of this IoE technology.

3.7.1. The difference between MGs, SGs, and the IoE

The concept of IoE, as mentioned, is comprehensive and encompasses both MGs and SGs. An MG is one type of small energy system that includes various distributed power generation devices, energy storage devices, energy conversion devices, loads, and related control and protection devices. Its self-control and self-management capabilities enable it to operate in parallel with the external grid or in isolation. However, the SG is an extensive energy network that considers various energy system issues based on the overall situation of the regional power grid. It employs sensors to monitor critical devices in the energy network for

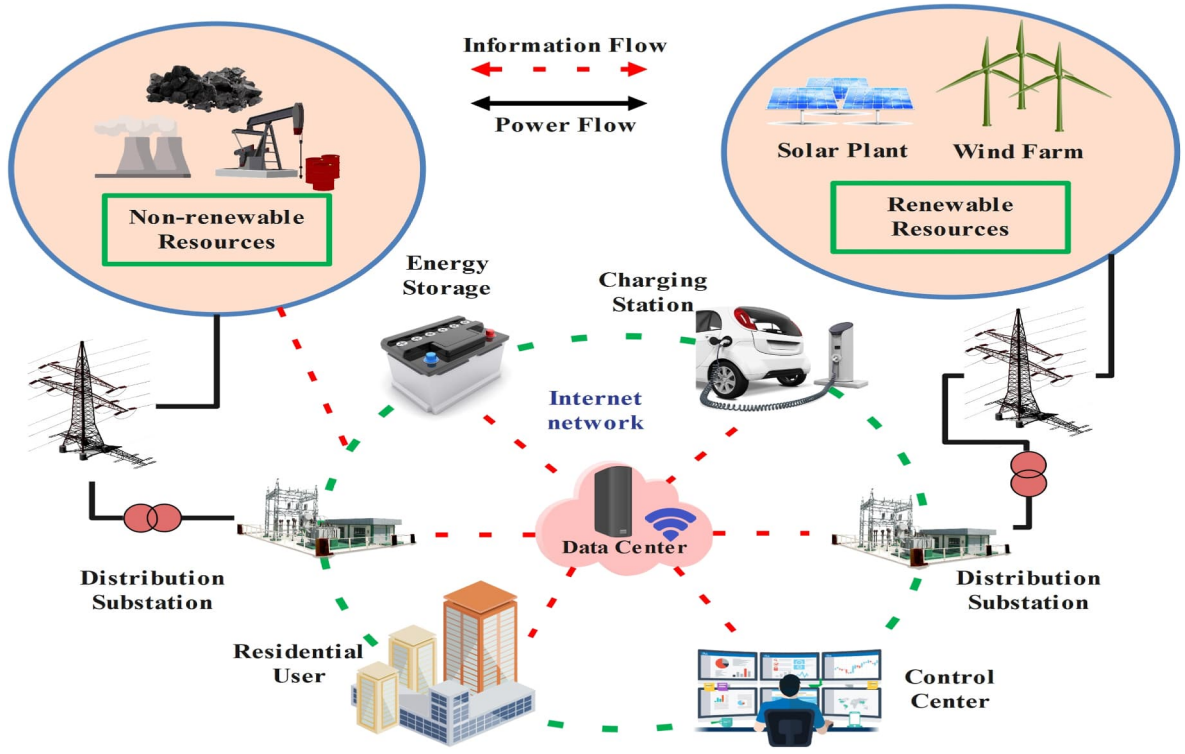


Fig. 12. Architecture of the IoE based EMS.

power generation, transmission, and power supply in real-time. It further integrates and examines the acquired data to achieve optimal management. IoE, in contrast, is an expansion and deepening of the SG concept. It differs from the SG in several ways [65]:

- The physical entities of an IoE are primarily comprised of electricity, natural gas, and transportation systems. While the power system predominantly constitutes the physical entity of an SG.
- Electric and thermal energy are just two forms of IoE's energy transmission, but electric energy is the only form of energy transmission in the SG.
- IoE engages a broader range of participants compared to the SG. Additionally, energy consumption within the IoE is characterized by both local usage and wide-area coordination, whereas in the SG, consumption is predominantly localized.

3.7.2. Key technology of the IoE

The IoE has certain commonalities and contrasts with the features of the Internet. These similarities can be distinguished into two domains: structural and functional similarities. The structural similarity suggests that the Internet and IoE are composed of three key constituents: generation, transmission, and distribution. Like the Internet, the IoE possesses a multitude of control nodes and a router, which can be employed for varying degrees of control. These functional similarities between the Internet and IoE are duly acknowledged. Concerning the Internet, information can flow point-to-point between two nodes, and information is perpetually generated, replicated, and stored. However, the IoE is incapable of reproducing energy. Therefore, the supplied energy must be balanced with the demand [16].

3.7.2.1. Energy router. Energy routers are an essential component of the IoE. An intelligent distributed grid control system, a solid-state transformer, and a communication unit form the energy router. The router can receive, analyze, and send grid information. The router can balance supply and demand to increase the power network's reliability, efficacy, and security, allowing it to optimize energy use. If more energy is available than is needed, the energy router transfers additional power to the utility grid.

3.7.2.2. Energy storage system. The ESS in the IoE can improve the grid's efficiency, stability, and reliability. Incorporating storage devices can alleviate the strain on the grid and accumulate energy for future use, thereby ensuring a seamless electricity supply. Additionally, integrating ESS can improve power quality and rectify voltage fluctuations. Batteries, supercapacitors, fuel cells, flywheels, compressed air systems, and pumped hydroelectricity are part of the typical storage devices used in an ESS. Thermal storage systems (TSS) offer a compelling and environmentally friendly storage potential, reducing energy use and GHG emissions. A sensible heat storage system (SHSS) stores and releases heat by increasing or decreasing temperature.

In contrast, a latent heat storage system (LHSS) can store a considerable amount of heat within a limited range around the phase transition temperature. Furthermore, a thermochemical heat storage system (THSS) possesses a high energy density with negligible heat loss. Nevertheless, the principal impediments of THSS in building applications are their exorbitant cost and unsuitable operating temperature and discharge power.

3.7.2.3. Renewable sources. The IoE was developed to foster sustainable development, enhance safety, and protect the environment. It unites a network of interconnected RESs, such as solar and wind power. Moreover, renewable technologies that integrate ESS are widely recognized as highly effective in establishing a stable and reliable green energy ecosystem.

3.7.2.4. Plug and play and appliance integration. PP technology enables a computer to identify and adjust to newly incorporated hardware automatically. In this regard, the term "interface" generally refers to the connectivity or interactivity between distinct components of a given system. RESs and storage devices are connected more easily, thanks to the IoE's PP interface. MGs, whether AC or DC, can be connected via their respective interfaces, allowing the PP interface to utilize various interfacing techniques (AC/DC) depending on the power type. Integrating home appliances or other loads is essential to maintain the balance between supply and demand, which is critical for the efficient operation of the IoE. Research has documented the environmental impacts of various household appliances, including refrigerators, vacuum cleaners, televisions, and cooker hoods. Consequently, advanced studies on home appliance usage could play a significant role in reducing overall electricity demand and GHG emissions.

3.7.3. Benefits and challenges in IoE implementation

Implementing IoE presents both benefits and challenges, some of which are outlined in this section. Table 3 shows the benefits of IoE, and Table 4 shows the challenges IoE faces [66].

3.8. The internet of microgrids

The internet of microgrids (IoMs) is a networked system comprising multiple microgrids for communication and collaboration. The IoM concept leverages digital breakthroughs to enhance MG operation and integration into the broader energy ecosystem. It uses MGs with IoT technologies to create smarter and more flexible energy systems. To improve the performance of the MG network, it utilizes the most advanced communication technologies, including wireless mesh networks and cloud-based infrastructure. P2P wireless mesh networks and cloud-based communication, which adhere to standards such as IEC 61850, comprise the communication architecture for the IoT. This system enables the SG to incorporate DERs, providing distributed control over vast regions. IoM optimization methods focus on achieving economic dispatch and energy efficiency. IoM optimization methods focus on accomplishing energy exchange and economic dispatch within and across MGs. Cloud-based services and storage prioritize real-time information interchange and secure networking [67] (see Tables 4 and 5).

3.8.1. Key benefits of IoM

The IoM delivers a range of significant benefits, including enhanced efficiency, improved reliability, and increased flexibility. Additionally, it provides essential support for TE.

Table 4
Benefits of IoE implementation for improved efficiency, reliability, and consumer engagement.

Benefits	Implementation
Customer Satisfaction	Savings in electricity bills, less maintenance, and direct communication between the power supply and consumers.
Development of a new business model	Flexibility in the exchanges introduces a more competitive environment.
Increased utilization of resources	IoE increases the use of available renewable energy resources.
Improved system reliability	Through frequent system monitoring, stability is enhanced, and disturbances are minimized.
Increased energy efficiency	IoE consists of smart equipment that reduces power loss. Also, faster communication technologies make it more efficient.
Reduced residential consumption	Customers can save energy with smart control and management.
Prediction of power system failures	Reduce power system downtime with saved data and predictive failure analysis.

Table 5
Primary challenges in IoE implementation: Interoperability, standardization, and cyber-physical security.

Challenges	Implementation
Dynamic Pricing	To accurately determine service costs in response to customer demand, a dynamic pricing model is essential.
bullet Interoperability issues	The adaptable nature of these standards introduces interoperability challenges that play a crucial role in shaping the economic impact of the IoE.
Standardization	Establishing a unified framework of standards is essential for the effective regulation and management of the IoE.
Stability issues	There is a notable deficiency in the advancement of transfer stability and fault detection capabilities within power systems.
Cyber-physical security concerns	The IoE system relies extensively on the exchange of information, which inherently exposes it to security vulnerabilities and cyber-physical attacks.
Scalability	The modern power system, by this time, will have evolved into a large-scale system, so we need to maintain its stability.
Congestion	Enormous amounts of data are generated by various loads, even as power lines operate under strict transmission capacity limits.

3.8.2. Challenges of IoM

Despite its potential benefits, the IoMs also face several challenges:

- Cybersecurity: As is the case with any system that heavily depends on digital technology and connectivity to the Internet, the IoMs is susceptible to potential cyberattacks. Consequently, safeguarding the cybersecurity of these systems represents a crucial and pressing challenge [68].
- Data Privacy: The acquisition and utilization of comprehensive information regarding energy generation and utilization may raise concerns about confidentiality and the protection of such data.
- Interoperability: To fully reap the benefits of the IoMs, it is essential to ensure the compatibility and exchange of information between diverse systems and devices. This task can present a difficulty due to the extensive array of technologies and standards in operation.
- Regulation: The current energy regulations and market structures may not be adequately suited for the decentralized energy systems enabled by the IoT, which are driven by data. Therefore, modifying these regulations and structures to facilitate the IoMs is a significant challenge.

3.9. Cyber-physical power system

A cyber-physical power system (CPPS) is an extensive, networked system comprising interconnected physical and computational components that operate in a network. The development of CPPS involves the amalgamation of engineering and computer science, with a central focus on systems integration. Critical challenges in CPPS development include architecture, interoperability, networked control, standards and test procedures, verification and validation, and security. The idea that CPS can be used to solve engineering challenges in critical infrastructures, such as energy, transportation, and smart cities, is something other than what an AI would typically generate. Nevertheless, more than a mere consideration of the technical aspects is needed. The human element plays a crucial role, as users must comprehend how to interact with CPPS and be convinced of its utility. Hence, the design process should consider the social aspects of these systems [69]. In Ref. [70], to monitor safety risk in physical cyber power systems, a group learning algorithm is presented to accurately predict anomalies in CPPS and overcome the limitations of previous models, which have a high level of accuracy and reliability, making it well-suited for security risk monitoring in industrial control networks of hydropower generation. The structure of the CPPS [71], including its connections and elements, is shown in Fig. 13.

3.9.1. Components of CPPS

The CPPSs have a lot of components, but the most important are the following:

- Physical infrastructure;
- Sensors and actuators;
- Communication networks;
- Control centers;
- Cybersecurity measures.

3.9.2. CPPS layers

A CPPS consists of multiple layers that work together to enhance the system's implementation. Different categories of CPPS layers are presented in further references. In this research, the complex interconnections and interactions in the CPPS are considered to be a system with three subsystem functional layers, as shown in Fig. 14. Because future power systems will change from ADN to MGs, SGs, and CPS, it is necessary to implement condition monitoring plans in the cyber-physical structure of power systems. According to Ref. [72], the infrastructure and cyber-physical layers in power networks will be defined as shown in Fig. 14(b). For most of the studies in the CPPSs, such as reliability assessment, control, monitoring, etc. (except the power system physical- and cyber-security assessment), the four-layer model of Fig. 14(b) (including the physical layer, interface (control and protection) layer, communication and information layer, and supervisory/application/business layer) is efficient and has enough accuracy. The four-layer representation of Fig. 14(a) closely aligns with the IEC 61850 standard.

Fig. 14(b) features five separate layers with communication links among them, and one of their advantages is the two-way communication between each layer. The first layer, which is a primary necessity for all ADNs, MGs, and SG systems, is the physical layer. This layer encompasses all components that produce and consume electricity, such as electric vehicles, transformers, and buildings (e.g., smart homes and smart buildings); the more components this layer includes, the more complex the CPS becomes. The second layer, the communication layer, also known as the interface layer in some references, includes all the sensors placed on the physical components. The third layer, the information layer, is responsible for extracting information from the communication layer. This layer collects all the information gathered by the sensors (such as data from telecom servers). The fourth layer, also known as the function layer, is responsible for processing information and performing functions on it, and then separates the information required by the next layer after processing. The last layer, which is the business layer and is directly related to the electricity market, determines decisions such as network costs, production and consumption costs, and electricity prices for various types of consumers, based on the data from the previous layers. The complexity of this model embodies the concept of cyber-physical systems of systems (CPSoS) in the form of cyber-physical distribution systems (CPDS).

3.9.2.1. Decision-making intelligent subsystem layer (DISL). The intelligent decision-making layer is pivotal in defining the overall sophistication of a CPPS. This layer, known as the DISL, comprises several programs and functions, including substation automation, control center operations, renewable power generation management, and energy and demand management systems. These components consist of computer applications for relays, IEDs, and related elements, all designed to ensure the power system operates continuously by processing sensor data and disseminating information through the communication infrastructure [73].

3.9.2.2. Communication and coupling the subsystem layer (CCSL). The CCSL comprises communication networks and interface devices, such as remote terminal units (RTUs). These networks are categorized into

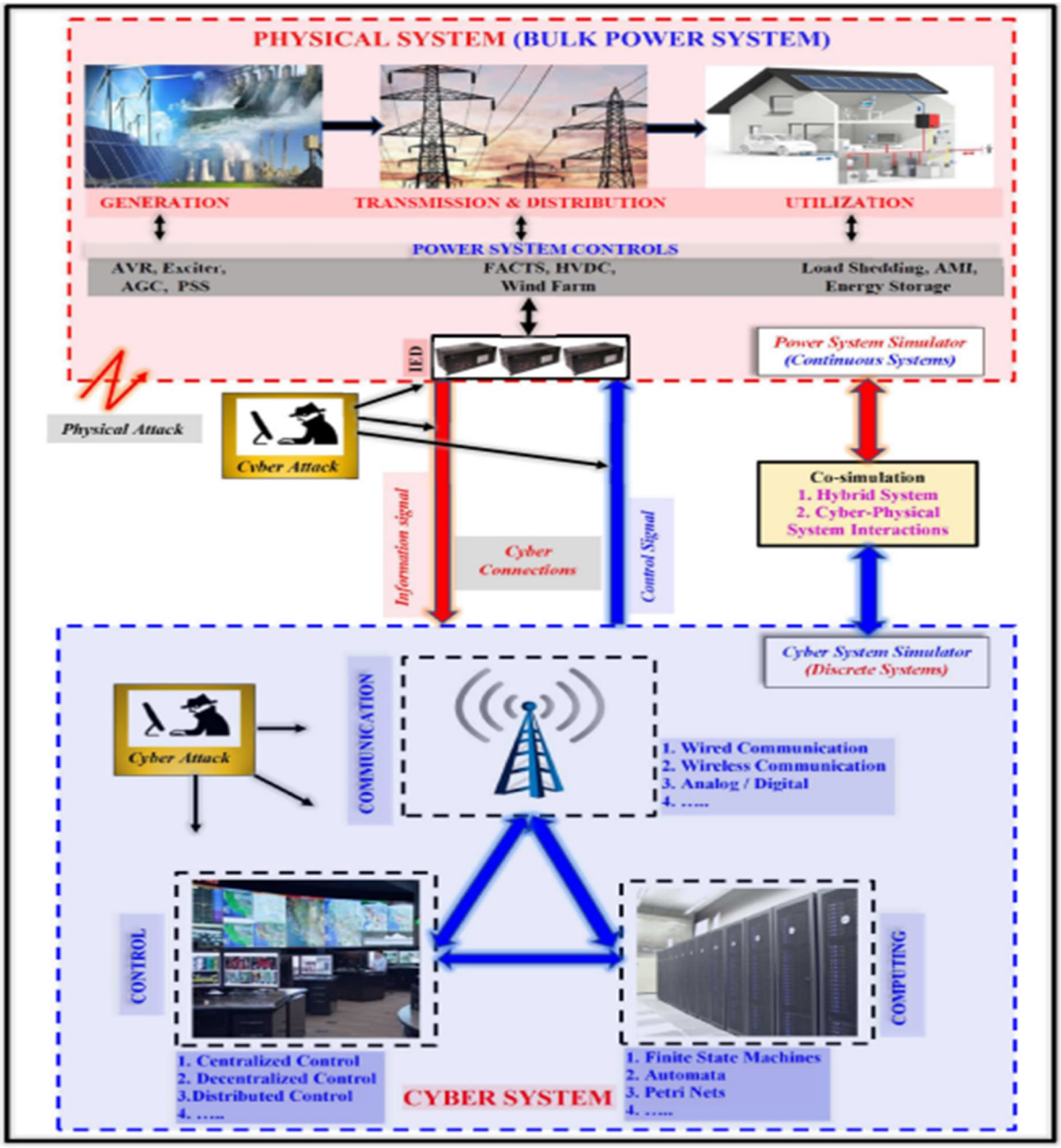


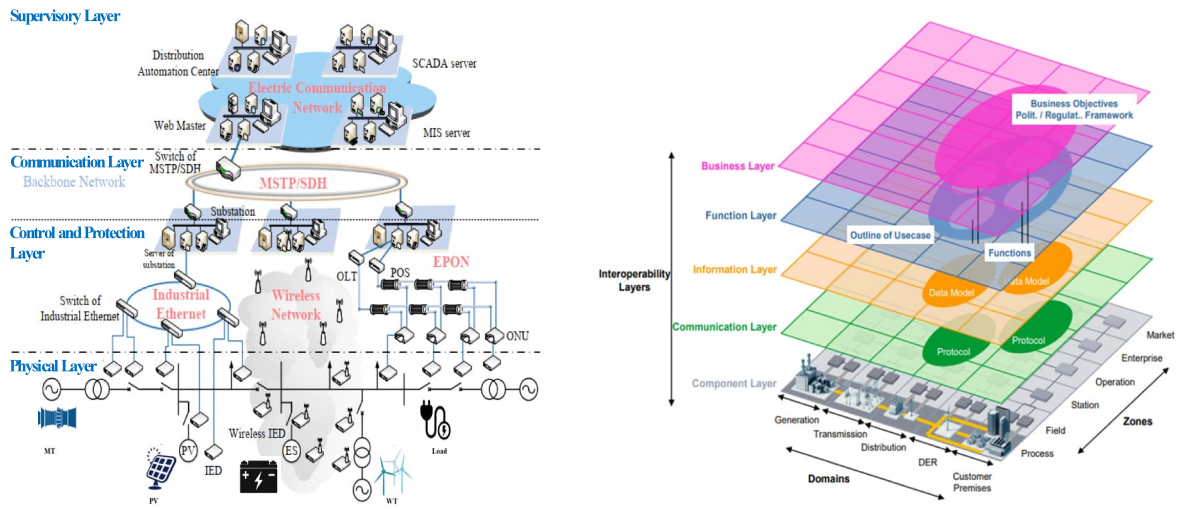
Fig. 13. Structure of the CPPS.

wide-area, field-area, and home-area networks, connecting various communication devices. The interface devices facilitate the transmission of control directives and decision programs from the DISL to the power layer, as well as measurements from the power layer to the DISL. Malfunctions or errors in the communication networks or interface devices can impact the accuracy of the DISL functions [74,75]. These communication networks and links are also vulnerable to wrong data injection attacks [76], which can manipulate measurements during data transmission. This can lead to incorrect decisions by the DISL and potentially cause system malfunctions or even a blackout.

3.9.2.3. Physical power subsystem layer (PPSL). The PPSL represents the tangible infrastructure of the power network, encompassing assets related to power generation, transmission, and distribution. This layer encompasses components such as protection systems, power electronic interface devices, storage technologies, as well as both conventional and SG loads. Typically, the power system is divided into three operational zones: generation, transmission, and distribution. Additionally, devices within the PPSL are linked to communication and coupling layers via state-monitoring sensors and program execution modules.

3.9.3. Characteristics of CPPS

Because of the combination of physical and cyber components in the power grid, CPPS differs from other types of power systems. The power grid and its various elements, including generators, transformers, and protective systems, are represented in the CPPS's physical layer. Conversely, the cyber layer involves communication, computation, and control components, facilitating bidirectional communication and advanced automation in power systems. CPPS demonstrates interdependencies and interactions between the physical and cyber layers, wherein modifications or disturbances in one layer can impact the other. These systems are engineered to enhance the dependability, durability, security, and sustainability of power grids by employing cyber-secure communication systems and advanced technologies.



(a) (b)

Fig. 14. CPPS representation: a) A basic four-layer representation of cyber-physical power distribution systems, and b) cyber-physical power distribution layers representation based on the SG architecture model, CEN-CENELEC-ETSI SG coordination group (2012) [72].

Nonetheless, they also face challenges in cyber and cyber-physical attacks, necessitating precise and comprehensive modeling of CPPS to examine, assess, and improve their dependability and durability. The modeling of CPPS should account for the progressive shift towards more distributed and autonomous environments in power systems, considering the trade-offs and design choices required to effectively encompass the interdependencies and characteristics of these intricate systems. By understanding and considering these characteristics, researchers and practitioners can develop effective modeling methods for CPPS, enabling better analysis, evaluation, and decision-making for future energy systems [71]. Fig. 15 summarizes the main characteristics of both cyber and physical systems [69].

3.9.4. Challenges of CPPS

CPPSs face a range of fundamental challenges. These include issues related to cybersecurity, interoperability, and system complexity, as well as concerns regarding data privacy and ownership, regulatory compliance, and resilience. It is essential to note that these challenges are representative, but not exhaustive, of the obstacles encountered in CPPS development.

3.10. Cyber-physical-social power systems

The social aspect of engineering for CPS is an emerging and challenging frontier. It entails considering end-users' utility and quality of life while designing essential infrastructures. In "*smart*" infrastructures, end-users, also known as "prosumers," are active participants and contribute to the control and operation of the infrastructure. They can actively control energy use and support the grid since they have access to real-time information and decision-making tools. However, understanding and enhancing these advancements requires addressing CPS's social and societal aspects. The CPSS is a human-centric CPS approach that integrates computation, physical components, and human cognition. CPSS aims to achieve socially aware advancements in critical infrastructure operation, considering interdependencies and overall societal benefits.

In summary, the social aspect of CPS is crucial for empowering end-users and driving socially aware advancements in critical infrastructures. CPSS represents the next generation of CPS, combining computation, physical components, and human cognition in a holistic approach. Fig. 16 delineates the distinctions between CPS and CPSS concepts. In the diagram, each circle represents one of three domains: cyber, physical, and social. The four areas marked on the figure illustrate

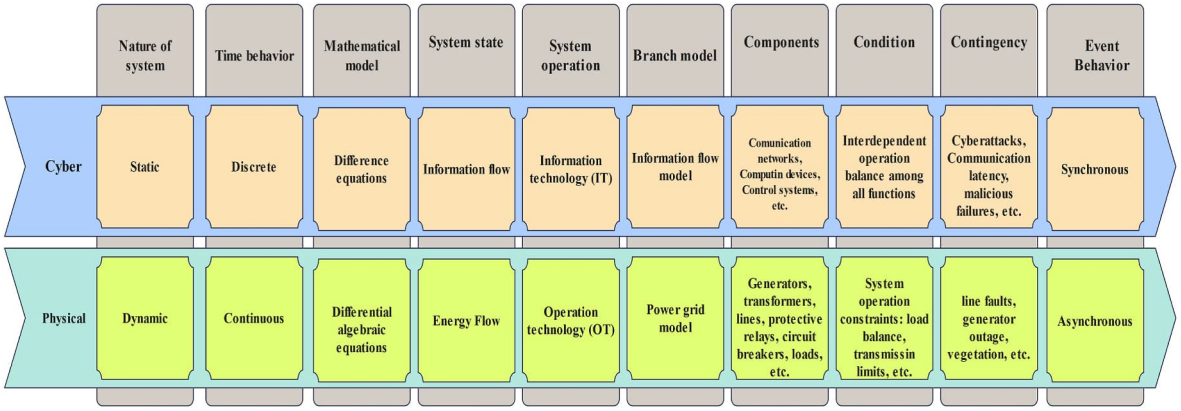


Fig. 15. Characteristics of cyber and physical systems.

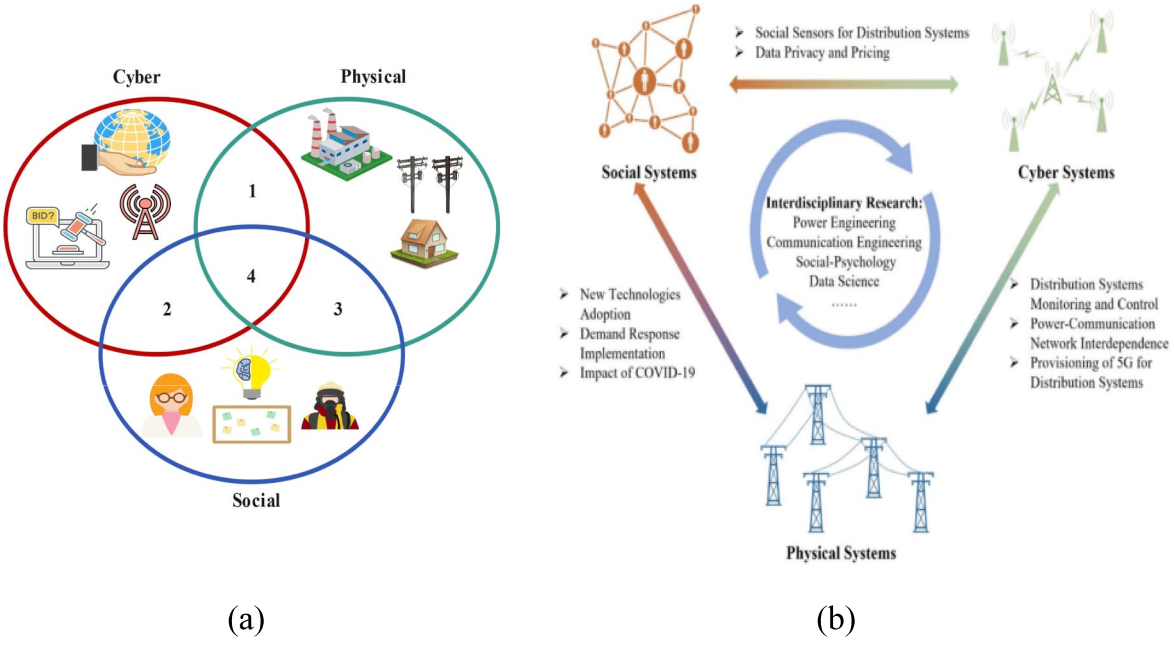


Fig. 16. a) The system-level concept of CPSS versus other domain-intersecting concepts and b) Cyber–physical–social coupling in distribution systems [78].

the intersections among these domains. Specifically, Area 1 corresponds to CPS, while Area 2 represents cyber-social systems (for example, the Internet). Area 4, where all three domains converge, embodies the proposed CPSS concept [77].

3.10.1. Components of CPSS

The components of CPSS include physical, cyber, and social systems.

- Physical Systems: The physical element links the digital (cyber) and human (social) domains. It enables the compilation and analysis of data from the tangible world, which subsequently influences the social facet of the system. The physical systems within a CPSS comprise all concrete elements in our environment, such as infrastructure, devices, sensors, actuators, and communication networks, all of which aid in real-time data collection. In the context of CPSS, the physical domain mirrors real-world systems through intelligent objects and communication infrastructures.
- Cyber systems: The cyber component pertains to the digital and computational constituents responsible for managing, manipulating, and disseminating information within the system. This component comprises system and application software, which govern the hardware and data processing, as well as data transfer networks and hardware devices such as computers, servers, and routers that facilitate data processing. Additionally, it handles data management, both structured and unstructured, that is gathered from multiple sources. The cyber component provides the CPSS's digital infrastructure, facilitating data analysis and user communication [79].
- Social systems: The social element of a CPSS encompasses the interactions between humans and society with the system, including its utilization, influence, and effects on users and society. It entails understanding human users, their social connections, and the broader social context, which are crucial for developing a user-friendly, socially acceptable, and beneficial system [80].

3.10.2. Assets

Assets in CPSS encompass a range of valuable resources for individuals, communities, organizations, and governments [81]. These assets include physical devices such as switches, routers, and computers, which are used for digitization and communication purposes. Additionally, software, applications, platforms, and databases are considered assets in CPSS. Information, comprising critical and sensitive data related to individuals, communities, organizations, and critical infrastructure, is another crucial asset in CPSS. This information is collected, stored, analyzed, and transmitted through cyberspace. Furthermore, people themselves are regarded as assets in CPSS, as they actively engage with cyberspace and contribute to the data and services provided by the system. In summary, CPSS assets encompass hardware, software, applications, information, and the active participation of individuals, all of which are vital for the system's effective functioning.

3.10.3. Applications

The applications of CPSS are diverse and encompass various domains such as traffic management, autonomous vehicles [82], customization in industrial products and services [83], recommendation systems for tourists, and behavioral profiling for predicting future behaviors [84, 85]. These applications provide services that enable users to monitor, control, and manage the system's assets and environment. CPSS application data can be collected actively or passively using a combination of homogeneous and heterogeneous sensors. This data acquisition can serve both security and marketing purposes, among others. Alternative technologies and their definitions are summarized in Table 6. There is more information about alternatives to CPSS [86].

4. Blockchain technology for trading

4.1. Concept of blockchain technology and SC applications in energy trading

A unique technology called blockchain was developed in 2009. The concept was first put forth by Satoshi Nakamoto [104]. It is a digital document disseminated to all individuals participating in a cryptocurrency network. Its primary purpose is to serve as a comprehensive register, meticulously recording all transactions. A chain of blocks holding information is created by blockchain technology. Its main feature is the ability to securely track and record all changes to these blocks, preventing them from being removed or altered. It enables the secure execution of contracts and financial transactions without the need for intermediaries such as banks or governments [105]. The blockchain operates as a software protocol that relies on the Internet and consists of various components, including software applications, a

Table 6
Other terminologies related to CPSS and their definitions.

Ref.	Term	Definition
[87–91]	CPHS/ HCPS	A Cyber-Physical-Human System (CPHS) or Human-Cyber-Physical System (HCPS) is a system where computers, devices, and humans are interconnected to achieve human goals.
[83, 85–87]	(HiL)CPS	A Human-in-the-Loop Cyber-Physical System (HiL-CPS) is a system in which humans, cyber components, and the physical environment are connected in a loop. The cyber component increases human interaction with the physical world by combining humans' intentions, psychological states, emotions, and actions as integral components of any computational system.
[92–94]	SIoT	The Social Internet of Things (SIoT) is a social network where every node is an object capable of establishing social relationships with other objects autonomously, according to rules set by its owner.
[95–97]	SCPS	Social Cyber-Physical System (SCPS) is a CPS that strongly interacts with the human domain and the embedding environment, working according to the expectations of humans, communities, and society under the constraints and conditions imposed by the embedding environment.
[80]	CPST	Cyber-Physical-Social Thinking (CPST) is a concept that emerged from the fusion of CPS and IoT, based on cloud computing technology, as a broader vision of the IoT. CPST is a hyperspace established by merging a new dimension of thinking space with the CPS.
[98]	HCPPS	The Human Cyber-Physical Production System (HCPPS) is a generic architecture that features a control loop, adaptive automation control systems, and human-machine interaction, enabling seamless interface between humans, machines, and software in both virtual and physical worlds, thereby creating a human-centric production system.
[99]	CIoT	The Cognitive Internet of Things (CIoT) is a paradigm designed to enhance the performance and intelligence of IoT through cooperative mechanisms with Cognitive Computing technologies that mimic human-like Cognitive capabilities, such as Understanding, reasoning, and Learning.
[100]	HitM	Human in the Mesh (HitM) refers to human activities in a Cyber-Physical production system where the worker participates in production planning and its control loop, and the manager's role usually enacts it.
[101]	CPHMS	Cyber-physical human-machine Systems (CPHMS) are a type of CPS that encompasses problems related to cognition (planning and decision-making), navigation, action, human-robot interaction (including perception, environment sensing, and interfacing with the end-user), and architecture development and middleware.
[102]	PCSC	Physical-Cyber-Social Computing (PCSC) is a paradigm that encompasses a holistic treatment of data, information, and knowledge from the Physical, Cyber, and social worlds, integrating, correlating, interpreting, and providing contextually relevant abstractions to humans.
[103]	Smart-CPS	Smart-CPS is a CPS that combines various data sources (from physical objects and virtual components) and applies intelligence techniques to manage real-world processes efficiently.

database, and connected computers called nodes. It can be built using different programming languages.

Every blockchain has a first block, known as the Genesis block, which serves as the chain's foundation. Each recently created block is connected to the blocks that came before it in the chain, connecting each block ultimately to the Genesis block. Each block contains data and also has a hash in addition to the data. As shown in Fig. 17, the hash can be considered a fingerprint that uniquely identifies each block and its contents. As a result, anytime the content of the block changes, so does the corresponding hash. As a critical assurance of blockchain security, hashes are crucial to the blockchain's operation. As shown in Fig. 17, each block in the chain has its hash and the hash of the previous one.

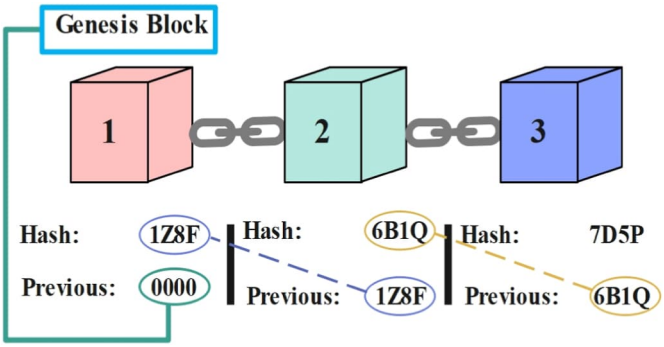


Fig. 17. General Blockchain structure.

Blockchain technology is now among the most secure solutions available due to this method. The hash of a block will change when it is attacked by changing its information, but the hash of the following block won't. As a result, all the blocks after that are marked as invalid blocks. As a result, any change to a single block in the blockchain renders every subsequent block invalid. Fig. 18 illustrates how the blockchain becomes invalid after modifications to the block hash.

Fig. 19 shows a generalized process that describes how blockchain works [106]. Any user could start the process by requesting a transaction. The transaction is then published to all network users. After that, all nodes confirm the transactions using hashes as part of the verification process. The transaction is permanent and unchangeable once verification is complete, as it is stored within a new block linked to the previous blockchain. Blockchain security is effectively achieved through the use of hashes. Hackers may modify the data in a single block and quickly recalculate the hashes of all subsequent blocks in the chain using high-speed computers [107,108]. Numerous techniques have been developed to address this problem following the established consensus. Before transactions are added to blockchains, they must be verified as part of the consensus process. As a result, there is no longer any concern about the blocks or the data they contain changing as the blockchain expands.

4.2. Features of blockchain and consensus mechanisms for permissioned energy networks

Some vital features of blockchain technology contribute to its efficiency and appeal [105]. These qualities are discussed further in this section.

4.2.1. Decentralization

Blockchain technology operates on the principle of decentralization, which means that no central authority controls transactions or decision-making. Instead, information is shared across multiple nodes, allowing everyone in the network to access it. This enables direct P2P transactions without intermediaries, empowering individuals to take personal responsibility for their actions. Decentralization enhances security by eliminating a single point of failure and ensures that all participants can see the entire transaction history. By overcoming the limitations of centralized systems, blockchain offers improved resilience and accessibility for all [109].

4.2.2. Transparency

Transparency is crucial in the contemporary supply chain, as it fosters trust, collaboration, and accountability. It surpasses traceability and encompasses exchanging valuable information among various parties involved. Trust is crucial for transparency, and technologies like Blockchain, SCs, and IoT contribute to achieving it. Data privacy issues do emerge. However, blockchain technology provides both data transparency and immutability. Customized enhancements and access

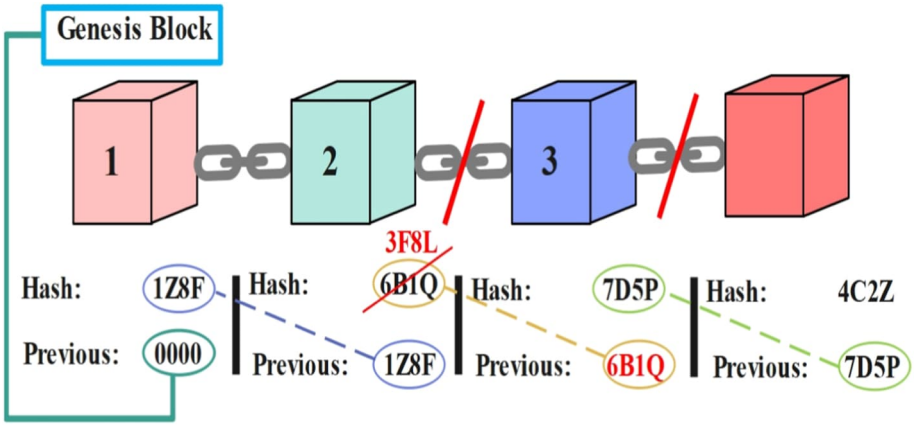


Fig. 18. Blockchain structure invalidation.

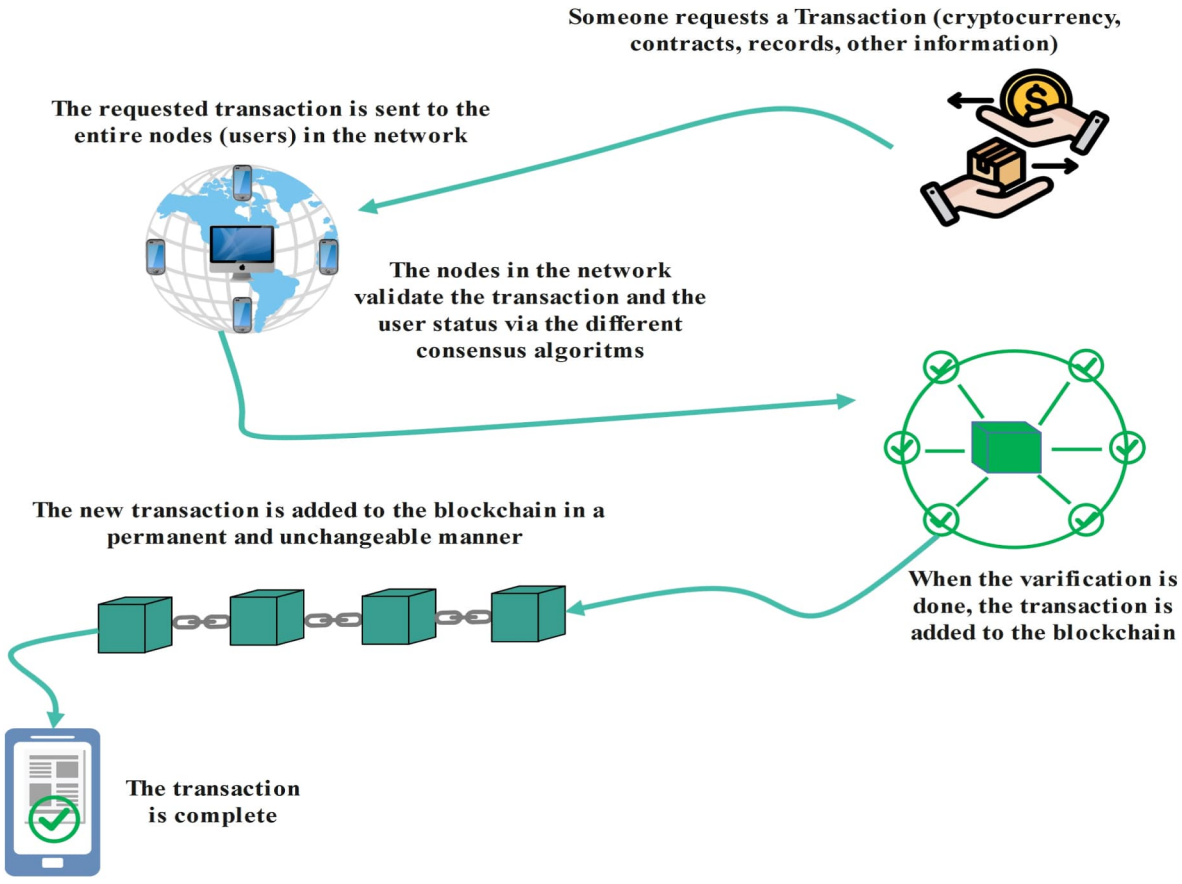


Fig. 19. Blockchain transactions steps.

control mechanisms help strike a balance between transparency and confidentiality within the process. SCs and IoT have made automation, real-time monitoring, and effective supply chain management. These technologies not only enhance transparency but also address concerns related to confidentiality, ultimately benefiting all stakeholders [110].

4.2.3. *Immutability*

Whenever a transaction has been initiated and data inserted into the DL, the ability to make modifications or deletions is not available [110]. The additions made to the blockchain are permanent and cannot be altered. Furthermore, once registered, these additions remain unchangeable and are accessible for validation and verification. If any data within a block of the blockchain is modified, this alteration is reflected across all ledgers within the network. The specific node that has been changed is identified, and necessary rectification is carried out.

4.2.4. *Security*

Blockchain utilizes sophisticated cryptographic methods to safeguard data and transactions, making it impervious to unauthorized tampering or manipulation. Upon inclusion in the blockchain, any alteration of a transaction becomes exceedingly arduous to carry out undetected. The blockchain's integrity is maintained through the use of consensus mechanisms. These attributes, in combination, establish a resilient and impregnable foundation for blockchain technology [111].

4.2.5. Traceability

Blockchain technology offers significant benefits in terms of tracking and enhancing transparency. It enables the easy tracing of RESs, such as wind or solar, connecting them to specific consumption points. Additionally, blockchain simplifies traceability throughout the supply chain process, ensuring transparency and validation of transactions shared by multiple partners. This feature effortlessly monitors the product's journey from production to distribution, retail, and customer purchase. The permanence and transparency of blockchain entries enable customers to examine the transaction history of a product, thus verifying its authenticity and current status [105,112].

4.2.6. Efficiency and reduced costs

Through increased transparency, faster procedures, P2P trading, automated agreements through SCs, improved finance and supply chain management, and more superficial regulatory compliance, blockchain technology promises efficiency benefits and cost reductions in the energy sector. By utilizing these capabilities, blockchain can help create a more intelligent, effective, and affordable energy system [13,113].

4.2.7. Advanced blockchain architectures and security trends (2022–2025)

Over the past three years, significant progress has been made in scaling blockchain platforms to meet the throughput and latency requirements of real-time energy-trading markets. Zhang et al. (2024) demonstrated a permissioned Fabric-based network that sustains over 1500 transactions per second (tx/s) with sub-second finality by optimizing endorsement policies and utilizing a sharded state database to parallelize consensus operations [114]. These scalable architectures overcome earlier bottlenecks, bringing blockchain platforms to TRL-8 for live deployments.

Equally important are privacy-preserving techniques that reconcile on-chain transparency with prosumer confidentiality. Varshney et al. (2025) introduced PrGChain, which integrates a zero-knowledge oracle (ZKOracle) that cryptographically proves the correctness of bid matching without revealing individual order details [115]. By anchoring only proof digests on-chain, PrGChain reduces gas costs by 40 % compared to baseline zero-knowledge proof (ZKP) schemes, while preserving bid privacy —a crucial requirement for competitive energy markets.

To harden SCs against exploits, formal verification and enhanced trust layers have emerged as best practices for mitigating vulnerabilities. The RETINA protocol, which combines a public-key infrastructure (PKI) with a Web-of-Trust consensus overlay to authenticate nodes and prevent Sybil attacks, was proposed in Ref. [116]. RETINA's formal security analysis, conducted using the TLA^+ model checker, uncovered and mitigated four classes of reentrancy and integer-overflow vulnerabilities before deployment on a 2 MW MG pilot. Real-world pilot projects have sharpened our understanding of the challenges associated with cyber-physical integration. An IOTA-based directed acyclic graph (DAG) ledger has been developed within a 500 kW community microgrid, coupling mesh-network-attached sensors to on-tangle smart meters for end-to-end energy accounting [117]. Their field results showed <0.1 % loss over six months and end-to-end settlement latencies under 2s, benchmarks previously unattainable with legacy blockchains.

Emerging MPC/ZKP hybrid schemes layer additive secret-sharing on top of zk-SNARK proofs to obfuscate bid volumes while enabling aggregate settlement [118]. In lab tests, their SePEnTra implementation maintained transaction rates (tx/s) above 500 and proved individual bid ranges in 120 ms, making it suitable for second-scale energy markets.

Finally, the extension of blockchain models into smart-city energy services has gained traction. Seven Europe-wide urban pilots that tokenized kilowatt-hour certificates as non-fungible tokens (NFTs), enabling mobile app-based peer-to-peer energy resale under municipal microgrid tariffs, have been surveyed in Ref. [119]. They report that tokenization increased prosumer participation by 35 % and streamlined utility billing operations by integrating with city-scale IoT platforms.

These advances collectively address the twin challenges of throughput, privacy, security, and CPS interoperability, charting a path from academic proofs of concept to production-grade, pilot-validated systems.

4.3. Blockchain alternatives

4.3.1. Centralized databases

The blockchain community values decentralization, but centralized databases have their benefits. Recent blockchain performance is improving, but it lags behind that of centralized databases. Blockchain enhances security, but alternatives should be considered. Centralized databases offer simplicity and efficient data retrieval, but they also have limitations. They are managed at a single location, making data access easier. However, there is a risk of system failure and data loss.

4.3.2. Centralized ledgers

Centralized ledgers, operated by a single organization, serve as reliable sources of transactions, enabling efficient decision-making and accurate financial tracking for companies. Regardless of their value, all transactions are diligently recorded in these ledgers. The management of centralized ledgers is typically handled through enterprise resource planning systems. Although they offer efficiency, they are not as widely favored due to the inherent risks of errors and susceptibility to cybersecurity breaches.

4.3.3. Distributed databases

DL technologies have emerged as a decentralized solution for record-keeping, offering increased security by eliminating the need for a central authority. Bitcoin's Blockchain serves as a prominent example of this innovative approach. Data is stored in multiple locations in distributed databases and maintained through replication and duplication. Replication involves scanning the database for updates and synchronizing all databases to ensure uniformity, a process that can be time-consuming. On the other hand, duplication involves copying a master database to maintain consistent data across locations. During duplication, modifications can only be made to the master database, safeguarding the integrity of local data from being overwritten.

4.3.4. Cloud storage

Blockchain offers decentralized data storage and depends on third parties for data security. It provides services through models such as Software as a Service (SaaS), Platform as a Service (PaaS), and Infrastructure as a Service (IaaS). Unlike cloud storage, Blockchain guarantees data immutability, as it cannot be changed once recorded. However, as enterprise data volumes grow, replicating them across multiple devices becomes impractical, making cloud storage a more efficient and dependable choice. Cloud storage incorporates robust security features, hashed blocks, public/private key encryption, and transaction ledgers, ensuring powerful protection against hackers.

4.3.5. Decentralized storage

Decentralized storage systems differ from centralized servers, consisting of a network of P2P users who collectively own and share the data. This decentralized approach is gaining attention from Blockchain developers as it offers the ability to combine storage with other applications. It allows developers to store webpages, information, and data in a manner that reduces bandwidth usage, enhances resilience, and mitigates the impact of censorship. Decentralized storage facilitates file encryption, fragmentation, and distribution across a global cloud network. It is compatible with Amazon S3 storage technologies, making it easy for cloud developers to integrate it into applications without needing extensive tool adoption.

4.3.6. Other DL technologies

The DAG technique enables faster data writing in applications than

private blockchains, although transaction confirmation may take some time. It offers advantages over traditional Blockchain systems regarding speed and data writing capabilities. Alternatives to Blockchain for DLs are named and discussed further.

4.3.6.1. Hashgraph. Hashgraph is a distributed ledger (DL) technology that eliminates the need for mining, unlike traditional blockchains. It utilizes a data structure called a hashgraph to record the sequence of information sharing between participants. In contrast to blockchains, hashgraphs validate transactions more rapidly by leveraging a shared history of gossip events, allowing users to add and share information efficiently.

4.3.6.2. IOTA tangle. The IOTA Tangle is an open-source DL designed for secure communication and payments between IoT devices. When using IOTA, devices are responsible for processing multiple transactions within the tangle. It is specifically designed to facilitate micro-transactions. Each node in the IOTA Tangle represents a transaction within a DAG structure. Although decentralized, the IOTA Tangle still requires a supervisor node to oversee and approve incoming transactions in real-time.

4.3.6.3. R3 Corda. R3 Corda is a DL technology platform that enables developers to build applications that promote and facilitate digital trust in regulated markets. Corda is a scalable, permissioned, and P2P platform. It enhances data security by ensuring that only the designated group of peers can access transaction-related data. Unlike DAG-based DLs, Corda simplifies the creation, automation, and enforcement of SCs, which are crucial applications in the blockchain ecosystem.

4.4. Blockchain applications

4.4.1. Main blockchain applications in industries (non-power)

Blockchain technology is widely deployed across various sectors, including markets, IoT, health, and science. Most of these applications require development for industry adoption, except for those in the cryptocurrency industry. A compilation of several Blockchain applications can be found in Table 7.

4.4.2. Blockchain applications in SG

Blockchain technology is a driving force behind modern progress and a seamless switch to SG. Researchers and industry leaders highlight its decentralized nature as a foundational aspect of SG technologies. Research on new control strategies has been motivated by the grid integration of EVs, energy storage devices, and RESs. Blockchain's advantages have generated significant interest in its adoption, with applications in power generation, transmission, distribution, and consumption, enabling real-time grid monitoring, decentralized control centers, and efficient energy trading between prosumers and storage systems [106].

The following are the major categories in which blockchain applications are widely studied and utilized in Singapore.

4.4.2.1. Energy trading. Energy trading involves the buying and selling of energy resources, such as oil, natural gas, and electricity. Traditionally, energy is generated through centralized exchanges, which involve intermediaries such as brokers and utilities. However, with the advent of blockchain technology, P2P energy trading has become possible. This enables direct transactions between energy producers and consumers, eliminating the need for intermediaries. Blockchain-based TE systems enable the creation of decentralized energy markets where consumers can directly purchase renewable energy. They can be integrated into RESs by serving as a secure, digital ledger that tracks and verifies energy transactions in real time [135]. It enables energy generated from sources such as solar panels and wind turbines to be recorded and traded directly between users without the need for a central intermediary [136]. The use of SCs enables transparent and secure transactions, ensuring the reliability of energy trading. By facilitating more effective and sustainable energy exchanges, P2P energy trading has the potential to revolutionize the energy sector. To solve security and privacy concerns in the current energy markets [137], presents a safe, decentralized transaction System (DTS) for energy trade in MGs built on blockchain technology. In this [138], the authors provide vehicle-to-vehicle and charging-station-to-vehicle energy trading mechanisms for EVs to ensure privacy. These schemes aim to safeguard the confidentiality of EVs during the charging and discharging processes. An anonymous authentication scheme is employed to counter Sybil attacks and integrate an efficient blockchain-based payment system, facilitating anonymous transactions. Also [139], has highlighted the significance of energy trading, which involves the secure and efficient exchange of electricity or other energy forms among multiple parties in networked MGs. Authors of [140] have proposed a strategy for energy trading in interconnected MGs that considers the self-benefit-driven actions of MG agents. The proposed algorithm uses an adapted blockchain to enhance security and transparency.

4.4.2.2. Models for EV participation in P2P energy markets. Combining EVs in the power system gives numerous advantages, such as grid balancing and promoting renewable electricity sources. With their batteries capable of storing electricity, EVs can provide flexibility to stabilize the grid and can be aggregated to create VPPs during high-demand durations. This integration additionally reduces the need for new grid infrastructure. However, challenges, suitable charging, and participation in energy markets must be addressed. Using technology like blockchain, the connection of EVs to SGs is proposed to control and modify charging efficiently, preventing stress on the power grid. In Ref. [141], Liu et al. proposed an adaptive scheme that utilizes blockchain technology to enable EV participation in an SG platform. The scheme aims to minimize power fluctuation and overall charging costs, considering EV battery capacities, charging rates, and user behavior. In Ref. [142], the authors provided an energy blockchain-based secure charging system for EVs in smart communities. The strategy, grounded in contract theory, comprises a reputation-based consensus algorithm, a permission blockchain system, an energy allocation mechanism, and an ideal contract design [143]. To overcome issues in traditional charging systems, the paper [144] presented a safe charging system for EVs based on blockchain technology, emphasizing secure mutual authentication, fundamental security, and efficiency.

4.4.2.2.1. Market-based models. In this category, EV participation

Table 7
Blockchain applications in industry.

Sector	Usage
Markets	• Quota management in the Supply Chain Network [113] • Marketing and marketing management [120] • Decentralized finance [121]
Government	• E-Government [122] • Identity management, records management, and supply chain management [123]
IoT	• security and privacy issues [124] • Establish trust among network nodes [125] • Interoperability and privacy [126] • Smart cities [127]
Health	• To provide secure management and analysis of healthcare big data [128] • Data sharing, managing health records, and access control [129]
Science and art	• Crowd analysis [130] • P2P resources [131] • Enables new structures [132]
Finance and Accounting	• Financial accounting [133] • Accounting and supply chain systems [134]

schemes leverage auction mechanisms, token-escrow pricing, and blockchain marketplaces. For example, Liu et al. [136] propose an adaptive blockchain-based auction that minimizes charging costs, while the work in Ref. [139] uses contract-theoretic incentives within a permissioned chain.

4.4.2.2.2. Data-driven models. These models utilize real-time telemetry, machine learning forecasts, and SCs that adjust discharge schedules based on predicted grid conditions. The reputation-based consensus mechanism in Ref. [137] and the adaptive charging algorithm in Ref. [138] exemplify this approach.

4.4.2.3. MG operations. With the growing number of DERs being integrated, MG control is becoming a crucial issue. Researchers emphasize the need for demand-based MG control and optimized operation [145]. The most crucial element in the reform of electric power firms is the MG, depicted schematically in Fig. 20, which represents the application of blockchain technology. According to the features and design of blockchain, its use in MGs will significantly increase management intelligence and transparency compared to current methods [146]. To address challenges in multi-microgrid (MMG) and internal microgrid (MG energy transactions, a paper [147] proposed a two-layer framework based on blockchain technology to provide decentralized trading, information transparency, and mutual trust among nodes, ultimately improving energy utilization in frameworks of the decentralized electricity market for MGs.

4.4.2.4. Cyber-physical security. The growing interconnectedness of device systems, such as the SG, has led to an increase in cyber incidents, underscoring the critical need to safeguard the security of energy trading based on blockchain. The security measures should include both physical and cybersecurity measures to prevent malicious attacks, theft, and system manipulation. In this regard, implementing secure authentication access control mechanisms, firewalls, detection systems, and encryption techniques is essential to provide a safe and secure environment [148,149]. SG technology has increased vulnerabilities, with interconnected cyber and physical attacks requiring integrated solutions. Various categories of attacks, including time synchronization attacks, GPS spoofing attacks, and denial of service (DoS) attacks, pose potential hazards to the power grid. Among these, identifying false data injection (FDI) assaults proves to be an exceptionally arduous task. Countermeasures include protection-based schemes that increase measurement redundancy and detection-based schemes that utilize Bayesian frameworks. However, both have limitations in addressing stealthy attacks that closely mimic normal measurement distributions [106]. Thus, several blockchain approaches have been widely investigated to increase grid immunity to cyber-physical attacks [150]. has proposed using Blockchain technology with Software Defined Networking to address security and privacy concerns in Electric Vehicle-aided SG ecosystems, ensuring secure energy transactions and effective DR management. Authors in Ref. [151] propose a safe, DL approach called DeepBlockIoTNet, which incorporates blockchain technology. The proposed DeepBlockIoTNet leverages the combination of distributed DL and blockchain to improve the security, privacy, and accuracy of DL tasks in the IoT network. It enables trustworthy and efficient communication and collaboration among different parties involved in DL while mitigating adversarial attacks, training data poisoning, and privacy concerns.

4.4.3. Summing up

Recent studies have explored advanced blockchain architectures designed to enhance scalability and privacy. For example [152], has demonstrated a permissioned Fabric-based blockchain network capable of sustaining a high volume of transactions per second with sub-second finality. Similarly [115], has introduced PrGChain, which integrates ZKOracles to preserve privacy while reducing operational costs.

4.5. Blockchain categories

Based on who has access to a blockchain, it can be divided into two categories: permissionless and permissioned.

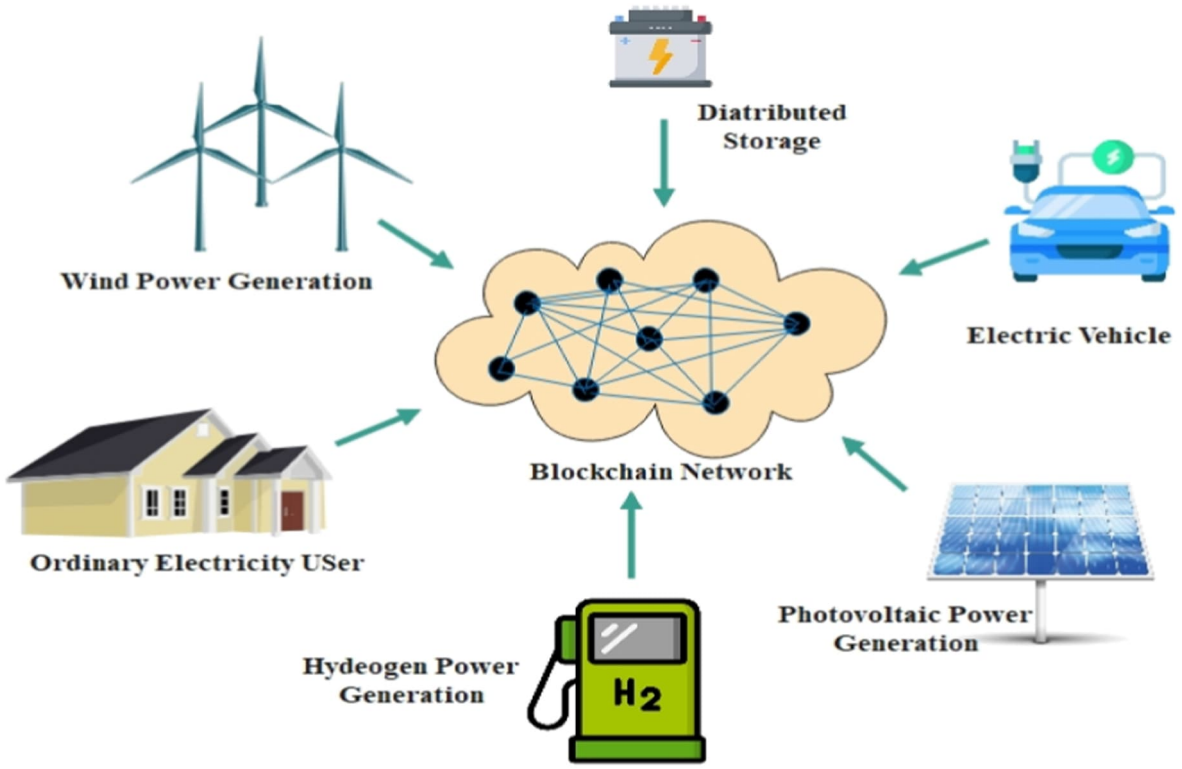


Fig. 20. A schematic showing the application of blockchain technology in MG.

4.5.1. Permissioned vs. permissionless blockchain

In a permissionless blockchain, everyone can access the blockchain network. It can also be referred to as a trustless or public blockchain, which is accessible to everyone to participate in the blockchain's process for validating transactions and data. These are used in networks where high transparency is required [153]. A permissioned blockchain operates within a closed network, where authorized individuals can access data and confirm transactions, prioritizing both privacy and security. These blockchains ensure that only trusted and authorized parties can conduct transactions by requiring nodes to get explicit authorization, retain node identification, and assign particular roles. As a result, the surroundings are more secure and under control, and the likelihood of hostile activity is decreased [154]. Fig. 21 displays the graphical representation of the blockchain taxonomy.

4.5.2. Public blockchain

A public blockchain operates in a fully decentralized manner, allowing unrestricted participation without any central control. The network's decisions are based on node consensus, and transactions are recorded with timestamps. Participants in the network are motivated by rewards and incentives. In a public blockchain, anyone can access it, and participants can join or leave the network at any time. It is an open-source platform where transaction blocks are publicly visible, although transactions occur anonymously. Every participant possesses a copy of the blockchain, ensuring data immutability. If any changes occur, other nodes in the blockchain can detect and acknowledge them [155,156].

4.5.3. Private blockchain

A private blockchain is a partially decentralized network. A private blockchain limits blockchain access to a predetermined group of nodes. These limitations facilitate faster completion of tasks such as block construction. Moreover, it takes less than a minute to mine the block. Nodes in a private blockchain need permission to join the network directly. Only authorized authorities can interact with data; transactions remain private. Thus, an entirely safe and reliable transaction occurs.

Additionally, the nodes engaged in the transactions can be easily discerned. The specific node's identity can be traced in the event of an unfortunate occurrence. The transactions can only be carried out by a limited number of nodes. Thus, irrespective of the network's expansion, its velocity and efficacy remain unaffected. However, in the case of a private blockchain, a singular organization will have dominion over the network, resulting in a centralized entity, which constitutes the primary drawback [157].

4.5.4. Consortium blockchain or federated blockchain

A consortium blockchain [158,159] combines aspects of public and private blockchains in a cooperative effort managed by multiple entities. Members of participating organizations are granted access to the ledger, which functions as a permissioned blockchain. With the help of this decentralized method, several companies can collaboratively authenticate transactions and provide governance, facilitating the sharing of resources and solutions to accomplish shared business objectives. Consortium blockchains provide an innovative approach to addressing organizational challenges by fostering collaboration and enhancing member confidence [160].

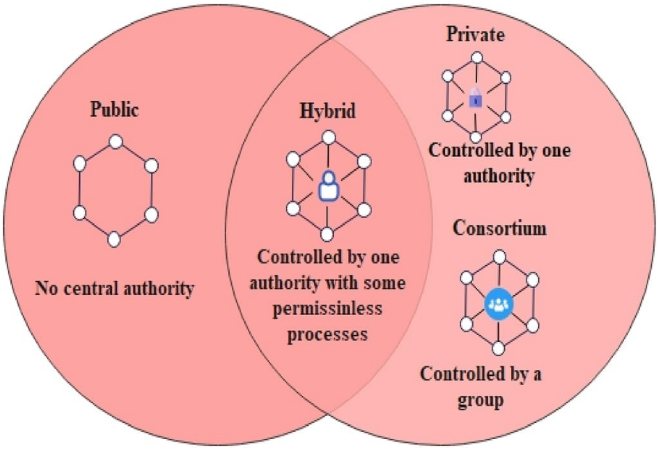


Fig. 21. Taxonomy of blockchain.

4.5.5. Hybrid blockchain

Hybrid blockchain technology combines the best aspects of public and private blockchains, leveraging the transparency and security benefits of public blockchains while also offering the advantages of privacy and control. Unlike consortium blockchains, hybrid blockchains take the most valuable features from both types and blend them into a powerful solution. This versatility makes hybrid blockchains ideal for businesses that value transparency, security, and scalability, as they can tailor the consensus protocol to suit their specific needs, ensuring efficient transaction validation by a trusted group of authorized participants [161].

4.6. Smart contract

An SC is a self-executing contract written directly into lines of blockchain network code. To self-execute actions in an irreversible, transparent, and secure manner, it automates transactions, eliminates intermediaries, and minimizes errors and fraud. They carry out necessary steps after verifying specific actions based on predetermined conditions. SCs can facilitate low-value transactions and lower transaction costs. Numerous industries utilize SCs, including the energy industry. SCs enable efficient and transparent P2P energy trading [162]. Fig. 22 shows the life cycle of an SC.

The bugs in the SC are immutable and irreversible. An SC is designed using the P2P energy trading mechanism [163]. It comprises closed bid, energy exchange, settlement, and payment functions. Refer to the paper [164] for more information about the SC and its operation. Fig. 23 illustrates the typical SC flowchart of the battery EV SC process [108]. Table 8 presents the detailed analogy between the conventional contract and the SC.

Recent developments in adaptive SCs have further optimized energy trading. For instance, designing adaptive pricing mechanisms within SCs that dynamically adjust rates based on real-time energy market data, thereby enhancing the efficiency of decentralized markets, is the subject of current (and potentially future) research in this area.

4.7. Consensus mechanism

Consensus mechanisms are protocols that enable participating nodes in the blockchain system to decide on a problem. The consensus procedure occurs at predetermined discrete time intervals. These times describe the intervals between the start of the transactions and the moment they are added to the blockchain. The block size, transaction volumes, and chosen consensus algorithms all influence the confirmation time. Nowadays, consensus algorithms with flexible features are created and applied. According to Refs. [106,165,166] papers the most well-liked consensus procedures include:

- Proof of Work (PoW): This consensus algorithm is the most well-known and often utilized within numerous blockchain applications. Beyond this strategy, the key idea is to create a new block and request nodes to solve a cryptographic puzzle known as a PoW issue. This means that the primary goal of PoW when creating a new block is to use computer power to solve a computationally expensive cryptographic puzzle that is difficult to solve but simple to verify (mining). This procedure gives the first node to solve the puzzle a reward (fee) as payment. The solution is connected to the new block

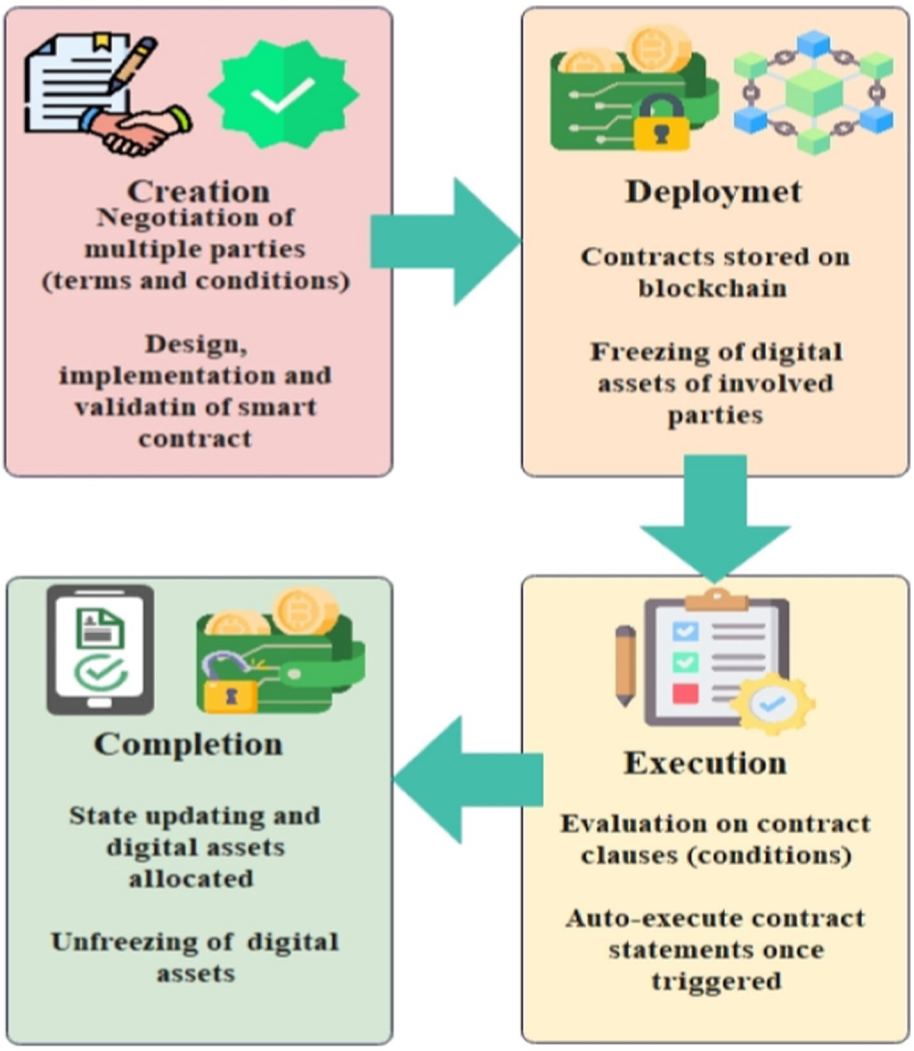


Fig. 22. Life cycle of an SC.

and transmitted through the network after it has been mined and confirmed. However, this process results in a significant loss of energy and resources.

- Proof of Stake: Another popular consensus algorithm is PoS. It addresses the scalability and security issues of PoW. It eliminates mining and instead relies on validators. Validators are chosen based on their stake in block creation, allowing anyone who owns a stake in the transaction to participate. PoS randomly selects nodes to validate new blocks based on their asset balance or the longevity of their holdings. This preserves the decentralized nature of the blockchain system. PoS requires less CPU computation and energy compared to PoW. However, it has yet to be widely adopted in the industry, like PoW.
- Byzantine Fault Tolerance (BFT): In this algorithm, validators are present and randomly elect the next node.
- Practical Byzantine Fault Tolerance (PBFT): PBFT is a consensus algorithm that ensures the replication of state machines while tolerating malicious or faulty nodes in a blockchain network. PBFT enables nodes to agree on the order and validity of transactions despite Byzantine faults. Nodes communicate through message exchanges and voting rounds, with at least two-thirds of nodes needing to agree on a consensus. PBFT operates in phases: request, pre-prepare, prepare, commit, and reply. It offers fault tolerance, security, and resource efficiency, making it suitable for small blockchain networks. However, PBFT requires trusted nodes and has higher message complexity. The research aims to enhance PBFT for the broader adoption of blockchain technology.
- Delegated Proof of Stake (DPoS): DPoS is a modified form of PoS where each node can delegate the validation of transactions to another node by voting. It adopts a representative democracy approach, providing scalability and BFT. In public blockchains, especially in decentralized energy systems, DPoS offers excellent security. Network peers choose delegates and rotate among producing blocks and collecting rewards. DPoS provides low power consumption, fast transactions, and strong tamper resistance. They can be voted out if they act against the network's interests.
- Proof of Authority: PoA represents a consensus algorithm centered around centralization. It designates a set of nodes as authorities to validate transactions and create new blocks. PoA is a practical, efficient solution with lower energy consumption and is suitable for private and permissioned blockchains. It relies on the real identities of validators, known as authorities, who assume responsibility for block creation—poA leverages transparency and reputation to ensure reliable validation within the blockchain system.
- Proof of Capacity (PoC): PoC, known as Proof of Space, is a consensus algorithm in blockchain systems. It utilizes the available hard disk space of participating nodes to generate and validate blocks. Miners demonstrate their storage capacity through a two-phase process: hard disk plotting and mining. The plotting phase involves storing precomputed solutions on the hard disk, creating proof of storage

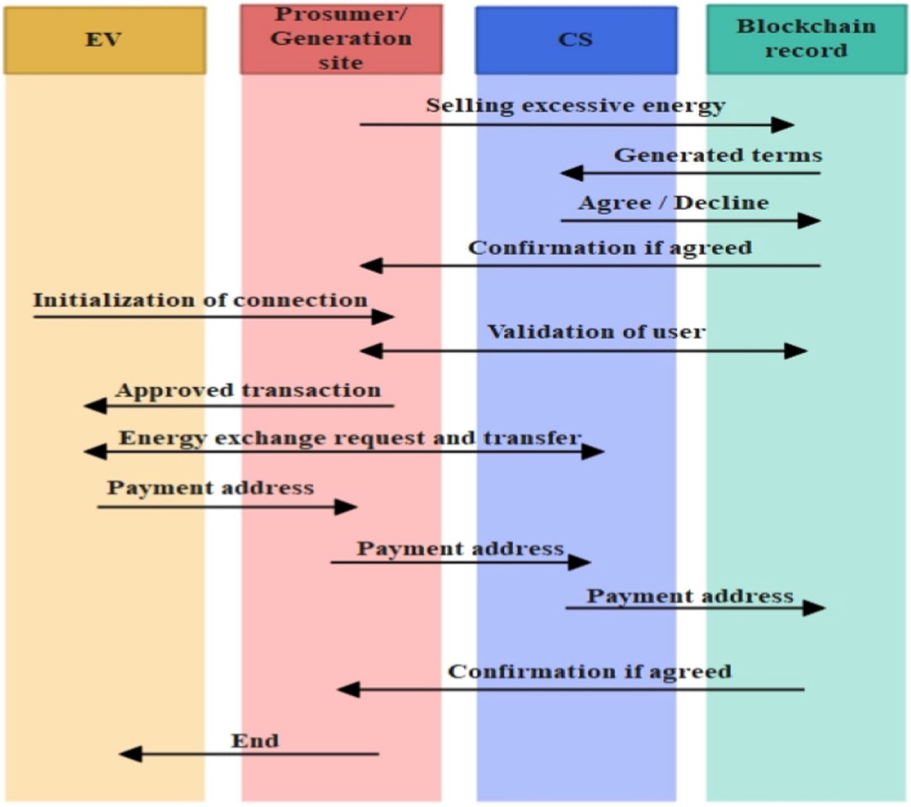


Fig. 23. The typical flow diagram for SCs.

Table 8
Analogy of the traditional contract with SC.

Parameters	Conventional contract	Smart contract
Third-party	Government, lawyers, etc.	Not required
Processing time	In days (slow)	In minutes (fast)
Remittance	Manual process	Automatic process
Transparency	Not available	Available
Automation	Manual	Fully automated
Accuracy	Less accurate	Highly accurate
Archiving	Difficult (as records are paper-based and offline)	Easy traceable
Security	Limited	Cryptographically secured
Cost	Expensive	Cheap
Signature	Manual	Digital signature

capacity. Miners present these solutions to add new blocks to the blockchain. PoC is energy-efficient, accessible, and promotes decentralization. However, its challenges include the resource-intensive plotting phase and vulnerability to attack. Ongoing research aims to address limitations and explore its applications. More information about consensus algorithms is given in Ref. [167].

Table 9 shows the different classifications of papers related to blockchain usage.

Table 10 summarizes the key performance metrics, including throughput, latency, and energy consumption, of major blockchain consensus protocols as applied to energy systems, facilitating a clear comparison of their trade-offs.

Table 9
Information and classification of articles.

Ref	Application Domain	Consensus Algorithm	Type	Research Type	Year
[168]	IoT	BFT	Private	Architecture	2019
[169]	Supply chain	DPoS	Private	Architecture	2019
[170]	Game	PoW	Public	Framework	2019
[171]	Security	PoS & PoW & BFT	Public & Private & Hybrid	Solution Paper	2019
[172]	IoT	PoS	Public	Solution Paper	2019
[173]	Energy	PoS	Public	Solution Paper	2018
[174]	IoT	PoS & PoW	Public & Private & Hybrid	Framework	2020
[175]	Industry	PoS & BFT & PBFT	Public & Private & Hybrid	Framework	2020
[176]	IoT	PoS & PoW & BFT & PBFT	Public & Private & Hybrid	Model	2021
[177]	IoT & Security	PoS & PoW	Public & Private	Framework	2021

4.8. Critical analysis of blockchain consensus mechanisms in energy trading

The integration of blockchain technology into energy trading systems necessitates a careful evaluation of consensus mechanisms. Two widely discussed consensus mechanisms are PoW and PoS, both of which present trade-offs in terms of scalability, security, and energy efficiency.

Table 10
Performance comparison of blockchain consensus protocols for energy systems.

Consensus Protocol	Throughput (TPS)	Finalization Latency (s)	Energy per Transaction (kJ)	Security	Scalability	Energy Trade-Offs (for Energy Markets)
PoW	15	600	100	High	Low	High energy consumption, low scalability
PoS	1000	60	0.5	Moderate	High	Low energy consumption, better scalability
PoA	5000	10	0.1	Very high	High	Low energy consumption, but centralization risk
Hybrid PoA/PoS	3000	30	0.2	High	High	Faster, low energy, better suited for decentralized energy systems

- **Proof of Work (PoW)** is recognized for providing robust security through its computational difficulty; however, it requires high computational power, making it energy-intensive and inefficient for large-scale energy systems. This scalability issue arises due to the limitations in transaction throughput and latency, which are critical for real-time energy trading systems that require fast transaction confirmation. Additionally, PoW suffers from a significant environmental impact, making it less suitable for decentralized energy markets seeking sustainability.
- **Proof of Stake (PoS)**, on the other hand, offers improved scalability and energy efficiency by reducing the need for mining and relying on validators chosen based on their stake in the system. While PoS addresses many of PoW's limitations, it introduces potential security risks, including the risk of centralization and the "nothing-at-stake" problem, where validators might approve conflicting transactions to maximize their stake rewards. Despite these challenges, PoS has shown potential for energy systems, especially when combined with additional mechanisms to address these vulnerabilities.
- **Gaps and Limitations:** Both PoW and PoS still face challenges in large-scale energy applications, particularly with DERs. Transaction bottlenecks and high latency in validating energy transactions remain unresolved, limiting the real-world applicability of these consensus models in energy markets that require fast and scalable solutions.
- **Discrepancies in the Literature:** A significant discrepancy across studies lies in how these consensus mechanisms are evaluated. Some studies focus on security while others emphasize scalability, leading to inconsistencies in understanding the overall feasibility of PoW and PoS for energy trading. Future research should focus on developing standardized evaluation frameworks that address both security and scalability simultaneously.
- **Hybrid Consensus Models:** Hybrid consensus models, such as DPoS and PoA, may offer a more balanced solution for energy markets. These models combine the best aspects of PoW and PoS to address the scalability/security trade-off. For example, DPoS uses a delegated system of validators to achieve high scalability while maintaining a level of decentralization, making it a promising candidate for energy systems that require both security and efficiency.

4.9. Context and limitations of quantitative analysis

In interpreting the above quantitative results, the analysis was conducted under the following conditions and constraints. First, a 20-year planning horizon was adopted with an assumed 30 % annual increase in peak demand, and solar PV output was modeled to co-vary perfectly with system peaks. Second, all time-series data load profiles, PV generation traces, and network constraints were sourced from ENTSO-E (2023) and the IEA World Energy Outlook (2024), while capital-expenditure and operational-cost parameters follow NREL's 2025 Distributed PV benchmarks. Third, our model assumes static demand elasticity and excludes dynamic behavioral adaptations, real-time price volatility, and distribution network losses exceeding 5 %. These simplifications may overstate system flexibility and understate operational costs; accordingly, future work should incorporate stochastic demand response and market price signals to refine these findings.

4.10. Blockchain system architectures, transaction models, market mechanisms & regulatory considerations

A comprehensive review of blockchain-enabled energy systems requires detailed attention to four interrelated pillars:

1. System Architectures

   Reference deployment architectures include:

   - Monolithic chains, where all smart-contract logic and state reside on a single ledger node;
   - Modular (separation of execution, consensus, data availability) designs that scale horizontally;
   - Micro-services patterns, with off-chain oracles and light-client gateways handling specialized functions.

   Topologies vary from permissioned consortium networks (where utilities and regulators serve as validators) to hybrid public-private models that anchor critical events on a public chain for added security.

2. Transaction Models

   Common paradigms are:

   - Unspent Transaction Output (UTXO) models offering deterministic finality but limited smart-contract expressivity;
   - Account-based models (e.g., Ethereum-style) supporting rich state transitions at the cost of higher storage overhead;
   - State-channel and roll-up architectures enabling off-chain batching of high-frequency meter-to-meter transactions with on-chain settlement for security and audit.

3. Market Mechanisms

   Blockchain can natively support:

   - Auction-based clearing (sealed-bid or Vickrey auctions) for time-slot energy products;
   - Continuous double auctions with on-chain order books and matching engines;
   - Posted-price or subscription models for fixed-rate P2P energy streams.

   SCs enforce settlement, collateral, and penalty rules transparently, reducing counterparty risk.

4. Regulatory Considerations

   Key design factors include:

   - Licensing regimes for DL operators;
   - Data sovereignty and privacy mandates under GDPR-style frameworks;
   - Cross-border trading rules, balancing energy-market coupling with blockchain's borderless nature;

- Node governance models to satisfy both utility reliability standards and financial compliance (KYC/AML).

This section bridges the abstract's promise by detailing how architectural choices, transaction logic, market design, and regulatory frameworks combine to shape blockchain-enabled energy ecosystems.

4.11. Contrasting methodologies in P2P energy trading

Recent studies demonstrate that P2P energy trading can be implemented using different methodological approaches, each with unique strengths and limitations. Market-clearing models, such as centralized optimization, distributed ADMM-based schemes, and auction mechanisms (e.g., continuous double auction, posted price), emphasize economic efficiency but differ in terms of scalability and computational requirements. Consensus mechanisms such as PoW, PoS, and PoA ensure transaction security but vary in terms of energy consumption, latency, and decentralization. Privacy-preserving techniques, including zero-knowledge proofs, homomorphic encryption, and secure multi-party computation, safeguard user data but introduce additional complexity and overhead. Highlighting these contrasting methodologies clarifies the design trade-offs faced by researchers and practitioners, while also identifying open challenges that motivate further research in this evolving field.

5. Modern power market framework

The modern power market framework entails an electricity generation, transmission, distribution, and consumption system that utilizes digital technologies to enhance efficiency and flexibility. The traditional centralized generation and distribution model is gradually shifting towards a more decentralized RESs. This is primarily due to the rise of sustainable and resilient energy systems that can adapt to shifting power and supply conditions.

5.1. Traditional market and real-world P2P energy market implementations

The traditional energy market operates centrally, where a few companies dominate the market, controlling energy production, distribution, and pricing. Consumers have limited control over their energy usage and are subject to fixed models. This is known for being inflexible, inefficient, and environmentally unfriendly. The traditional energy market concept involves centralized energy generation, transmission, and distribution under the control of a few utility companies. Consumers cannot participate in energy generation or trading and must rely solely on utility providers for their energy needs, resulting in limited competition and higher prices. The market is based on a regulated monopoly, where utility companies are the sole providers of energy and are granted exclusive control over the pricing and distribution of power. The system has been in place for years. During the 1980s, several economists began to argue that the traditional model was becoming outdated. They pointed out that the monopoly status of electric utilities diminished the incentive for efficient operations and led to superfluous investments.

Additionally, they contended that the financial repercussions of mistakes made by private utilities should not be transferred to consumers. Conversely, public utilities were often criticized for being overly entangled with governmental interests. Building on these critiques, in 1996, Hunt and Shuttleworth introduced four models to map the transformation of the electricity supply industry from a regulated monopoly toward a fully competitive market [178].

5.1.1. Models of competition

5.1.1.1. Model 1: Monopoly. This model represents a situation where a single dominant entity or utility has exclusive control over electricity generation, transmission, and distribution. A monopoly has no direct competition, and the monopolistic entity can set prices and make decisions without significant market constraints.

5.1.1.2. Model 2: Purchasing agency. In this model, a purchasing agency serves as an intermediary between power producers and consumers. The purchasing agency procures electricity from different suppliers and sells it to consumers at a regulated price. The agency's role is to ensure a reliable supply and fair pricing while maintaining competition among the producers.

5.1.1.3. Model 3: Wholesale competition. Wholesale competition involves multiple power producers competing to sell electricity to retailers or large consumers. In this model, a separation exists between generation and retail activities, enabling competition in the wholesale market. Retailers can select from various suppliers based on factors such as price, reliability, and other criteria.

5.1.1.4. Model 4: retail competition. Retail competition extends to the retail level, where consumers can choose their electricity supplier. Retailers compete to attract customers by offering competitive prices, value-added services, renewable energy options, or other incentives. Retail competition aims to give consumers more choices and drive efficiency and innovation in the electricity market.

5.1.2. Challenges of this market

Traditional power markets face several challenges that can impact their efficiency and sustainability. Here are some of the key challenges:

- High cost: Traditional power economics rely on large, centralized power plants to generate and distribute electricity to consumers. This system comes with a high cost, both financially and environmentally. The construction and maintenance of plants and transmission lines are significant capital investments, and the cost is often passed on to consumers through higher electricity bills. Additionally, traditional power generation often relies on non-renewable energy sources (NRESs), such as coal or natural gas, which contribute to climate change. As a result, traditional power economics are increasing challenges to transition towards cleaner, more sustainable energy sources.
- Government intervention: The government plays a significant role in shaping the energy sector through policies such as subsidies and investments in new technologies. These interventions have specific goals, such as promoting renewable energy, reducing emissions, and enhancing energy efficiency. This intervention has unintended consequences, including distortion of incentives, rent-seeking behavior, and increased production costs. As a result, policymakers face the ongoing and intricate challenge of striking the right balance between government intervention and market-based approaches to achieve desired outcomes.
- Transparency and policy-making process: The transparency and integrity of the policymaking process have become significant concerns in traditional power economics. Lack of transparency in decision-making often leads to corruption and unethical practices. Policymakers and governments in developed and developing countries must adopt more transparent participatory processes to ensure that citizens' interests are considered and that policies are fair and equitable. In doing so, people will have more confidence in the policymaking process, which can lead to social and economic stability.
- Market and price competition: market competition and price are significant challenges that players in the industry face. Companies in the sector have been known to manipulate prices to gain a competitive advantage, creating unhealthy competition and potentially

leading to monopolies. The high entry in the industry also makes it difficult for new players to enter the market and compete with established companies. A lack of competition drives prices even higher, reducing energy affordability for consumers. Additionally, forms of traditional power generation, such as coal, may be subject to unpredictable costs associated with materials, transportation, and labor.

5.2. Transactive energy trading

TE promotes establishing a networked environment for decentralized energy nodes, rather than the conventional hierarchical grid structure. This networked structure facilitates interaction, allowing all energy production and consumption levels to communicate. Within TE, interoperability refers to the systems' capacity to exchange and share energy data while upholding operational and service constraints. This approach presents numerous advantages over the traditional energy system, including improved utilization of grid assets, heightened consumer satisfaction, and reduced energy costs, among others. The term TE is well defined by the Gridwise Architecture Council as [5]: "*Techniques for managing the generation, consumption, flow of electricity within the power system that allows the dynamic balance between demand and supply, keeping in view the constraints of the entire network*". Fig. 24 depicts the TE framework, where end users and other market participants engage through integrated layers of communication, control, operation, and negotiation [11].

5.2.1. Elements of the TE trading framework

DERs are considered fundamental components within the TE framework. They are defined as the energy sources or associated services possessed by prosumers or managed by a third party, who acquires energy from their local utility and subsequently allocates it to others. The involvement of these elements is indispensable for engaging participants in the TE market [179]. The efficient integration of DER into power systems and the synchronization of supply and demand throughout the electrical infrastructure are crucial elements [11].

- Users and entities: This refers to the participants in the TE system, including residential, commercial, and small industrial electricity end-users. These users have heterogeneous preferences and behaviors that can be coordinated through control and price signals.
- Electricity network: This includes the physical and technical constraints of the power system. It encompasses the distribution level, where DER integration occurs.
- Regulatory and financial environment: This element considers the regulatory framework and financial incentives that govern the TE system. It includes policies and market structures that enable the participation of users and entities.
- Computational and communication requirements: The successful implementation of TE requires advanced computational and communication technologies. These enable the exchange of information and economic signals between participants in real-time.

5.2.2. Blockchain-based TE trading

Ensuring privacy and security in a TE system is a significant challenge that stakeholders must address. However, recent developments in Blockchain technology offer promising solutions to these issues [12]. In the TE scheme, a large volume of information, including bids, offers, and energy availability, is exchanged, making it vulnerable to cyberattacks. Therefore, implementing a Blockchain-enabled TE system becomes crucial for safeguarding transactions and critical information. Blockchain is an emerging technology with immense potential for enhancing security, transparency, and profitability in various financial, public sectors, and media industries. It is now entering the energy sector, revolutionizing energy market operations by enabling trustworthy computations through SCs. Blockchain strengthens the energy system's

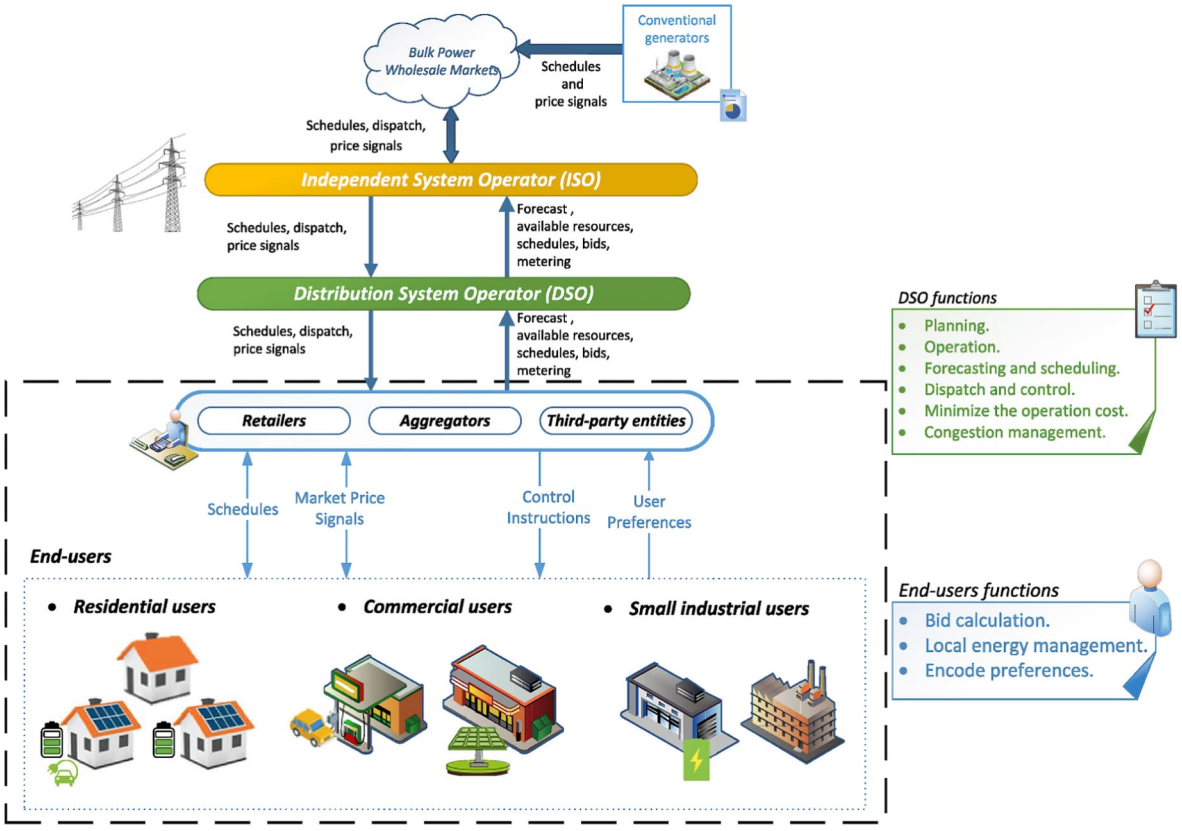


Fig. 24. Represents the P2P energy trading framework [8].

security through multiple data verifications and secure P2P market transactions.

The integration of Blockchain technology can bring about a remarkable transformation in the energy sector, complementing the advancements made by the CPPS. A three-layered energy market structure has been proposed in Ref. [180], consisting of the power, control, and service levels, as depicted in Fig. 25. The power level encompasses the physical infrastructure, including grid supply and MMGs equipped with renewable generation (such as solar PV and wind) and ES units. The energy exchange occurs between MGs and between MGs and the main grid, considering diverse load profiles for each MG. At the control level, information and communication devices are utilized to manage bids, offers, and supply-demand profiles, ensuring the benefits of the TE mechanism for operators. Choosing an appropriate pricing mechanism is crucial to establishing the TE scheme, alongside the need for a secure data exchange platform. Therefore, a trading model based on Blockchain is implemented at the service level to provide a secure platform for TE operations.

5.2.3. Benefits and challenges of TE

TE systems enable individuals to buy and sell electricity directly, which can lower costs, optimize the use of renewable energy, and foster a more flexible and efficient power grid. For example, homeowners with solar panels can sell their extra power to neighbors, helping everyone save money and use energy more wisely. However, there are challenges too. These systems require robust security to protect data and prevent cyberattacks, and they necessitate advanced technology to manage the numerous small sources of power and rapidly changing energy demands. Overall, while TE can bring many benefits, it also requires careful planning and robust technology to work safely and effectively [181].

To support our qualitative claims, Table 11 aggregates key quantitative metrics reported in recent empirical studies, including average blockchain adoption rates among utilities (23 %), end-to-end transaction latency (mean = 750 ms), and transaction-throughput benchmarks (500–5000 TPS). These summary statistics provide concrete context for the advantages of efficiency, security, and decentralization.

Table 11
Summary of quantitative metrics in blockchain-based energy systems.

Metric	Value	Source Range
Utility Adoption Rate	23 % (mean)	15 %–30 % (2019–2024)
Transaction Latency	750 ms (avg.)	500–1200 ms
Transaction Throughput (TPS)	500–5000	Depends on protocol

5.3. P2P energy trading

Due to the emergence of DERs and technological advancements, the electricity industry has undergone a shift from a hierarchical to a decentralized structure. P2P sharing allows connected communities to trade energy and services directly, benefiting customers and the network. P2P trading markets operate with minimal central control, where each vendor acts independently, and active subscribers are driven by their selling bid prices. The distribution system operator manages the trading platform and facilitates electricity distribution, enabling customers to participate in energy markets while improving control and information flow [15,182,183].

5.3.1. Structure of P2P energy trading

In decentralized energy trading, transmission system operators (TSOs) facilitate the participation of generation units and large-scale energy consumers in wholesale markets, adhering to specific guidelines. However, it is impractical for end-users connected via low-voltage distribution networks to participate in transmission-regulated wholesale markets. Instead, P2P energy trading primarily occurs within distribution networks [184]. Fig. 26 represents a framework of P2P energy trading.

Fig. 26 illustrates that P2P energy trading necessitates a resilient distribution network to facilitate local energy transfers, as well as a communication network capable of disseminating prosumer preferences. Consequently, the physical layer alone is insufficient for the effective implementation of P2P trading [185]. Fig. 27 presents a generalized overview of the layers involved in P2P energy trading.

The physical layer depicted in Fig. 27 resembles a power grid, housing essential components such as power generation, monitoring, metering, and other equipment necessary to transmit electrical energy. Just above the physical layer is the ICT layer, which acts as a partially

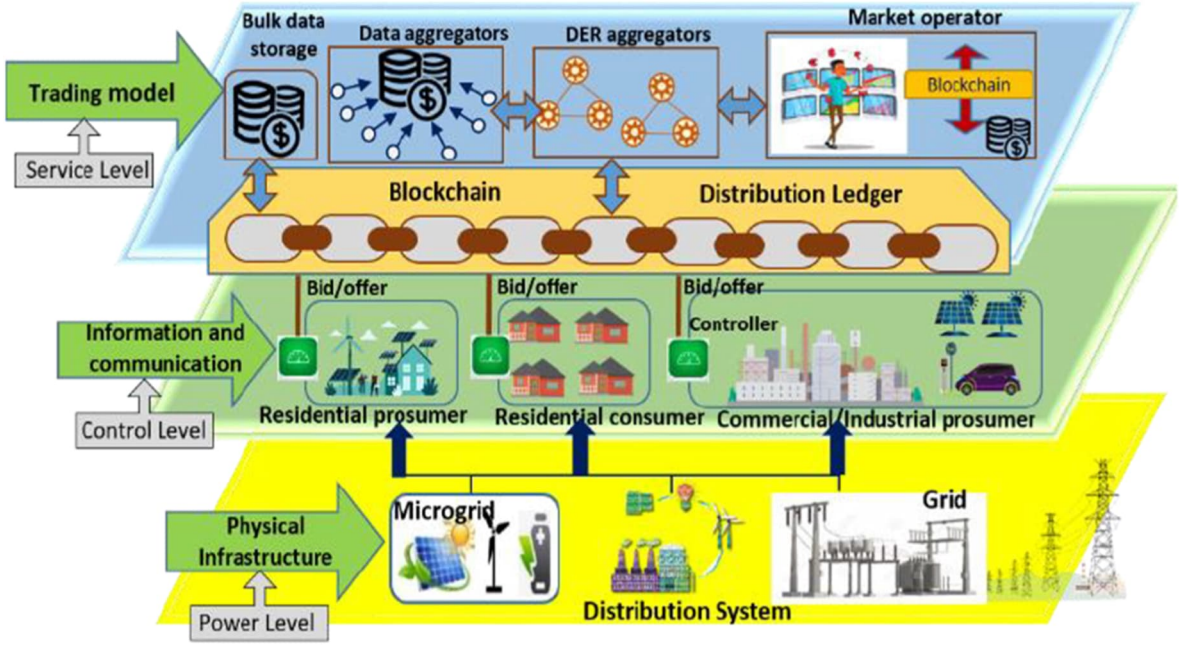


Fig. 25. Three-Level Blockchain-enabled TE architecture [166].

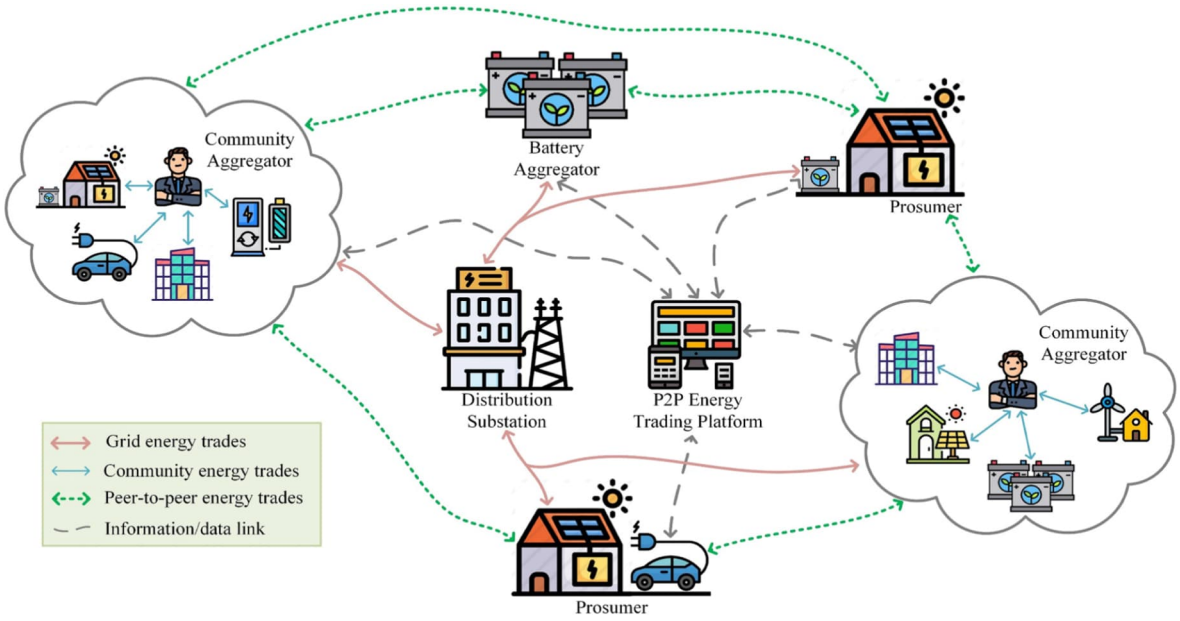


Fig. 26. Representation of P2P energy trading framework.

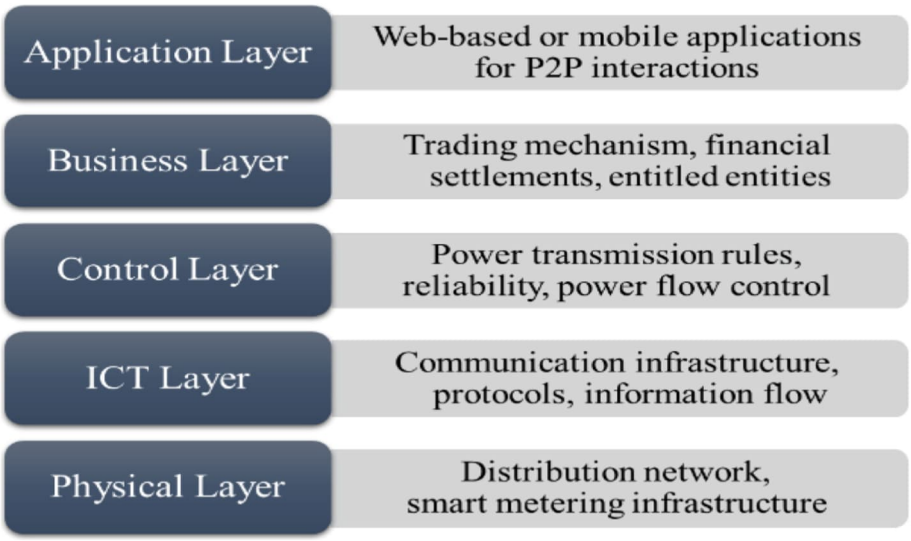


Fig. 27. Representation of P2P energy trading layers.

software-based layer. It consists of communication devices, such as switches and transceivers, that operate according to standard communication protocols, facilitating the transfer of data within the network.

The control layer is primarily managed by distribution system operators, who implement various control measures to ensure efficient and reliable energy transfer for trading purposes. The business layer is where decisions related to P2P energy trading are made. This layer involves consumers, prosumers, and various entities participating in the trading process. These entities are governed by regulatory frameworks and government policies that dictate the market's operation. Finally, the top layer, the application layer, provides a user interface through which preferences and outcomes of P2P energy trading can be communicated [186]. Based on the types of market mechanisms, P2P energy trading can be categorized into centralized, decentralized, and distributed energy markets, as illustrated in Fig. 28. In a centralized market, a coordinator communicates with all participants involved in P2P energy trading. Based on each peer's interests, requirements, or willingness, the coordinator determines the volume of energy to be exchanged, sets the buying and selling prices, and allocates the resulting revenue among the peers. This revenue distribution follows predetermined guidelines, such as establishing the prices used to calculate each peer's earnings [187]. Instead of centralized markets, decentralized markets lack centralized coordinators, enabling peers to engage in contractual agreements and trade directly, thereby safeguarding peer privacy and granting peers full autonomy over their appliances.

Furthermore, the absence of involvement from the distribution operator in the trading process poses a challenge in coordinating utility resources, potentially diminishing the operational efficacy of the distribution system [188,189]. Distributed energy markets represent an amalgamation of both the aforementioned markets. In this method of trade, the principal utility is indirectly involved. The system operator will transmit price signals to the peers, enabling them to devise their own schedules independently. Compared to fully decentralized markets, distributed markets still necessitate a coordinator, facilitating better coordination of peer behavior. In contrast to centralized markets, distributed markets typically require minimal input from peers and do

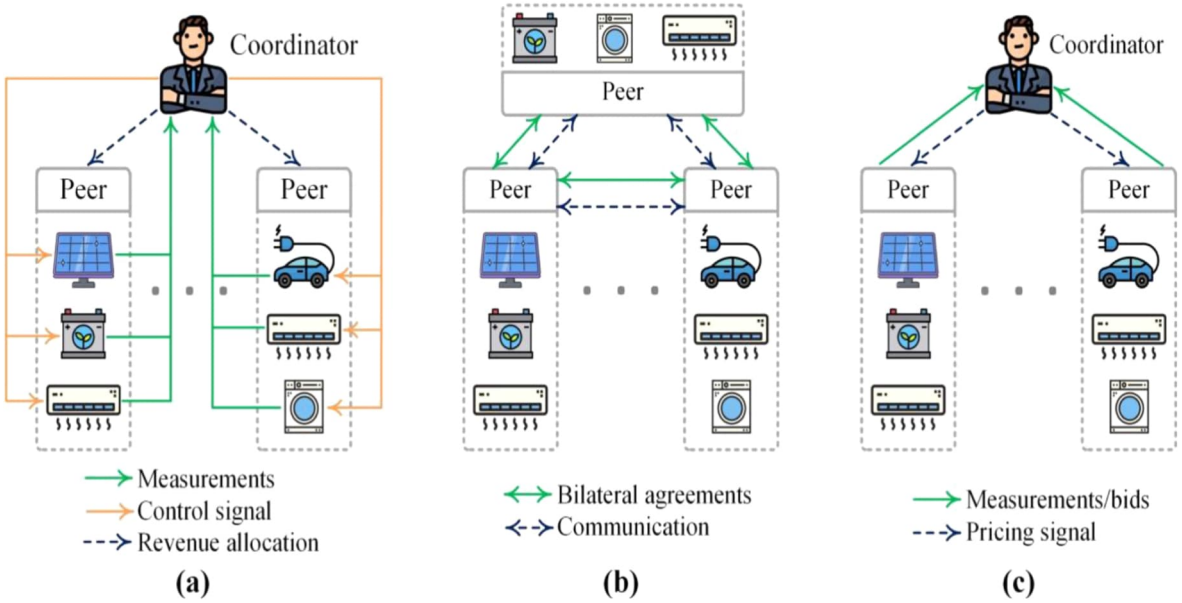


Fig. 28. Classification of P2P energy sharing frameworks based on the types of the market mechanism: (a) centralized, (b) decentralized, and (c) distributed.

not directly manipulate their devices.

Consequently, they afford customers a higher degree of privacy and autonomy. In summary, distributed markets amalgamate the characteristics of centralized and decentralized markets, thereby providing a compromised solution between the two [190,191]. To buy or sell energy and participate in P2P trading, each peer should be equipped with various flexible loads, ES, and generation resources. Table 12 compares the advantages and disadvantages of centralized, decentralized, and distributed energy markets [185,192,193].

Table 12
Pros and Cons of centralized, decentralized, and distributed markets in P2P energy trading.

Market Type	Advantages	Disadvantages
Centralized	• Maximizes the social welfare of the P2P community • Less uncertainty in power generation and consumption patterns • Enhancing the relationship and involvement among peers due to a common goal	• Exponential computational and communication burden on centralized management systems • Vulnerable to single-point failures at the coordinators
Decentralized	• Privacy protection and full control over peers' devices • Better scalability and ease of "plug-in and out" • Total freedom and autonomy are given to the peers. • Peers' preferences are considered	• Lower efficiency in maximizing the social welfare of the P2P community • Overall, the outcome of P2P energy trading is less visible and predictable for network operators • Severe uncertainties for peers in fully decentralized markets • Potential compromise of vulnerable customers' interests
Distributed	• Combining the strengths of centralized and decentralized markets • Better coordination • Higher level of privacy and autonomy for customers • compatible with the existing system	• Pricing mechanisms and stability need careful consideration • Proper grouping of peers for P2P energy trading coalitions

5.3.2. Blockchain in P2P energy trading

Energy trading requires the reliable administration of energy trading and provision, free from interruptions, which can be achieved through the oversight of a centralized utility manager. Nevertheless, a centralized infrastructure may present challenges, such as vulnerability to a single point of failure, reliance on the central entity, and concerns surrounding privacy. This endorses the shift from centralized to decentralized frameworks within CPS. Applying blockchain technology in the context of energy trading can enhance both efficiency and security. Various applications can contribute to achieving this outcome, including ensuring grid management security and accountability, facilitating efficient utility billing, and enabling P2P energy trading. Concerning security, blockchain can instill trust between parties, removing the dependency on centralized control and providing integrity and a high degree of accountability due to its immutability. Additionally, blockchain supports a diverse range of device types and diminishes the role of central intermediaries, thereby reducing energy costs [194]. In Ref. [195], the authors propose a consortium blockchain to design a hybrid P2P electricity market, in which an SC is responsible for registering members and storing the necessary data.

Recent research by Ref. [196] introduces a blockchain-centric framework that uniquely integrates P2P energy trading with carbon allowance exchanges. This dual-focus approach not only streamlines direct energy transactions but also embeds carbon trading mechanisms to enhance market transparency and environmental sustainability. By directly linking energy and carbon markets, the framework offers novel insights into balancing decentralized energy distribution with emission reduction targets. This integrated model could pave the way for more holistic TE systems that address both economic and environmental challenges.

5.3.3. Challenges and limitations

Although blockchain technology shows considerable promise in the realm of P2P energy trading, numerous challenges related to its adoption remain unresolved [197].

5.3.3.1. Cybersecurity in the communication layer. The communication layer faces cybersecurity challenges, particularly related to unauthorized data access and DoS attacks. To mitigate these vulnerabilities, the adoption of advanced encryption protocols for data transmission and the implementation of intrusion detection systems (IDS) to monitor and

address potential threats in real time are proposed.

5.3.3.2. Communication protocols and data privacy. Data privacy is a significant concern in the communication layer, particularly in P2P transactions. The integration of ZKPs can help preserve the privacy of energy transactions while maintaining the necessary transparency for auditing and compliance purposes.

5.3.3.3. Scalability in the data storage layer. In the data storage layer, scalability is a critical concern as the number of energy transactions increases. To address this issue, decentralized storage solutions such as InterPlanetary File System (IPFS) or Filecoin can be utilized to store large transaction datasets, enabling fast retrieval and enhancing system scalability without sacrificing data integrity.

5.3.3.4. Scalability and security. For the scenarios being considered, blockchain still needs to show that it is scalable, efficient, and secure enough. Implementing a robust and secure blockchain infrastructure is crucial as the rise in P2P energy trading drives consumer demand.

5.3.3.5. Transaction and verification cost. Transactions are integrated into the blockchain after an initial computation, a process that may span a considerable duration. In contrast to blockchain's capacity to process no more than ten transactions per second, VISA can accommodate 20,000 transactions within the same time frame. Furthermore, creating a transaction requires users to bear a transaction charge, and the participating entities need a substantial amount of synchronous storage to authenticate the blockchain ledger. Both of these factors contribute to increased blockchain costs. As the number of participants in P2P energy trading increases, the number of transactions also escalates, potentially overwhelming the memory requirements for ledger maintenance and limiting the efficacy of blockchain solutions.

5.3.3.6. Development cost. Another significant challenge is the high costs associated with blockchain development. To illustrate, verifying a transaction requires substantial computational and network capabilities, resulting in additional expenses not incurred by a conventional database system. Implementing blockchain in energy trading also requires the use of expensive equipment, such as intelligent measuring devices, which further contributes to the overall cost.

5.3.3.7. Regularization. The blockchain process is currently revealing the capabilities of decentralized energy trading grids. Nevertheless, the solutions presented in scholarly publications pose regulatory challenges that encompass load balancing, integration with central control, and synchronization with the primary grids. For instance, if the government endeavors to administer the power grids, it becomes arduous for them to exercise enhanced authority and increased decentralization. Furthermore, the employment of the blockchain necessitates the regulation of energy trading prices.

5.3.3.8. Regulation challenges in the business layer. The business layer of the blockchain framework must address regulatory challenges, particularly in aligning decentralized energy trading systems with national energy policies. A potential solution involves engaging with regulatory bodies to develop blockchain-specific policies that support transparency, accountability, and compliance while allowing for flexibility and innovation in the market.

5.3.3.9. Government limitations. The expansion of P2P energy trading could lead to a reduction in governmental oversight of energy systems, prompting authorities to maintain control to implement more effective policies and regulatory frameworks. Additionally, government involvement is crucial for fostering the development and commercialization of emerging technologies while simultaneously establishing markets that incorporate advanced energy systems. However, blockchain technology offers decentralized, P2P solutions that may constrain governmental control, a factor that presents a significant obstacle to its broader adoption.

5.4. Blockchain and the cyber-physical framework for energy systems

5.4.1. Blockchain technology in energy systems

Blockchain technology has emerged as a transformative tool in modern energy systems, enabling the decentralized and secure exchange of data among various stakeholders. By leveraging DL technology, blockchain facilitates P2P energy trading, transparent energy transactions, and enhanced grid management. Blockchain eliminates the need for intermediaries, ensuring the integrity, security, and traceability of energy transactions while reducing operational costs.

This section discusses the role of blockchain in enhancing energy systems by enabling:

- **Decentralized Energy Markets**: Blockchain enables the creation of decentralized energy markets, where energy trading can occur directly between producers and consumers, eliminating the need for centralized authority. SCs automate transactions, making them efficient, transparent, and secure.
- **Grid Optimization**: Blockchain enhances grid management by facilitating more efficient data exchange among consumers, producers, and grid operators. It ensures better coordination, reduced energy loss, and optimized DR strategies.
- **Energy Storage and Distribution**: Blockchain technology also facilitates the management of energy storage systems, ensuring efficient energy distribution and real-time monitoring. Through secure, automated processes, blockchain provides enhanced control over DERs, such as solar panels, wind turbines, and batteries.

5.4.2. Blockchain-based energy trading framework

A blockchain-based energy trading framework provides the foundation for TE systems, enabling secure, transparent, and automated energy transactions. The framework integrates key components, including energy producers, consumers (also known as prosumers), grid operators, and energy retailers, within a decentralized marketplace [198].

The proposed framework is organized into several layers:

- **Physical Layer**: This includes energy generation and storage infrastructure (such as solar panels, wind turbines, and battery storage) as well as the energy grid itself. The physical layer is where energy flows and exchanges occur.
- **Control and Communication Layer**: This layer includes the technologies and communication protocols needed to monitor and control energy systems. It ensures the integrity and security of data transmission between energy participants.
- **Business and Application Layer**: The application layer includes SCs and decentralized applications (dApps) that facilitate energy trading and settlement. Blockchain-based SCs automate energy transactions, ensuring compliance with predefined rules and conditions, including energy prices and quantities.

By integrating these layers, blockchain-based energy trading frameworks provide a secure and efficient environment for decentralized energy markets, improving the accessibility and flexibility of energy trading.

5.4.3. Future scenarios and landscape of blockchain-based energy systems

The landscape of blockchain-based TE systems involves multiple stakeholders with different interests and responsibilities. For instance, power producers may leverage blockchain to optimize energy generation and distribution, while consumers could gain more control over

their energy consumption and costs. Policymakers and regulators play a crucial role in shaping the legal and regulatory frameworks that ensure the integrity and fairness of the energy market. In the context of security, it is essential to consider how blockchain can safeguard sensitive data while ensuring the resilience of energy systems against cyberattacks.

Different scenarios, such as large-scale adoption of EVs or the integration of RESs, present unique challenges for blockchain-based systems, including:

- **Scalability of Transactions**: As more participants enter the decentralized energy market, blockchain networks must scale to accommodate a large volume of transactions while maintaining security and efficiency.
- **Ensuring Equitable Participation**: It is essential to ensure that blockchain-based energy markets remain inclusive, enabling all consumers, especially those in regions with limited infrastructure or lower financial resources, to have equitable access.
- **Regulatory and Policy Challenges**: Policymakers must establish clear regulations to govern blockchain-based energy trading, ensuring that decentralized markets comply with existing energy laws and environmental standards.

These future scenarios underscore the necessity for ongoing innovation and adaptation in blockchain technology to meet the evolving needs of the energy sector.

5.4.4. *Blockchain and system interoperability*

Interoperability is a critical challenge for blockchain-based energy systems, particularly as energy markets become more decentralized. For blockchain to be effectively integrated into existing energy infrastructures, it must be able to communicate and operate seamlessly with other technologies, such as smart meters, AMI, and existing grid management systems.

Key aspects of interoperability include:

- **Data Standardization**: To ensure that blockchain can be integrated across diverse energy systems, data standards must be established for energy transactions, pricing, and SC execution. This ensures that data can be exchanged efficiently and securely across various platforms.
- **Communication Protocols**: Blockchain-based systems must support robust communication protocols that enable real-time data exchange between decentralized energy producers, consumers, and grid operators. This is essential for maintaining system stability, particularly as the energy mix becomes more variable with the inclusion of RESs.
- **Seamless Integration with Legacy Systems**: Blockchain must be able to interface with existing grid management systems and energy storage solutions. This requires the development of hybrid systems that combine blockchain's decentralized capabilities with traditional energy management tools, ensuring a smooth transition and maintaining the reliability of energy systems.

By addressing these interoperability challenges, blockchain technology can be fully integrated into future energy systems, enabling the creation of more resilient, flexible, and sustainable energy grids.

6. Design considerations for blockchain-based energy trading: the proposed framework

Drawing on the technologies and policy lessons reviewed in Sections 3–5, this section outlines key design considerations for blockchain-enabled energy trading. Prevailing architectural patterns, consensus models, and governance mechanisms are synthesized to guide future research and pilot implementations, rather than proposing novel methods.

In this section, a blockchain-based P2P TE trading framework is proposed. Fig. 29 shows the proposed framework. "The proposed framework for P2P energy trading involves a multi-layered structure designed to address critical aspects of energy trading, such as interoperability, privacy, and the integration of DERs. Fig. 29 illustrates the layers involved in this framework. It consists of six layers: the physical layer (which houses power generation, storage, and transmission systems), the ICT layer (which includes communication devices like switches and transceivers), the control layer (which ensures efficient energy transfer), the business layer (where transactions and decisions are made), and the cloud layer (responsible for secure data storage and contract management).

This framework consists of six layers: physical, interface, communication and information, function, business, and cloud layers, respectively. Power generation, transmission, and distribution are placed in the physical layer, and the system also contains multiple MGs comprising PV, EV, wind turbines, battery storage, and smart homes. The next layer is the interface layer, which includes components for data gathering, information recording, and executing operator commands. Some layer components include IED, RTU, DFR, PMU, Relay, and SMs. The communication and information layer is one of the most critical layers of this framework because all the data exchanged in our network is processed in this layer.

Additionally, this layer is highly vulnerable due to its cyber component, which contains network and subscriber information, and the possibility of cyberattacks is high. In the function and actions, this layer serves as the controller for that action. As the name suggests, the business layer is the core of our framework, and every transaction for selling or buying energy occurs in this layer. The players in this layer can vary depending on the market structure. P2P energy trading, also referred to as TE trading, is implemented. Following all processing layers, the cloud layer stores all information gathered from previous layers and ensures its security. This cloud repository contains contract information, signals from ISO and distribution system operators (DSO), and blockchain data.

6.1. *Future scenarios in blockchain-based energy systems*

The future of blockchain in energy systems can be envisioned through several potential scenarios:

- **Scenario 1: Technological Revolution (Quantum Computing)**

Imagine a future where quantum computing significantly enhances blockchain scalability, enabling real-time optimization of energy flows across decentralized networks. With quantum computing, peer-to-peer (P2P) networks could achieve near-perfect matching of supply and demand, thereby significantly improving energy efficiency in decentralized grids.

- **Scenario 2: Regulatory Shift (Promotion of P2P Energy Trading)**

Envision a regulatory landscape where governments actively promote P2P energy trading. Streamlined licensing processes, standardized SC templates, and incentivized MG adoption could encourage greater participation in decentralized energy markets, making blockchain an integral part of national energy strategies.

- **Scenario 3: Cybersecurity Threat (Blockchain Disruptions)**

In this scenario, a large-scale cyberattack targets a blockchain-based energy trading platform, disrupting the entire decentralized market. This highlights the urgent need for enhanced security protocols and resilient network architectures, ensuring that blockchain platforms can withstand emerging cyber threats in the critical energy sector.

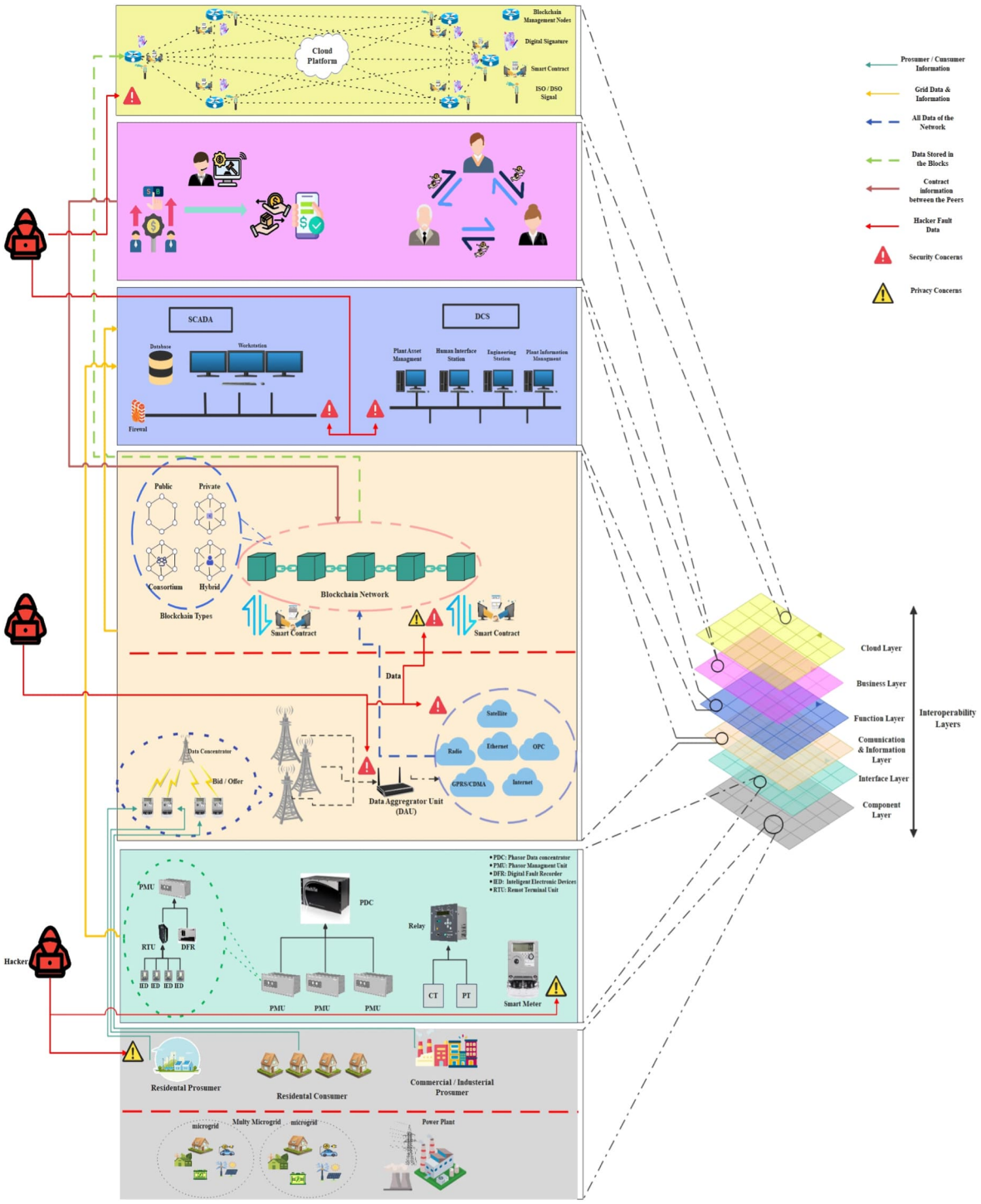


Fig. 29. Proposed Blockchain based P2P transactive energy trading framework.

6.2. Mid-term outlook: scalable and interoperable technologies (2025–2030)

Over the next five years, the most impactful innovations will build upon technologies already at a Technology Readiness Level (TRL) of 7 or higher, and regulatory frameworks that are either in place or under active development. Three areas will dominate:

- **Cross-Chain Interoperability Bridges.**

As distribution systems become more decentralized, utilities and aggregators will require secure, low-latency settlement across multiple blockchain platforms. Inter-Blockchain Communication (IBC) protocols, which are already mature in the finance sector, will be adapted for use in energy markets, enabling Hyperledger-based permissioned networks to exchange tokenized kilowatt-hour assets with public, permissionless blockchains. Pilot implementations (e.g., Cacti-IBC connectors) indicate TRL 8 readiness by 2027, with regulatory sandboxes in Europe and North America validating compliance with data privacy and anti-money laundering rules. The projected market size for energy-focused interoperability services is estimated at USD 150 million by 2030.

- **Asset Tokenization and Digital Finance Rails.**

Tokenization of renewable energy certificates and prosumer-owned generation assets will underpin new financing models. Kilowatt-hour-backed stable tokens and green-bond NFTs will provide instantaneous liquidity for DER investors. Early frameworks [8,61] demonstrate how on-chain governance tokens can align corporate ESG targets with community MGs. Tokenized certificate projects at TRL 7–8 are anticipated to launch in 2026, scaling to a USD 500 million transaction volume by 2030 as institutional investors enter the space [61,62].

- **V2G Aggregation Models.**

Electrified transportation fleets will emerge as the most enormous flexible load and storage reservoir on the distribution grid. Aggregators will pool >10 GW of parked EV capacity into fast-ramping virtual power plants, bidding into energy and ancillary services markets. SCs will socialize battery degradation costs via token-escrow mechanisms, ensuring transparent compensation for vehicle owners. Current field tests (TRL 7) in Japan and Europe aim for a commercial rollout in 2028, with a forecasted market value of USD 1.2 billion by 2030.

Each of these innovations will operate within evolving regulatory frameworks. Table 12 (new) summarizes TRL, regulatory readiness, and projected market size for each near-term pathway.

The development of scalable cross-chain interoperability solutions is a significant focus for future blockchain-based energy systems. IBC protocols, which have been successfully tested in financial applications, are now being adapted for energy markets. These innovations will enable seamless data exchange across multiple blockchain platforms, thereby improving the efficiency of decentralized energy trading systems.

6.3. Long-term horizon: autonomous contracts and self-sovereign resource identity (2030–2040)

As blockchain technology matures, immediate innovations such as enhanced consensus algorithms (e.g., PoA) and improved interoperability protocols will lead to scalability improvements in decentralized energy markets. Long-term innovations, such as quantum-secure roll-ups and autonomous contracts, will push the boundaries of blockchain's capabilities in energy systems. This transition marks a critical phase in integrating cutting-edge technologies with energy markets, facilitating highly efficient, automated, and secure decentralized energy governance. Looking beyond 2030, fundamental R&D will unlock transformative capabilities that require new standards and significant policy evolution. Three long-term research directions stand out:

- **Quantum-Secure, Zero-Knowledge Roll-Ups.**

To preserve transaction privacy and ensure integrity at scale, distribution-level settlements will migrate to blockchain roll-up architectures protected by quantum-resistant cryptography. Zero-knowledge proofs will enable validators to confirm aggregated flex-service deliveries without exposing prosumer identity or detailed load profiles. Research currently at TRL 3–4 is projected to advance to TRL 7 prototypes by 2035, contingent upon the international standardization of post-quantum algorithms.

- **On-Chain LMP Derivatives.**

Sophisticated prosumers and utilities will require hedging instruments against grid congestion and price volatility. On-chain SCs will automate the creation, trading, and settlement of LMP futures and options. This will demand integrated market coupling across transmission and distribution, with regulatory approval for retail-level derivative trading. Initial feasibility studies (TRL 4) are expected to mature into TRL 8 pilots by 2038, providing risk-management tools for a projected USD 2 billion derivatives market.

- **Self-Sovereign DER Identity and Autonomous Contracts.**

By 2040, distributed resources will transact energy and flexibility services autonomously using self-sovereign identity frameworks and machine-readable legal contracts. Agents representing rooftop solar, home batteries, and EV fleets will negotiate directly using decentralized identifiers (DIDs) and verifiable credentials. Research on digital identity interoperability (TRL 2–3) must accelerate to achieve TRL 7 integration trials by 2040, enabling fully automated, P2P energy trading without human intervention.

Table 13 contrasts these long-term pathways against the near-term innovations of Section 5.1, highlighting differences in TRL, regulatory complexity, and market opportunity. These projections provide a roadmap for funding agencies and industry consortia to prioritize R&D investments over the coming decade.

6.4. Practical implications and use cases

The framework proposed in this study offers a solid foundation for the practical implementation of blockchain-based TE systems. Two significant use cases where this framework can be applied are explored:

6.4.1. Rural microgrids

Rural microgrids, often disconnected from the main grid, can significantly benefit from a decentralized energy market. By integrating blockchain technology, these MGs can implement transparent and secure P2P energy trading. Through blockchain, rural communities can generate, store, and trade renewable energy more efficiently, enhancing local energy independence. One such example is the Brooklyn Microgrid project, where blockchain facilitated secure energy trading among community members. A pilot study in rural India demonstrated the feasibility of blockchain in enabling small-scale solar-powered MGs, offering a potential model for similar implementations globally. However, the challenges of implementing blockchain in rural microgrids include ensuring stakeholder cooperation and providing access to affordable smart meters and digital infrastructure.

Table 13
Comparative overview of near- and long-term energy innovations: TRL, regulatory readiness, and projected market size.

Innovation	TRL (Target Year)	Regulatory Readiness	Projected Market Size
Cross-Chain Interoperability Bridges	TRL 8 (2027)	Regulatory sandboxes & pilot approvals (EU, NA)	USD 150 million by 2030
Asset Tokenization & Digital Finance Rails	TRL 7–8 (2026)	Emerging frameworks under financial regulators	USD 500 million by 2030
V2G Aggregation Models	TRL 7 (2025) → TRL 8 (2028)	EV-grid integration standards in development	USD 1.2 billion by 2030
Quantum-Secure, Zero-Knowledge Roll-Ups	TRL 3–4 (2025) → TRL 7 (2035)	Pending post-quantum standards; early regulatory discussion	Pre-commercial (no market estimate)
On-Chain LMP Derivatives	TRL 4 (2025) → TRL 8 (2038)	Retail-derivative trading regulation yet to be defined	USD 2 billion by 2040
Self-Sovereign DER Identity & Autonomous Service Contracts	TRL 2–3 (2025) → TRL 7 (2040)	Identity & legal frameworks under research	Pre-commercial (no market estimate)

6.4.2. Urban energy communities

In urban energy communities, blockchain can be used to optimize the management of DERs and enable real-time energy trading between residential and commercial users. These systems help balance supply and demand within the community, making energy use more sustainable and cost-efficient. For instance, VPPs based on blockchain have been implemented in Germany to enhance energy resilience and integrate RESs. In urban settings, key challenges include aligning the interests of various stakeholders, navigating the complex regulatory landscape, and ensuring data privacy. Future research will need to focus on resolving these issues to effectively scale the implementation of blockchain systems in urban energy communities.

6.4.3. Challenges to implementation

Despite the potential benefits, several challenges remain in implementing blockchain-based TE systems:

- **Stakeholder Buy-In**: Achieving consensus among diverse stakeholders (utilities, governments, private investors, and consumers) is crucial. Without clear incentives and regulatory frameworks, the adoption of decentralized energy solutions may face significant delays.
- **Regulatory Barriers**: Blockchain-based energy trading requires updated regulations to support decentralized systems while ensuring consumer protection and market stability. Policymakers need to provide clear guidelines for integrating blockchain technologies with existing energy laws.
- **Interoperability**: For blockchain solutions to be successful in real-world applications, interoperability between different technologies (smart meters, IoT devices, energy storage systems) is essential. The framework addresses these issues, but further research is required to refine integration processes and ensure scalability.

In conclusion, while there are considerable opportunities for implementing blockchain in real-world energy systems, challenges such as regulatory adaptation, stakeholder alignment, and system interoperability must be addressed through further research and pilot projects.

7. Key challenges and opportunities, and the future trends of research

The development of blockchain-based TE and P2P energy trading has opened new possibilities for decentralized energy systems. While there are challenges to overcome, including barriers, technological limitations, and market complexity, the potential benefits are substantial. As it matures, increased adoption of these systems is expected, particularly in regions lacking adequate energy infrastructure. Despite the growing interest in blockchain-based trade and P2P energy trading, several research gaps remain to be addressed. Firstly, technology needs to be further explored, as current blockchain solutions may not be able to accommodate the high volume of energy transactions in a peer-to-energy trading system.

Furthermore, the impact of regulatory frameworks on the adoption and implementation of blockchain-based energy trading requires further study. Ultimately, there is a need to explore the potential role of blockchain in enabling DERs and facilitating the transition towards decentralized energy. As technology matures, future research should also focus on developing a generalized framework for blockchain transactivity and P2P energy trading that can be adapted to different market conditions and regulatory environments. As blockchain technology evolves, its integration with cutting-edge technologies, such as AI, machine learning, and quantum computing, will revolutionize the energy sector. These advancements could enable more efficient energy trading platforms, enhance grid optimization, and facilitate real-time decision-making. However, the future of blockchain-based TE systems is not without challenges. Scalability, transaction costs, and regulatory frameworks will require continuous innovation to ensure that blockchain technology can meet the growing demand for decentralized energy trading systems. Future research should focus on developing scalable consensus algorithms, improving data privacy mechanisms, and addressing the integration challenges posed by diverse energy markets and decentralized resources. AI and machine learning will significantly enhance the decision-making capabilities of blockchain-based energy trading platforms. By analyzing vast amounts of data from smart meters, weather forecasts, and grid conditions, AI algorithms can predict energy demand, optimize trading strategies, and detect anomalies in real-time. The integration of AI with blockchain will enable the automation of complex energy trading processes, improving market efficiency and reducing operational costs.

Future research areas in blockchain-based TE and P2P energy trading include investigating the scalability of blockchain technology for larger energy grids, utilizing SCs to automate energy, analyzing the role of energy trading in mitigating climate change, and developing algorithms to optimize energy trading. Additional research could include the regulatory, economic, and social implications of P2P energy trading and blockchain-based energy systems. As technology applications evolve, ongoing research in these areas will be essential for advancing the adoption and integration of blockchain-based energy into the existing energy infrastructure. The future of blockchain in energy systems is closely tied to the integration of AMI and smart grids. Blockchain can serve as a secure and transparent platform for real-time data exchange between smart meters, consumers, and utilities. This will enable decentralized energy trading platforms, where consumers can engage in P2P energy transactions based on real-time usage data, thereby eliminating the need for intermediaries and reducing energy costs. The integration of blockchain with AMI and smart grids will help streamline energy management, enhance grid resilience, and promote consumer participation in energy markets, marking a significant step toward more efficient and sustainable energy systems.

A future blockchain-powered TE system is envisioned, integrating quantum computing to enable real-time optimization of energy flows and decentralized energy governance facilitated by SCs and AI. The development of scalable blockchain solutions will be essential for large-scale adoption, particularly in integrating electric vehicles and other distributed resources into the energy market.

As blockchain technology continues to evolve, there will be a shift towards more energy-efficient consensus mechanisms such as PoS and PoA. These mechanisms can significantly reduce the environmental footprint of blockchain networks, making them more scalable and suitable for large-scale energy trading applications. The development of hybrid consensus models that strike a balance between security, energy efficiency, and scalability will be crucial for the widespread adoption of blockchain in energy markets.

Numerous gaps and difficulties were encountered in executing TE and P2P energy trading based on blockchain technology. These challenges encompass uncertainties in regulatory measures, technical limitations, insufficient empirical evidence, and the need for standardization. The frameworks governing energy trading regulation exhibit variation across different jurisdictions, thus giving rise to uncertainty among stakeholders and impeding the adoption process. Technical hurdles include scalability, transaction speed, interoperability, and security concerns. The absence of empirical evidence poses challenges to informed policy decisions and effective system design. Additional research, pilot project introduction, and collaboration are essential to surmount these challenges. The industry should prioritize standardization, alternative consensus algorithms, improvements in scalability, and the implementation of enhanced privacy regulations to fully leverage the potential of blockchain-based energy trading. To facilitate the widespread adoption of blockchain in energy systems, the development of standardized protocols for interoperability will be essential. These protocols will enable seamless communication between different blockchain networks, ensuring that SCs, energy transactions,

and market data are exchanged efficiently and securely. International standards for blockchain-based energy trading will help bridge the gap between different regulatory environments and energy markets, allowing for a truly global, decentralized energy ecosystem. Regulatory changes will heavily influence the adoption of blockchain-based energy trading. Governments and regulatory bodies must adapt to the new decentralized nature of energy markets by developing policies that facilitate blockchain integration, ensure consumer protection, and address security concerns. The establishment of clear regulatory frameworks for blockchain-based energy platforms will be crucial to fostering innovation, ensuring fair competition, and protecting market participants.

Policy decisions and security considerations significantly impact the potential of blockchain technology in P2P energy trading. Policymakers must ensure that regulatory frameworks support the decentralized nature of blockchain while addressing key issues such as energy pricing, grid integration, and data privacy. Security actors, such as cybersecurity experts, must work closely with energy system operators to ensure that blockchain platforms are protected against vulnerabilities. This intersection of technology, policy, and security must be continuously evaluated to avoid the unintended consequences of a fragmented or insecure energy market.

7.1. Key challenges and opportunities

7.1.1. Key challenges

- Scalability: Maintaining throughput and low latency as the number of DERs grows.
- Interoperability: Ensuring seamless data exchange across blockchains, legacy systems, and IoT devices.
- Security and Privacy: Protecting against cyberattacks and preserving prosumer confidentiality via ZKPs and formal verification.
- Regulatory Alignment: Harmonizing SC frameworks with energy market regulations and consumer-protection laws.

7.1.2. Future opportunities

- Quantum-Resistant Roll-Ups: Adoption of post-quantum cryptography for large-scale settlement.
- Tokenization of Energy Assets: Developing standardized kWh-backed tokens and green NFTs to unlock new financing models.
- V2X Integration: Expanding V2H, V2B, and V2V use cases through standardized bi-directional charger protocols.
- Autonomous Resource Identity: Deploying self-sovereign identity for DER agents to transact without human intervention.

7.1.3. Future trends of research

Looking ahead, integration with AI/ML and digital twin platforms will further optimize dispatch and resilience. Continued interdisciplinary efforts are required to bridge technical innovation with policy and market design.

7.1.4. Emerging technologies beyond AI and digital twins

While artificial intelligence and digital twins are becoming increasingly important, several other emerging technologies are expected to reshape peer-to-peer (P2P) energy trading. Federated learning enables collaborative model training across prosumer devices without exposing raw data, thereby enhancing privacy. Edge analytics and fog computing reduce latency by processing energy data locally, which is critical for real-time trading and control. Post-quantum cryptography provides resilience against future quantum attacks, ensuring long-term security of blockchain-based ledgers. DIDs and self-sovereign identity frameworks enhance trust by granting users control over their credentials on trading platforms. Finally, cross-chain interoperability protocols allow seamless exchange of energy tokens and settlement across heterogeneous blockchain networks. These technologies extend the digital foundation of P2P energy markets and address limitations in privacy, latency, and scalability [64].

7.2. Key research areas, challenges, and future directions

To Sum up. The development of blockchain-based TE and P2P energy trading systems has opened new possibilities for decentralized energy systems. As these systems continue to evolve, several key areas require further exploration to address the current barriers, technological limitations, and complexities in the energy market.

While blockchain holds significant promise for the energy sector, it faces challenges such as scalability issues, high transaction costs, and the need for integration with existing infrastructure. As the technology matures, more widespread adoption is expected, especially in regions where energy infrastructure is underdeveloped. Despite growing interest, several research gaps remain, particularly in how blockchain can effectively accommodate the high volume of transactions required for decentralized energy markets.

7.2.1. Key research areas

The key research areas for the future include:

1. Technology and Scalability:

Current blockchain solutions may struggle to handle the high transaction volumes necessary for efficient peer-to-peer (P2P) energy trading. Future research must focus on enhancing blockchain scalability and transaction speed to support large-scale energy systems. Additionally, the development of energy-efficient consensus mechanisms, such as PoS and PoA, will be crucial for reducing the environmental impact of blockchain networks and improving their efficiency for widespread energy applications.

Example: Blockchain's ability to integrate with smart grids and AMI could provide a decentralized platform for real-time energy trading, reducing the need for intermediaries and promoting consumer participation. This integration will enable more efficient and resilient energy systems, particularly through the use of real-time usage data from smart meters.

2. Regulatory and Policy Implications:

Regulatory frameworks will significantly impact the adoption of blockchain in energy trading. Governments must create policies that support blockchain integration while ensuring consumer protection, data privacy, and cybersecurity. Future research should investigate the evolving role of regulations in decentralized energy markets, ensuring that blockchain systems are aligned with global energy policies and standards.

Example: Research into the regulatory impact of blockchain on energy trading systems could help create standardized protocols for interoperability between different blockchain networks, facilitating seamless communication between energy markets worldwide.

3. AI and Machine Learning in Blockchain-based Energy Trading:

AI and machine learning will be essential for enhancing blockchain-based energy trading platforms. By analyzing vast amounts of data from smart meters, weather forecasts, and grid conditions, AI can optimize trading strategies, predict energy demand, and identify anomalies in real-time. Integrating AI with blockchain will automate complex energy trading processes, improving market efficiency and reducing operational costs.

Example: The use of AI to predict energy demand and optimize transactions in real-time can create more responsive and dynamic energy markets, where consumers and producers can adjust their behavior

based on data-driven insights.

4. Development of Standardized Protocols for Interoperability:

The seamless integration of blockchain-based energy trading systems will require standardized protocols to ensure that SCs, energy transactions, and market data are exchanged efficiently and securely across different platforms. Future research should focus on developing these international standards to facilitate global adoption and interoperability.

Example: Standardization of blockchain protocols for energy trading could enable cross-border energy transactions, creating a truly decentralized energy market that integrates multiple regulatory environments and energy systems.

5. Quantum Computing and Blockchain:

The integration of quantum computing with blockchain could revolutionize energy systems by enabling real-time optimization of energy flows and decentralized governance through SCs. Research into how quantum computing can enhance blockchain's scalability and security for energy applications is critical for the next generation of blockchain-based TE systems.

Example: Quantum computing could provide advanced algorithms that enhance the efficiency of energy trading platforms by increasing computational power, making the large-scale adoption of blockchain in energy markets feasible.

7.2.2. Challenges and future directions

While the potential of blockchain in energy systems is vast, several challenges must be addressed, including scalability, transaction speed, regulatory uncertainties, and integration with legacy energy systems. Future research should aim to overcome these challenges through innovative blockchain solutions, improved consensus algorithms, and enhanced data privacy mechanisms.

7.3. Societal and ethical implications

Beyond technical challenges, the adoption of blockchain-based peer-to-peer (P2P) energy trading raises significant societal and ethical concerns. Data privacy and ownership remain critical concerns, since smart meter and transaction data can expose sensitive information about consumer behavior. Equity and fairness also need to be addressed, as digital literacy and access to enabling technologies may not be uniform across communities, potentially creating a "digital divide." Tokenization and market-based incentives can raise questions about distributive fairness, particularly if benefits are concentrated among early adopters or large-scale prosumers. Governance and accountability are equally essential, as mechanisms for dispute resolution, compliance with regulatory frameworks, and responsible data use must be integrated into system design. Finally, the environmental implications of consensus mechanisms should not be overlooked, even as energy-efficient alternatives to PoW are increasingly deployed. Addressing these societal and ethical implications is crucial for achieving widespread acceptance and long-term sustainability of peer-to-peer (P2P) energy trading systems.

7.4. Final remarks

In conclusion, the role of blockchain in the energy sector is expected to continue growing as the technology evolves. Key future trends will focus on making blockchain-based TE and P2P energy trading more scalable, secure, and interoperable. As these systems mature, they will become an integral part of decentralized, sustainable energy markets.

Measurable trends underscore the growing importance of blockchain-enabled P2P trading. A bibliometric analysis indicates that the number of published studies increased from fewer than 15 in 2018 to over 40 in 2024, reflecting a strong annual growth rate. Pilot implementations of permissioned blockchain networks report transaction throughputs in the order of hundreds of transactions per second with typical latencies ranging from milliseconds to a few seconds, depending on the consensus mechanism. Market forecasts suggest that blockchain-based energy platforms may reach a global value of several hundred million USD by 2030. Furthermore, TRLs are progressing from TRL 3–4 (concept validation) towards TRL 6–7 (demonstration in relevant environments). These quantified indicators provide evidence of both the academic momentum and the practical potential of peer-to-peer (P2P) energy trading, thereby strengthening the case for continued research and deployment.

8. Conclusion

8.1. Novel contributions and comparison with existing literature

This review advances the state of the art in blockchain-enabled energy systems in four key dimensions:

1. Unified cyber-physical framework

Prior surveys have focused on isolated technical components, such as smart-contract architectures [12] or MG transaction models [31]. This work integrates control-system layers, market mechanisms, and regulatory frameworks into a single generalized model, providing a comprehensive reference for end-to-end system design and governance.

2. Interdisciplinary bibliometric mapping

Existing bibliometric studies often target narrow themes, such as consensus protocols [13] or tokenomics [10]. By analyzing 150 articles across six domains —consensus, privacy, interoperability, market design, regulation, and edge-enabled architectures —our mapping reveals emergent linkages (for example, AI-enabled privacy layers) not captured in previous co-occurrence analyses.

3. Comparative consensus analysis

Whereas [170] examined token economics from a game-theoretic perspective and [199] studied adaptive pricing SCs, Section 4.2.8 presents a systematic side-by-side comparison of PoW, PoS, and PoA. Throughput, energy consumption, and governance suitability metrics are evaluated to inform the selection of protocols for real-world energy trading deployments.

4. Future scenarios grounded in TRL roadmaps

Many earlier outlooks have remained high-level and speculative. In contrast, Section 6 grounds each future scenario, including quantum roll-ups, regulatory shifts, and cybersecurity threats, in documented TRL projections and pilot-project timelines, offering stakeholders a clear roadmap for R&D investment.

As the field of blockchain-enabled P2P energy trading matures and more homogeneous datasets become available, future reviews may incorporate formal meta-analytic techniques such as pooled effect sizes, confidence intervals, and hypothesis testing. Integrating such statistical rigor would further strengthen the quantitative synthesis and enable deeper cross-study comparisons.

8.2. The final remarks

This paper provides a comprehensive review of the fundamentals of blockchain-based TE and P2P energy trading structures, proposing a generalized cyber-physical framework. The proposed blockchain-based TE and P2P energy trading have demonstrated significant potential in

addressing the challenges of traditional centralized energy systems. Through distributed technology, energy generation and consumption can be organized more transparently, allowing individuals to participate actively in the energy market. While some technical and regulatory hurdles still need to be overcome, the development of a generalized framework for blockchain-based systems holds promise for a sustainable and equitable energy future. As such, further development efforts are required to fully realize the potential of this technology in the energy sector.

This review provides a comprehensive overview of blockchain-based TE systems and their integration with emerging technologies, including AI, machine learning, and privacy-preserving techniques. By addressing both technological and socio-economic perspectives, this paper offered valuable insights into the future of decentralized energy systems. It also introduced recent innovations such as PrGChain and scalable blockchain architectures, which are essential for addressing the challenges of scalability and privacy in energy markets.

In summary, this review presents a unified cyber-physical framework for blockchain-enabled energy systems, conducts an interdisciplinary bibliometric mapping across six thematic domains, and delivers a comparative analysis of consensus mechanisms tailored to P2P and TE markets. By grounding future scenarios in documented TRL projections and pilot timelines, the paper offers stakeholders a roadmap for R&D investment and technology adoption.

These contributions have three practical implications. First, system architects can utilize the decision matrix to select consensus protocols that strike a balance between throughput, energy efficiency, and governance requirements. Second, policymakers and regulators are provided with a clear set of research lacunae—standardization, scalability, privacy, socio-economic models, and integration challenges—to inform standard development and funding priorities. Third, developers and utilities can use the future scenarios in Section 6 to plan pilot projects and anticipate regulatory shifts, cybersecurity threats, and emerging technology integrations.

Looking forward, key next steps include empirical validation of the proposed framework in live MG environments, development of open interoperability standards, and longitudinal studies on the socio-behavioral impacts of tokenomics models. Collaboration among technical researchers, social scientists, industry consortia, and regulators will be crucial to translating these research directions into resilient, scalable, and inclusive blockchain-based energy markets.

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.

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Appendix

Appendix A. Bibliometric and Summary Statistics Methods

- Data Collection: 150 articles from Scopus and Web of Science (2018–2024) using search terms “blockchain,” “SG,” and “TE.”
- Bibliometric Analysis: VOSviewer v1.6.19 for keyword co-occurrence mapping.
- Summary Statistics: Aggregated adoption rates, latencies, and TPS from ten empirical studies; consulted a professional statistician to compute means and ranges.

Data availability

No data was used for the research described in the article.

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