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Review article

A systematic review on blockchain-based energy trading in a decentralized transactive energy system: Opportunities, complexities, strategic challenges, research directions

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A R T I C L E I N F O

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A B S T R A C T

The current hike in electricity demand, deterioration of electrical grids, and climatic conditions have necessitated the push for technology to enhance energy efficiency, optimize energy usage, and minimize greenhouse gas emissions. The Transactive Energy System (TES) is a highly favoured technology designed to provide solutions for optimizing energy usage since it incorporates economic and dynamic control mechanisms to balance the amount of energy generated and supplied. Cost savings present a clear advantage of TES for consumers, translating to reduced bills, and the platform enables customers with Distributed Energy Resources to trade their excess energy, transforming consumers into prosumers. However, energy trading in TES comes with challenges such as maintaining a dynamic balance between supply and demand, as well as issues of privacy, trust, and resilience. Blockchain Technology (BT)-based TES can address these challenges due to its reliability, transaction transparency, and robust encryption methods. However, BT has its shortcomings that need to be addressed. Therefore, this research analyzes the opportunities, limitations, challenges, and complexities of implementing blockchain-based energy trading platforms within a decentralized TES. This review adopted a systematic approach, known as the Preferred Reporting Items for Systematic reviews and Meta-Analyses, to provide in-depth insights into the review purpose, methodology, findings, recommendations, and future research directions. It was observed from the review that certain challenges underscore the necessity for standardization in BT-based TES implementation. Moreover, it was discovered that decentralizing the TES energy trading infrastructure promotes energy democracy and that adopting fast computing techniques will facilitate digital and intelligent operations in TES. It was also found that the Directed Acyclic Graph-based distributed ledger may soon replace generic blockchain, as it can simultaneously process large micro-transactions in P2P networks. It is observed that implementing a peer rating mechanism in the energy trading network will enhance participants' commitment to their reputational standing in the market, while adapting analytical modelling for performance evaluation of this energy solution could equally be encouraged.

1. Introduction and problem context

1.1. Background

The conventional power system is under strain to meet increasing energy demand. Fossil fuels in electric power generation have become a concern due to their direct impact on the environment, leading to the dreadful challenge of global warming [1]. Growing worries about environmental degradation and resource waste from energy consumption make managing supply and demand, minimizing operational costs, and lowering energy prices to consumers difficult. The dual issues of energy shortages and environmental pollution have prompted the integration of various technologies into energy architectures to enhance energy efficiency, reduce energy costs, and lower carbon footprints by incorporating more renewable energy sources (RES) [2]. Furthermore, integrating modern/smart control, communication mechanisms, and non-conventional energy sources by independent power producers, along with energy management approaches, assists in balancing energy supply and demand, and managing electricity consumption in response to fluctuations in electricity tariffs [3]. One such advanced energy solution is Transactive Energy (TE). The solution has been proven to be a viable alternative in addressing the challenge of maintaining a dynamic balance between energy supply and demand in a decentralized

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Nomenclature

Abbreviations

AI	artificial intelligence
ARIMA	auto-regressive integrated moving average
BFT	byzantine fault tolerance
BT	blockchain technology
CM	consensus mechanism
DAG	directed acyclic graph
DEP	dynamic energy pricing
DERs	distributed energy resources
DL	distributed ledger
DLT	distributed ledger technology
DR	demand response
EC	energy consumers
EP	energy provider
FDIA	false data injection attack
GHG	greenhouse gas
HEMS	home energy management system
IES	integrated energy system
IoT	internet of things
LEM	local energy market
MCP	market clearing price
MES	multistep electricity pricing
ML	machine learning
PRISMA	preferred reporting items for systematic reviews and meta-analyses
PoW	proof-of-work
PSO	particle swarm optimization
P2P	peer-to-peer
REPI	renewable energy price index
RES	renewable energy sources
RTP	real-time pricing
SC	smart contracts
SG	smart grid
SW	social welfare
TES	transactive energy system
ToU	time of use

Index

P	power consumption
q	user's preference
σ	pre-determined parameters

Parameters

R	number of energy provider
S	number of consumers
T	number of time slots/period
CI	capital investment
IC	inverter cost (applicable to solar panel system)
MC	maintenance cost
AV_{PG}	average of the power generated
$U(p,q)$	utility function

peer-to-peer (P2P) network, allowing consumers and prosumers to exchange energy without involving third-party entities [4].

Transactive Energy Systems (TES) is a solution designed with a blend of economic and control mechanisms to balance energy demand and supply over the entire electrical facilities through a value-based arrangement [5]. Zou et al. [6] described TES as an energy trading platform that operates mainly at the distribution layer and uses the TE concept to facilitate the direct participation of small and medium-scale energy producers and consumers in local energy markets (LEM), a platform for trading locally generated energy among customers. The approach allows participants to perform energy trading activities with one another to support a dynamic balance between supply and demand energy within local communities. TES is a new class of energy systems that uses value (price) to control market participants to maximize decision-making, achieve centralized or decentralized coordination of large-scale energy systems, enhance efficiency, cut transmission losses, facilitate lower carbon emissions, promote renewable energy adoption, and boost the economy [7–9]. It is a technology designed to improve grid operation by employing control and economics techniques to balance energy generation and demand for optimal utilization of distributed energy resources (DER) and enhancing prosumer integration into the system [10]. The DER is a small or medium-sized decentralized power generation system that allows RES to perform a complementary function to the conventional electrical grid [11]. The growing acceptability of DERs can be attributed to their high efficiency and reduced pollution emissions [12].

Furthermore, research has revealed the potential of TES in enhancing the grid's efficiency, safety, adaptability, and resilience, adapting the system to different configurations and infrastructure to support energy trading solutions. It takes into consideration the interests of both the supply and demand sides. It is an advanced solution to DR that uses the flexibility of several generation sources to balance energy supply and demand [13]. TES facilitates more effective use of DER, and its concepts find application in P2P energy trading. TES solution involves deploying two-way communication systems to create a dynamic balance between supply and demand using market-based models, with further consideration for grid reliability constraints [1,14]. This points to the fact that TES relies strongly on the associated cyber system, one of the control mechanisms, used in authorizing the effective usage of distributed resources of the electrical grid [15]. In conventional TES, participants interact and share quotation data via the trading platform. At the same time, the system operator executes the task based on the data available on the trading platform. An energy trading algorithm is important to determining the Market Clearing Price (MCP) and difficulties surrounding cybersecurity requirements needed to support effective market operations [16]. Recently, there has been much focus on decentralizing the energy market against the traditional centralized approach, which suffers from a single point of failure for improved energy delivery using technology [17] and it is difficult for the central authority to manage and coordinate diverse interests of participants as the energy system becomes more distributed [18]. One of the challenges in a decentralized energy trading system is the trust issue between participants and third parties when disseminating information to find trading partners and defaulting on agreed-upon energy transfer. Distributed ledger technologies (DLTs) are highly favoured in building the decentralized network of TES for energy transactions.

A derivative of DLT, Blockchain Technology (BT), is an underlying technology that has garnered increasing interest from academia, industry, and fields where decentralization, transparency, immutability, reliability, traceability, complex data exchange, and security of transactions are of high significance [19–21]. Initially, BT was designed for Bitcoin and its choice in an energy trading network (between consumers and prosumers) based on quick, reliable transactions and privacy protection [22]. It is an emerging decentralized technology in the circle of the internet and digitization, offering a high level of security (less vulnerable to security breaches), eliminating the need for third-party verification, and thereby establishing trust between the nodes in the network through consensus-based verification [23,24]. Blockchain has exceptional features for decentralized operations, making it the best fit to manage and coordinate multiple growing connections vis-à-vis a centralized approach [2]. A decentralized approach enhances scalability, privacy, self-governing trading, unanimous legitimate auditing, and ultra-low latency [25]. Despite the promising benefits of using BT to overcome challenges in energy trading, some complexities are associated with its use. Therefore, there is a need to identify mechanisms to facilitate the development and implementation of the new energy distribution solution (TES), and blockchain conspicuously distinguishes itself among the available technologies.

Thus, BT has shown to be a viable solution to the challenges of isolating intermediaries. Blockchain is revolutionizing transaction security and enabling the smart power grid to become decentralized [26]. Benefits of decentralized TES include prosumers interacting without negotiators, resolving disputes via protocols, transactions stored on the blockchain are unchangeable except for unanimous auditing, fault-tolerant (continue to function even if some prosumers behave maliciously), and a blockchain-based system can withstand availability attacks [27]. It offers reliable data computation and storage via smart contracts (SCs), eliminating the need for a trusted third party. BT has vast potential to unravel procedural bureaucracy and make transactions transparent. The blockchain components comprise SCs, distributed networks, and a distributed ledger (DL). Using BT, makes P2P transactions more automated, reducing the need for human involvement and enhancing security through transparent, indestructible, and secure systems, while SC further speeds up real-time settlements in the energy market [28]. A P2P energy trading framework allows market participants, equipped with PV panels within a community, to trade their surplus energy directly with each other [29]. P2P trading using BT is among the emerging innovations in the renewable energy ecosystem [30]. Despite that, blockchain-based DLT emerges as the most widely used P2P energy trading platform solution, as it was discovered that the cost of maintaining the platform and data management is on the high side, as well as the lack of transparency in the approach, which is yet to be decoded [31].

Another bottleneck in energy trading is the billing system. For instance, charging consumers fixed prices makes energy operators bear the variations in cost as end-users are unaffected by the differential in wholesale prices during the off-peak period [32]. This fluctuation reduces power supply reliability and efficiency of power systems, resulting in reduced profits for energy operators. This prompted the introduction of a dynamic electricity pricing technique based on a real-time electricity pricing regime in the power trading market. This approach minimizes energy costs, enabling consumers to plan their future energy consumption without compromising comfort. Earlier, energy pricing schemes such as the Stackelberg game, two-layer optimal scheduling, and instantaneous load charging schemes were developed as intermediaries/retailers between the wholesale energy market and end users [33]. Xue et al. [34] designed an option contract model based on a renewable energy price index using the Monte Carlo option pricing model. In [3], a dynamic energy management system was implemented based on local renewable energy generation forecasts and real-time pricing. These approaches still suffer from limitations such as compromising consumers' comfort.

1.2. Study motivation

One of the major forces behind improved social welfare (SW), economic expansion, and development has long been linked to electricity. The most developed countries are the ones with the highest levels of electrical power generation and consumption [35]. The advent of the Internet of Things (IoT) and Information and Communication Technology (ICT) has aided the operations and marketing of electrical energy. The integration of these technologies into the electricity sector is helping to address sustainability from the perspectives of social, technical (4IR), economic (commercializing electrical energy), and environmental (decarbonization and replacement of non-renewable energy with clean energies) [26]. Recent studies have also shown a significant increase in the application of BT in providing innovative energy trading in TES, where prosumers trade excess energy to participants in a decentralized approach and express their desire to trade energy through bids aimed at reducing energy bills or earning profit [36]. BT has a potential application in decentralized TES due to its high resilience rate [27,37]. It enables prosumers to commercialize electrical energy by selling it to consumers and injecting excess energy into the grid [38].

Trust between parties is essential to every business transaction and transparency in the energy market is fundamental, as third-party vendors access participants' data, such as comprehensive market load profiles and grid utilization [26]. This data is used to optimize the placement of their DERs and guide them in making informed decisions regarding their market participation [39]. Nonetheless, validating the integrity of market operations alleviates participants' fears of energy mismanagement by the market operator. For instance, verification can occur during bid auctioning to identify late bids through blockchain, despite their encryption.

The following section briefly introduces the identified research gaps, highlighting the limitations of the efforts made to narrow the gaps.

1.3. Research gaps

Previously, researchers had concluded that integrated Byzantine Fault Tolerance (BFT) in cataloguing transactions is adequate to secure the integrity of DLT [40]. This assumption is that the BFT does not ensure the reliability and efficiency of market operation in random bilateral transactions (private transaction negotiations between participants). The research deficit in the area of non-consideration of expenses relating to the depreciation of renewable systems and convergence of dynamic pricing equilibrium [41]. Others lack unified metrics, tools, and instruments for accuracy and efficient performance evaluation and behavioural features of different blockchain architectures. Another challenge facing developers of blockchain-based energy trading in TES is the lack of expertise, skill, and experience in implementing blockchain in TES. Furthermore, in analyzing and developing blockchain applications, computer simulation approximates the system's behaviour, and there are insufficient tools and instruments suitable for evaluating architectural features and various BTs' performance. This review classified the challenges facing BT-based implementation into operational and social. The operational challenges include finding a balance between abstraction and accuracy required to analyze the features, inadequate availability of historical data needed for data processing, standards for comparison, resource constraints necessary for the efficient development of distributed systems, and Machine Learning (ML) for improved blockchain automation. At the social layer are Adoption (awareness of the field), Expertise (inadequacy of experienced researchers in the field), and Standardization (non-uniform standards for performance evaluation).

Even so, Smetanin et al. [19] reported that simulations and analytical modelling are the most widely used standard instruments for evaluating the behaviour and performance of blockchain-based solutions. This is inadequate to assess and validate the system's performance. These are some of the issues that could lead to enormous negative impacts during the implementation or deployment phase.

1.4. Key contributions and article organization

The methodology employed in this review was based on the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA)-2020 expanded approach. The choice of systematic review was guided by identifying the current state of knowledge on energy trading in TES, with the primary target of addressing challenges that individual studies cannot solve and proffer research direction. This paper answers the research question, "What impact do mutually non-trusting participants in a P2P energy trading market have on the dynamic balance of energy supply and demand in a decentralized TES architecture?"

The major contributions of this article are outlined as follows:

i. Analysis of selected articles on the existing techniques for energy trading and synopsis of their corresponding limitations, thereby providing a robust and objective overview of current knowledge in energy trading in TES to guide in making informed policy and practice decisions,
ii. Examine the capability of blockchain in addressing relevant complexities currently being faced in TES energy trading to further enhance security, transparency of transactions, and cost minimization for participants,
iii. Justified the application of BT using existing information to establish the technology viability in the TES implementation platform, for cybersecurity enhancement and traceability of P2P transactions between mutually non-trusting participants in the energy trading market, and
iv. Adoption of the PRISMA 2020 systematic guidelines to facilitate suitable recommendations for practice and policymakers on providing insight into the complexity of energy trading.

Table 1 presents a comparison of this review with other existing Reviews.

The rest of the paper is arranged as follows. Section 2 showcased some of the challenges associated with Energy Trading Platforms, the benefits of TES (Economic, Social, Technical and Environmental) and the justification for BT application in TES. Section 3 brings to bear existing literature on Energy Pricing Models, focusing on their commonalities, differences, and drawbacks. Section 4 unveils the adoption of PRISMA methodology for the systematic Review with consideration for the data sources a search strategy, eligibility criteria (inclusion and exclusion), and data collection. Section 5 is a deep analysis of the suitability of DLT for decentralized transactions in TES, blockchain framework, SCs, computing approaches for Energy Trading, DLT for Decentralized Transactions in TES, Blockchain-Based TE Market, and complexities associated with the application of BT in TES. Decentralized Energy Trading Mechanisms; mathematical formulations; performance evaluation of blockchain-based energy trading systems; discussion, findings, and recommendations; and conclusion, limitations, and outlook on future research were reported in Sections 6 to 10, respectively.

2. Transactive energy system

In TES, various approaches have been presented for control and monitoring, which include centralized, decentralized, and distributed techniques [44]. A centralized approach is vulnerable to attack, a single point of failure, and a vast data volume [45]. Nonetheless, the shortcomings of the centralized framework are minimized in decentralized TES; there still exist limitations in terms of complexity in their structure and implementation. Distributed TES can be described as an advanced form of decentralized. It is the most complex, but its implementation can be realized through the application of BT.

Table 1
Differences between this review with other published review articles on TES.

Refs.	Features of Existing Review Articles	Limitations/Gaps
[1]	Concepts, Models, Metrics, Technologies, Challenges, and Policies	Security, participants' Privacy, and Energy Trading using BT
[6]	Participants Structure, Commodity, Clearing Methods, and Solution Algorithm	Cyber Threats, Efficiency, and Cost Reduction in BT-enabled TES
[13]	Evolution, Components, and Methodologies of the TE framework to facilitate Trading	Scalability and Adaptability of TES across different Energy Markets and Grid Infrastructures
[36]	Existing Architectures, DLT, and Market Analysis	Economic and operational benefits for stakeholders in BT-enabled TES in energy trading
[42]	Energy Flow, Information Processing, and Benefit of TES	Regulatory implications, role of government, and International Bodies enabling or hindering the adoption of BT-based TES
[43]	Policy, Optimization Methodology, Energy Sharing, and Physical Constraints in Energy Trading	Implementation Barriers in TES-Based Energy Trading Platform

2.1. Economic, social, technical and environmental benefits of adopting TES

TE allows for decentralization, enabling various participants to locally produce energy as prosumers instead of depending solely on centralized power infrastructure for energy efficiency. The TES promotes a more effective balance between supply and demand while ensuring consumers use energy at optimal times and levels. It enhances resilience in electricity availability by decreasing the frequency and duration of power outages. This improvement is due to the decentralized architecture of TES, which prevents total blackouts during power system disturbances, unlike a centralized energy system that may fail. A multi-factor technique was employed to evaluate the performance of the bidding node. According to the authors, the simulation results demonstrate that market participants can achieve greater economic benefits and enhanced privacy protection with the proposed method.

An economic optimization between P2P network participants was analyzed to determine the financial mechanism and optimal price in an integrated solar-thermal energy trading system in [46]. The proposed technique evaluated the energy network transaction process and the prevention of monopoly. Alafiza et al. [47] developed an economic decision analysis model for P2P, to manage thermal energy transactions in an integrated solar thermal system using a General Algebraic Modelling System. Chang et al. [48] proposed a TES based on multi-factor evaluation and contract net protocol to find energy trading techniques between prosumers for the economic and stable operation of the energy distribution system. Ref. [49] presents optimization and energy trading techniques in a multi-energy system for a hypothetical University circle, focusing on carbon emission.

Participation in the TES market benefits consumers (efficient energy consumption), energy stakeholders, and all sizes of businesses (unsealed earnings opportunities and minimization of costs via energy optimization). Consumers can become more resilient and efficient in their energy consumption, and businesses can. Minimizes urgent need for building or expanding new power-generating stations [50]. TES platforms need to be more proficient in satisfying the condition of improved flexibility than current energy systems to encourage the increased use of RES. Price signals are sent to consumers' smart devices to guide them on increasing or minimizing consumption. The superiority of blockchain is that modification of transactions, among peers, can only occur upon satisfying three conditions [29]. That is, the hashes (codes) of all the blocks must be changed to demonstrate the validity of the Proof-of-Work (PoW) of every block, and control more than half of the peers in the network. The above three procedures are difficult to achieve theoretically, thereby making any alteration attempts rigid. The technology allows for the validation of transactions among traders [23].

A P2P energy exchange framework for Swarm electrification was presented in [51]. The validation tests show that the approach performs better in achieving peak shaving and minimizes prosumer production losses of 16 % for the entire PV production. Using the PSO algorithm and heuristic technique to clear market mechanisms, a P2P energy framework for the computational implementation of semi-decentralized and decentralized trading mechanisms, with an interest in network constraints and privacy preservation, was developed using the PSO algorithm and heuristic technique [52]. The particle swarm optimization (PSO) algorithm was applied to solve equilibrium constraints. With the approach, a reduction of about 12.77 % of electricity peak power was achieved, improved economic benefit by 23.33 %, and a peak coefficient of variance of 0.93 for the carbon clearing price.

Globally, there is a prime focus on the decarbonization of energy systems for the sustainability of the environment. Efforts are being concentrated to reduce carbon emissions to meet the carbon reduction target. BT-based TES is a new paradigm that involves the comprehensive utilization of the available renewable resources, thus facilitating a sustainable, low-carbon environment [53]. It is a decentralized energy system that mitigates transmission losses and carbon emissions. Additionally, factors such as minimizing CO_2 emissions, maximizing the utilization of RES, and reputation-based blockchain (to encourage low-carbon behaviours) are now being incorporated into the objective functions of optimization problems to reduce carbon emissions [54]. Ref. [55] adopted a carbon trading approach as an essential procedure for reducing climate change by offering financial incentives and carbon credits for participants who have reduced their emissions.

2.2. Challenges in energy trading platforms

Introducing technologies into the energy market presents opportunities and challenges. BT, being the most famous of DLT, is more resistant to tampering with reliability, security, and scalability features than legacy transaction techniques [56]. Performance monitoring functions, transaction ledger storage on the network, and transaction charges through SCs, prompt its adoption in TES to enhance energy efficiency [57]. However, energy trading in TES faces notable implementation challenges despite its potential to address energy shortage and climate change. On the regulation aspect of TES, the current policy has failed to create or generate the required incentives to steer dynamic pricing in energy trading. Similarly, existing networks were not designed to accommodate two-way flow, as they rely on centralized infrastructure to supply electricity to all consumers. Other associated challenges include voltage violations, customer comfort, power flows, and losses. Security limitations include Data Privacy, Non-repudiability, Phishing, Message Integrity, Identity Privacy, and Double Spending (conflicting transactions) [58], trading constraints involve non-flexible pricing models, inaccurate consumption data [59], and the effect of uncertainties on the energy trading process, which reduces market efficiency [60]. Moreover, it has been observed that there is inadequate research on voltage regulation, which is the possibility that irregular power output from renewable sources such as solar can push the voltage beyond the permitted threshold [61].

On security concerns in TES, the act of cyber attackers can cause bid manipulation during energy trading, theft of surplus energy, and injection of false data to disrupt transactions [10]. These acts of sabotage by cybercriminals can cause damage to TE networks. Hence, a need for robust security measures to avert cybersecurity threats. In TES, the DERs installation demands huge investments (time, money, and labour), which impedes its complete adoption. Additionally, the challenge lies in integrating a growing number of DERs into the system while maintaining energy balance [42]. Another challenge is that renewable energy generation frequently varies according to environmental conditions. For instance, wind turbines only produce electricity when the wind blows at a serviceable speed, while solar panels produce less energy on cloudy days. These interrupt the planning process, thereby making the integration of sustainable energy challenging. Another barrier is the device communication across the network, as shared data must communicate with one another to carry out autonomous computational tasks. Standardization in TES is also essential in the design and development of its infrastructure as it could be confusing if entities are allowed to operate using different protocols. These limitations seem impossible to attain but can be achieved using a BT-based decentralized approach. The features of BT can, however, facilitate the resolution of these challenges to enhance the economy and improve the SW of consumers.

2.3. Why the choice of BT in TES?

The choice of BT for TE has led to remarkable development, as it permits non-trusting agents to transact energy services in a suspicious energy market [40]. In BT, alteration, modification, and removal of stored data is difficult, as all network participants have records and history of all transactions [62]. A secure DLT enables information sharing in a distributed pattern and eliminates the need for third-party and central data storage arrangements. The TE structure has a distinctive decentralized design that enhances the bidirectional distribution of generated energy, in sharp contrast to the centralization of the legacy grid system [63]. The legacy grid approach in power systems is ineffective, expensive, and prone to outage during disasters, as a fault in one component of the power infrastructure leads to concomitant failure. The BT in TES allows for more detailed tracking, measurement, and monitoring of small energy production and consumption than was feasible. The technology offers utilities new opportunities to reduce energy use at various times and shift loads from one part of the day to another. The BT answers practical questions on how to put mechanisms in place to reward or incentivize prosumers and to track the transactions of amounts of total energy consumed or generated and the amount willing to give back to the grid. It allows a transparent way to elevate trust in the entire energy system while removing the bottlenecks experienced in centralized systems by facilitating the communication processes across decentralized nodes.

Furthermore, the TES framework connects industrial, commercial, and residential consumers with Energy Storage Systems (ESS), utility grids, RES, and other technologies, such as smart meters. The scalable feature of the TE platform is essential and allows for physical equipment and virtual assets integration (such as mobile energy management apps) in a decentralized environment. These platforms enable customers to optimize their energy usage, track energy data, and control their appliances. In a TES arrangement, participants have devices that arbitrate when there is availability of excess energy and complete transactions. This energy trading system can be facilitated by integrating SCs to collate energy requests and calculate prices based on market algorithms for fast and efficient transactions.

The prospects of TES include reducing barriers to grid access. It has features to accelerate innovation in the energy sector, minimize the cost of renewable energy investments, and encourage broader participation in the DER market [64]. Additionally, it can support grid resilience and stability, foster LEM, support carbon emissions from power generation (combating climate change), and enhance economic efficiency.

3. Problem context on energy pricing models: commonalities, differences and drawbacks

The exponential increase in energy demand will expectedly induce more frequent system disturbances, especially during peak periods, with a corresponding increase in electricity tariffs. Energy consumption must be cut back due to the hike in energy prices and demand. Researchers have essentially proposed various energy management systems (EMS) to regulate the energy usage of high-demand appliances by scheduling/transferring their operations to off-peak hours when energy is cheaper [3,65,66]. However, this approach violates, disturbs, and disrupts consumers' comfort. Experts have developed various strategies, primarily on demand-side management (DSM), to achieve a desired change in demand profile and mitigate the effects of this demand on the networks [67]. The DSM techniques, such as valley filling, peak clipping, load shifting, strategic conservation, strategic load growth, and flexible load shape [11]. These strategies aim to delay the urgent need for new generating power stations, transmission, and distribution networks while simultaneously lowering the cost of providing customers with efficient energy and minimizing the impact of meeting this demand on the environment.

The two conventional ways of managing the energy deficit adopted by countries include [34]

i. Generation side: the development and utilization of RES (solar energy, hydroelectric power, and geothermal energy). This is done by giving liberal consideration like taxation, tax credits, investment funds, technology, and other means, which have been made possible.
ii. Consumption side: Countries encourage energy conservation to lower consumption (reduce demand), increase energy efficiency (smart energy utilization), and impose stringent laws, regulations, and administrative procedures to incentivize specific businesses and areas to cut back on energy use.

The remaining part of this Section extensively discusses the current state of work on energy trading and other relevant areas for research purposes. It outlined issues surrounding the methods, commonalities, differences, and drawbacks of existing literature on energy pricing models. Some of the research includes the one showcased by Xue et al. [34], where information obtained from the present state of development of the energy finance markets was used to create an option contract model based on a renewable energy price index (REPI). The author selected the daily electricity price value from the Nord Pool exchange system from January 2017 to August 2019 (973 days data) to create a REPI. The researchers used an auto-regressive integrated moving average (ARIMA) model to predict the price index and to determine the model's parameters. The Monte Carlo simulation pricing for electricity price index options was carried out, and the relative error was computed by comparing the true and forecasted values for Nord Pool for September 2019. From the outcome, the authors concluded that the design of the option contract for the REPI was reasonable. In addition to the Monte Carlo simulation, pricing being realistic and useful, the ARIMA model properly anticipated the REPI. The REPI option contract is a useful tool for investigating the diversity of the energy financial markets and advancing RES utilization globally.

A classical reinforcement learning (RL) algorithm, Q-learning, was utilized to design a distributed online learning algorithm to address the challenge of collecting accurate information from consumers [68]. The researchers developed a bi-level stochastic model for real-time pricing (RTP) within the Markov Decision Process (MDP) model framework, without necessarily obtaining the transition probabilities. Ref. [3] proposed a dynamic (5-min) HEM algorithm to minimize the total energy cost from the grid while improving consumers' comfort in residential apartments. The technique was demonstrated through simulation and experimental studies, which illustrated the efficiency of the presented HEM algorithm in regulating energy sources and load dynamics under time-dependent renewable generation and energy prices. Saha et al. [40] introduced an Electron Volt Exchange architecture with distributed protocol features (for pricing and scheduling prosumers' production/consumption) and for constraints and bid privacy protection. Additionally, a distributed procedure was introduced to detect theft using grid sensors or smart meters' data to confirm prosumers' compliance with planned transactions and mitigate the effects of FDIA. The authors, through simulation, employed Hyperledger Fabric to establish the adaptability and robustness of the method. The drawback of the approach is that market mechanisms and verification algorithms were not implemented.

The developed concept within contemporary power architecture enables the bi-directional flow of electricity and data among peers within the electric grid [11,52]. Two-way power flow is essential in TES to allow prosumers or local RES providers (ESS, wind turbines, and solar PVs) to sell surplus energy to the grid [67,69]. ESS can potentially facilitate the use of RES and support grid services. For instance, power loss minimization, load shedding, and boosting voltage profile across the electrical grid [70]. Furthermore, two-way power flow eases the implementation of various electricity rates/charges/tariffs offered by power utility companies. Conversely, connecting the supply and demand sides can only be realized through two-way communication between consumers and electricity utility companies [71]. Two-way or bidirectional communications support information exchange through the communication channel using wireless transmission technologies.

The blockchain network with a permission feature was presented for LEM participants using the open-source Hyperledger Fabric platform [4]. The numerical evaluation was conducted to ascertain the model's suitability for real-world applications in the design of auction-based LEM. Additionally, the authors offered insights into selecting parameters during market infrastructure planning and the daily operations of LEM. Mazidi et al. [72] propose an Information Gap Decision Theory-based EMS for optimal heat and power scheduling in LEM. The authors evaluated the effectiveness of the proposed EMS within a University community in Sweden and found that the hosting capacity can exceed 70 %. LEM classification was determined on the market participants, considering the physical layer, ICT layer, and market mechanism [73]. A non-cooperative game method was proposed to design an energy-based consensus protocol aimed at minimizing energy consumption using BT to enhance effective distributed energy trading (DET) from an incentive perspective while ensuring system security [74]. One system was proposed to increase the utilization of renewable energy for both industry and human consumption while appropriately lowering the energy costs associated with implementing BT [11].

A mathematical model was introduced to secure sharding-based blockchain protocols: Zilliga, OmniLedger, and RapidChain in [75]. This was done to assess the failure probability of the smaller protocols. The model's suitability was validated through numerical and comparative analyses, employing three probability bounds: Chebyshev, Chvátal, and Hoeffding. A framework was designed for a TE market, based on DLT, utilizing blockchain attributes to validate energy market mechanisms such as integrity, data security, scalability, and resilience management [13]. The framework was evaluated in real-time under a 5-minute double-auction energy market structure. A deep learning approach- a deep Stacked Auto-encoder -was proposed for detecting cyberthreats in the energy market to assess bid price and quantity alteration. The results indicated that manipulating the generated energy quantity and bid price influences energy locational marginal price and overall load demand [14]. The Nash bargaining game approach was presented for an integrated DET platform in [76], while a blockchain-based joint auction framework was proposed in [77], and a decentralized energy transaction system framework using BT and a double auction trading Mechanism was presented in [78]. Rasheed et al. [79] investigated the application of BT in addressing environmental and economic sustainability challenges. The researchers used a random sampling technique to collate data from 184 small and medium-scale enterprises in Peru, and a Positivist approach was used to implement the statistical induction technique. Table 2 summarizes the literature review highlighting the methods, results, commonalities, differences, and limitations.

4. Methodology for the systematic review

The methodology employed in this review is systematic and follows an organized approach to identify, sort out, and assess related articles on blockchain-based energy trading in TES. Consequently, this research adopted the PRISMA-2020 approach to analyze relevant articles in solving identified challenges associated with energy trading in a TES platform. PRISMA is a systematic review guideline (with a 27-item checklist) designed to assist systematic reviewers in transparently disclosing the authors' purpose of the review, the actions taken, and their findings [80]. It gives a transparent, complete, and accurate report of why the review was done, what was done, and what was discovered. The merit of a good systematic review depends on what was done, what was found, and the clarity of reporting [81]. Notwithstanding that PRISMA was originally developed to analyze research in health-related fields. However, it is now being broadly adopted in other disciplines. According to [82], the systematic review framework is classified into

Table 2
Articles on energy trading models in TES: commonalities, differences, and drawbacks.

Ref	Scope	Methods	Results	Commonalities and Differences	Drawback(s)
[34]	Design an options contract model based on a REPI using energy derivatives to advance sustainable energy development and cushion energy deficit, .	Auto-Regressive Integrated Moving Average (ARIMA)	Findings demonstrate ARIMA model was capable of forecasting and predicting the future trend of the REPI.	A comparison was made between the predicted results with the real REPI data using Monte Carlo simulation prices, which yielded robust and accurate predictions.	Consideration was not made for trading volume during the indexation process.
[67]	Efficient optimization of energy usage by exploring the impact of multiple users and load priority (MULP) in lowering energy expenses and energy usage.	Combining the MULP algorithm and the RTP pricing model with IBR pricing leads.	The technique led to notable drops in user fees and overall energy consumption during peak periods.	Compared to [34], they both considered the reduction of environmental pollution.	The authors failed to establish a trade-off between reducing energy costs to the overall consumed energy.
[88]	TE-bilevel trading framework	Nash bargaining theory, through the bargaining problem decomposed into two sub-problems	Numerical evaluation was validated on a modified IEEE 33-bus distribution system to establish the effectiveness of the proposed architecture.	The Energy Hubs have a relatively marginal impact on the load distribution for the entire network.	Algorithm does not accommodate enhancing the calculation efficiency.
[71]	Dynamic pricing model in HEMS for forecasting energy consumption based on historical data.	Three algorithms: PSO-regression vector machine (PSO-RVM), PSO-SVM, and back propagation neural network (BPNN).	Users' yearly electricity costs, RTP outperformed MEP and TOU. The PSO-RVM-based forecasting model exhibits low error, establishing its suitability in predicting short-term load.	The research considered HEMS but differed in the pricing scheme type. Ref. [3] uses RTP alone while [71] uses RTP, ToU, and MEP.	
[89]	Dynamic energy pricing (DEP) with the outlook of maximizing SW	Distributed gradient projection iterative algorithm	The presented energy pricing algorithm shows good convergence and availability, guaranteeing a convergence between the energy supplied and energy demanded for each time slot.	The approach is similar to what was presented in [90] in terms of consideration for the utility function but differs in applying BT to reduce human interaction in the energy market.	RES and the energy network constraints were not considered in the proposed model.
[32]	DEP Strategy.	Bi-Level Game Model between environmental and economic factors.	The proposed technique minimizes the planning cost and optimizes the power load curve, which helps to enhance RES utilization.	Stackelberg Game was adopted to establish Nash equilibrium as recorded in [33].	The authors failed to quantify the planning cost reduction and the profit maximization.
[91]	Day-ahead energy pricing in a regional integrated energy system	Bilevel Stackelberg game optimization model	The upper layer of the model was successfully applied to maximize the profits of EP while the lower level was utilized for cost minimization of EC.	The comparative analysis demonstrates that multi-energy DR implementation enhances the economic and collaborative performance of IESs and reduces the carbon footprint.	The authors failed to consider the competition and cooperation of different EPs and the effect of several ESPs on the efficiency of energy transactions.
[40]	Secure distributed ledger for TES	Electron Volt Exchange blockchain evaluated on IEEE-141 radial bus system.	A secure mechanism for pricing validates the economic transactions via a distributed consensus procedure.	The application of the Byzantine protocol makes reaching consensus difficult compared to PoW protocol.	The authors do not consider Hyperledger Fabric features like idemix and SC packaging
[92]	Optimal energy pricing for consumers through comparison of real-time pricing with ToU pricing and fixed pricing	Interval optimization technique to pool market price uncertainty modeling for improved energy scheduling	The deterministic approach shows the retailer's average profit in real-time pricing and ToU.	interval approach in comparison with the deterministic approach, slightly reduced average profit	The interval approach decreases average profit by 3.48 % for the real-time pricing.
[33]	Pricing strategy for a multi-energy provider in an integrated DR (IDR) arrangement.	Stackelberg game-based bi-level programming model	The IDR-based energy optimization manages multi-energy loads, minimizes the contemplated energy cost, and enhances MEP's benefit by 12.29 %.	Similar in terms of energy pricing strategy but differ in the application of the strategy in DR compared to TES.	It is necessary to probe its application in the TES energy trading market.
[68]	A bi-level stochastic real-time pricing model in a multi-energy generation system.	An RL algorithm in the framework of MDP	Findings show that the suggested pricing strategy and algorithm performed better in realizing peak shaving and valley filling.	The proposed real-time buyback pricing (RSRB) is compared with two conventional pricing thresholds and has the smallest peak-to-average ratio.	Need for the enhancement of pricing efficiency in the stochastic generation system failure scenario.

five parts: scoping, rapid, narrative, meta-analysis (PRISMA class), and mixed methods. The choice of the PRISMA framework over other systematic frameworks was based on the principle that it offers deep insights into the rationale for the review and wide acceptance in the research community, and enhances clarity, quality and transparency of the study [83,84]. It facilitates effective reporting of systematic reviews, preserves the standard of reporting [85]. It bettered the quality of systematic reporting [86] and it contributes to the quality assurance of the review [87].

This study adopted a research design involving a search method to identify the articles to be reviewed in solving a specific research problem. It includes a systematic review of the article's contents for analysis and synthesis. The PRISMA-2020 expanded guidelines were used to identify key publications on TES (fundamental keyword) "BT" "DLT" and "P2P" (Primary keywords) and "energy trading" (secondary keyword). The literature search was carried out in scientific databases, following the guidelines with slight modifications. The following Boolean search queries/strategies that were used include: "Blockchain Technology AND DLT", "Prosumers NOT Consumers", "TES AND Energy Trading", "Dynamic Energy Pricing OR Energy Market", "P2P OR Decentralized Transactions". The operator AND returns documents containing the two search terms, while the OR operator uses a Boolean search string to search for papers related to the specified two terms. The NOT operator excludes specified terms from the search results.

4.1. Data sources and search strategy

In a move to identify the key publications on the application of BT in energy trading for TES, a literature search was performed on scientific databases following the procedures outlined in the PRISMA 2020 guideline. The selection covers mostly scientific Journals and a few Conference articles from the IEEE Xplore, Science Direct, Springer, MDPI, Wiley, and Taylor and Francis databases. The TE, Energy Trade, Blockchain, and DLT search string was applied to ensure relevant papers for the review. Initially, the review identified 275 potentially relevant publications, and duplicates were removed after analysis based on titles, keywords, and abstracts. Furthermore, References to the selected articles were checked to find papers suitable for the work. After the selection process, 113 publications were selected. After completing the selection process, the authors read through the publications to identify challenges associated with energy trading in TES with the primary goal of proffering cost-effective solutions for its implementation.

4.2. Eligibility criteria

4.2.1. Inclusion criteria

For an article to be considered, standards were laid. These standards include that papers must pivot on BT, P2P, TES, or Energy Trading. Also, the article must show evidence of being thoroughly peer-reviewed and must have been published in reputable journals, conferences, or book chapters. Moreover, the paper must be written in English and readily accessible online. These guidelines were based on the foundation laid in [93] and [94]. The number of articles from the database was sorted in conformity with the following sorting rules: (i) the title and duplication, (ii) the abstract, and (iii) the full article.

4.2.2. Exclusion criteria

The section provides a collection of the databases visited and the corresponding number of articles sourced from the database, of which the final 109 articles were selected (specifically for the topic area), while duplicates were removed. Emphasis was placed on the publication year, citation count, and top-cited articles. In assessing the recency and quality of the papers, authors utilized publication year as a criterion for exclusion. All the references considered are within a five-year window, except for 23 articles (14 %) included to establish the critical view of the work.

4.3. Data collection

The databases were filtered based on the subject areas and summarized the available evidence with a comprehensive, unbiased overview of the state of the art in energy trading. Fig. 1 presents the PRISMA flow diagram for the review. This was used to report the search results. The findings of this systematic review are explained with sufficient evidence to allow readers to swiftly understand the main procedures followed in reducing irrelevant articles for the review.

5. Overview of BT transaction framework in TES

DLT is a foundational component of a decentralized information system that uses protocols for accessing, validating, updating, and storing records transparently and securely across a P2P network [95]. An SC is a collection of logical guidelines or procedures that specify how an agreement is reached. An extensive discussion on SC will be found in the latter part of this section. A consensus mechanism (CM) is a decentralized process where all nodes endorse and accept the same decision [2]. Fig. 2 shows the representation of the main components of DLT, which are DL, Cryptography, SC, and CM/protocol. The DL is similar to a data structure but can only be updated through consensus received by all system nodes. Cryptography performs the security function of protecting

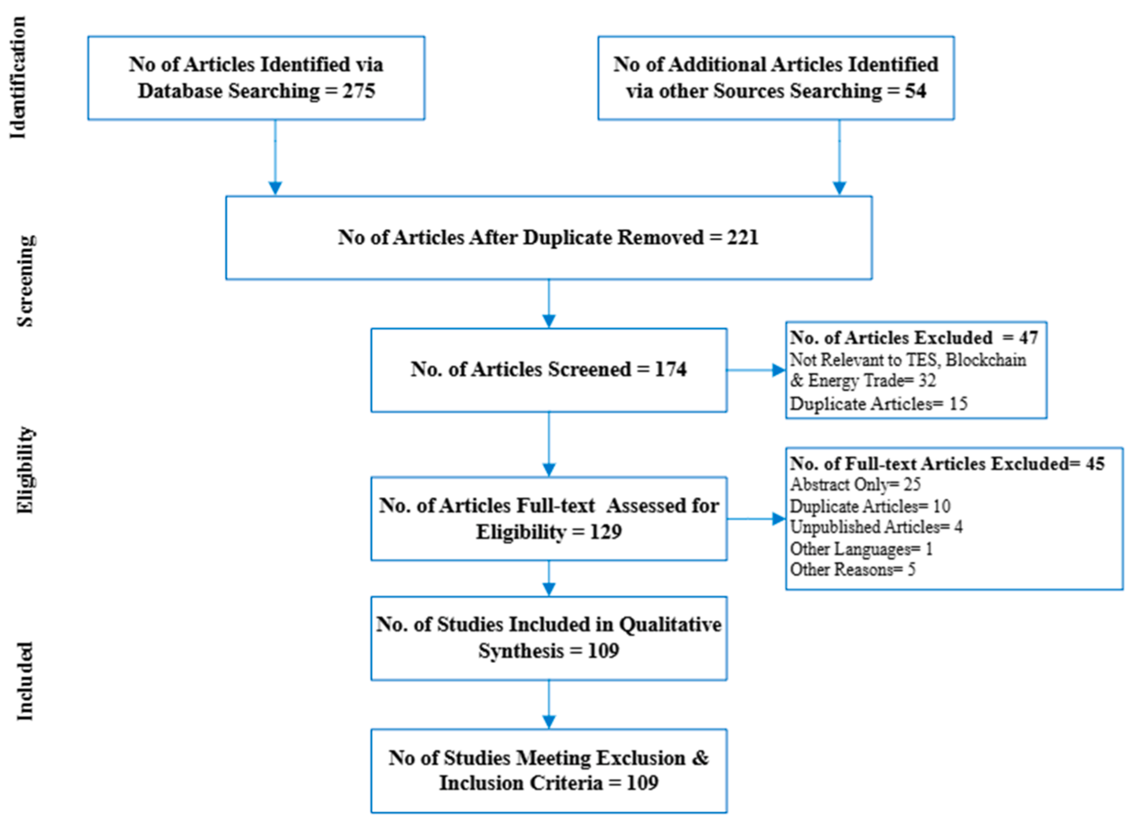

Fig. 1. PRISMA flow diagram for the review.

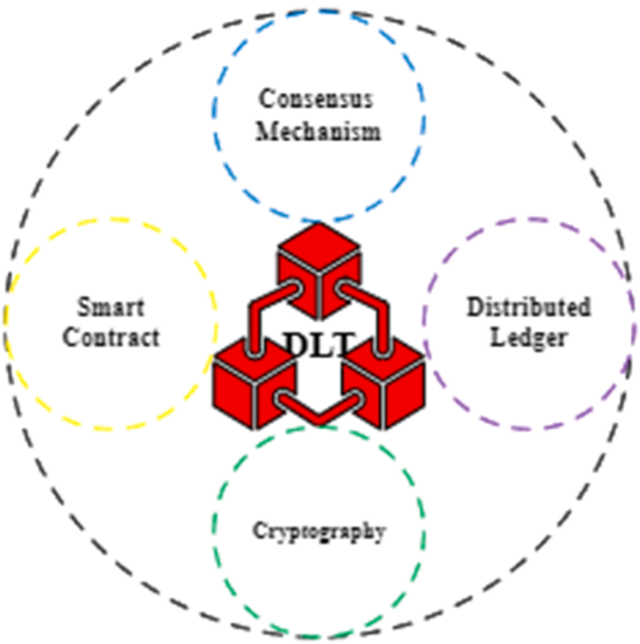

Fig. 2. Main elements of DLT.

data and information against cyber-attacks and is categorized into, symmetric-cryptography and asymmetric-cryptography [36]. This categorization is based on their secret key. Utilizing cryptography (public and private keys) for authentication and encryption of transactions on the blockchain network aids in sustaining the anonymity of the participants [96]. In symmetric cryptography, each node obtains only one secret key for message encryption and decryption. However, in asymmetric cryptography, each node obtains two separate secret keys (public and private). Other nodes utilize the public key for message encryption, while the private key is used for message decryption. In comparison, asymmetric cryptography offers better security against cyber threats than symmetric cryptography.

According to Shi et al. [57], not all DLT applications can be decentralized with anonymous users. Many still require centralized authentication, such as KYC (know your customer), for fraud prevention and regulatory compliance in financial services.

5.1. Blockchain framework

The blockchain, as presented in [39] has different kinds of layers. This includes the Blockchain stack (performs the function of 'Know Your Customer" to ensure consumers belong to the same distribution service area), Network configuration, SC design (for posting orders for the auction), Time-slotting (slot consisting of two phases; bid (BP), and reveal (RP), Data Slicing (a technique used in data analytics to extract specific subsets of data from a larger dataset), Bid encryption alternatives, and Privacy and security considerations (through encryption). The blockchain workflow is presented in Fig. 3. Under the Network configuration, Fabric networks follow permissions architecture; that is identity of the participants is known and authenticated while performing the role of Ordering nodes (assembling incoming transactions and requests into blocks and distributing them throughout the network), Peer nodes (carry out transaction proposals, verify incoming transactions, and keep the ledger up to date), and Client nodes (send transactions to the ordering nodes and transaction proposals to the peers).

5.2. Smart contracts in BT

An SC, a subset of BT, is a group of logic codes created by peers in a blockchain network and is immutable once formed or established. It is a computer protocol applied to make the execution of decentralized, automated, and secure transactions possible using if-when statements [45]. SC is a set of codes created by multiple peers in the blockchain. SCs are essential to execute back-end business logic, including user registration, transaction administration, market regulations, and payment settlement [8]. It is immutable, that is, modification of its content is impossible once it has been initiated [97]. In other words, the content can never be overwritten with the SCs and cannot be broken during the transaction. The primary reason for implementing SC in blockchain-based energy trading platforms is to automate the bidding or negotiation process, uphold the service contract's terms and conditions, sustain the trustworthiness of agents through reputation rating, and track and verify the transaction history [61,97]. The activities of participants that bring about the thrust issue involve fictitious practices where dummy/false bids are placed by a seller (agent) to create artificial scarcity with the target aim of inflating energy prices. An integrated DL and SC provide mechanisms for consensus and trust. Table 3 summarizes

Table 3
Basic procedure for SCs in blockchain [62].

S/N	Procedures	Activities
1	Contract Submission	Agreement Preparation and submission to the system Embed SCs into Blocks and add them to the blockchain
2	Control Execution	Each participants run it as a programme
3	Results Submission	Each participant is allowed to submit their result of an SC Participants of the system agree to build a block to hold the SC result Add the block to the ledger

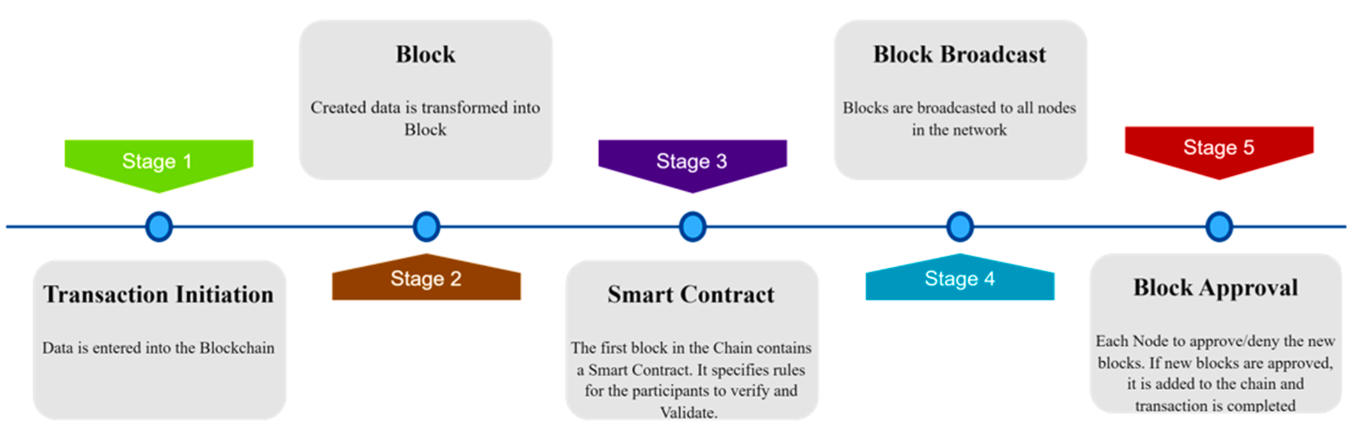

Fig. 3. Blockchain workflow.

the basic procedure for SC in BT.

In a theoretical analysis of SC reported in [45], examined the visibility of using BT to build a decentralized structure for TES. It was discovered that the approach must be critically vetted before application it to avoid creating more complexity in the transaction security through SC. Similarly, in [8], Hyperledger Caliper benchmark tool was used to evaluate the performance of the developed modular SC and it was discovered that market-agnostic design, extensive framework and energy market diversity are hinder the adoption of BT in P2P energy trading platforms. In [98], a threat-mitigating model utilizing a set of pre-defined SC to reduce processing time. There was a significant potential for system optimization since there were no intermediaries involved. The two most popular consensus mechanisms used in blockchain-based SC system, BFT and PoW (with the longest chain benchmark) protocols, to demonstrate the correctness of SC [62]. The BFT was introduced to guard against Sybil attacks through a centralized identity management system. The authors did not provide definitive answer regarding whether a specific mechanism determines correct consensus but noted that it depends on the degree of rationality possessed by the participants. Hu et al. [99] proposed an energy trading mechanism to enhance transaction efficiency using SC to address trust issues. The researchers adopted the Encourage-Real-Quotation principle to establish the clearing price, optimize security, and maximize revenue in the energy trading market. In their analysis, the proposed technique can only improve transaction security and transparency in a small-scale energy market. El-din et al. [100] proposed an architecture that integrates Digital Twin and BT to enhance the implementation of Energy performance-based contracts. The approach enhances data integrity and transaction security, but the implementation complexity remains an issue. Therefore, there is a need to explore cross-chain interoperability to address identified limitations. Ref. [101] introduced a blockchain architecture that integrates SC for improved security and efficiency in a P2P energy trading system. The developed model used an ideal Proof-of-Closeness (PoC) consensus algorithm to reduce latency and facilitate transaction efficiency for real-time energy trading. The results demonstrate an adaptability of 1.6 tps throughput, fail rates of 0.01 %, and latency of 3 s for 20 nodes. These results indicate that enhanced supply and demand stability between prosumers and consumers in an MG. Tkachuk et al. [59] evaluated the performance and scalability of CMs in a decentralized energy market using the Ethereum-based BT client Hyperledger Besu to automate the trade settlement process. The authors do not establish whether there is trade-off between performance and the system's security.

In a distributed network, such as BT, a consensus algorithm is used to achieve agreement on a value [102]. BT relies on the consensus algorithm and is typically regarded as the basis of blockchain because of its pivotal role in defining the network's security properties and efficiency, secure storage, and data integrity [103]. The lightweight consensus algorithm employs random lotteries and reputation-based voting to add new blocks to the chain [104]. The consensus algorithm comprises three segments (Proposal, Voting and Commit) [103]. The lightweight consensus algorithms (also referred to as Proof-of-Elapsed Work and Luck) can be integrated in constrained smart grid devices (smart meters and embedded devices) by adopting the Proof-of-Luck algorithm, since it is semantically similar and employs random lotteries for block proposals [105].

Summarily, it can be deduced from the reviewed articles on SC that some complexities still hamper the adoption of BT in P2P energy trading, which include the need to examine the approach before implementation in a decentralized structure critically, lack of market-agnostic design, energy market diversity and extensive framework which impedes the development of modular SC, how to reduce process time and most of the proposed approaches are only capable of enhancing transaction security in a small-scale energy market.

5.3. Energy implications of various consensus mechanisms and their suitability in TES

Consensus Mechanism (CM) is a key element of BT; it protects against cyber threats and coordinates nodes on how to come to an agreement to authenticate transactions and block unauthorized access [106]. The design of CM must be prosumer-centric to support multiple interest party optimization challenges in TES [107]. The security of a blockchain-based energy system relies solely on a proof-based consensus protocol such as CM [108]. CM is an essential component of blockchain that establishes a process by which participants agree on the behaviour of the blockchain architecture. It is used to facilitate agreement between fundamentally different interests among the participants [109]. The components of the CM are Block Proposal, Information Propagation, Block Validation, Block Finalization, and Incentive Mechanism. PoW is the most popular CM technique (first implemented in the development of Ethereum and Bitcoin). Other CMs are BFT, Proof-of-Stake (PoS), other versions of PoS (e.g., Delegated POS, Extended PoS), Proof-of-Capacity, and Proof-of-Authority [109]. The complex optimization problems linked with the decentralized power grid are imperfectly integrated into the existing blockchain applications. For instance, a distributed system does not have a perfect consensus algorithm regarding consistency and availability; hence, the need for a trade-off between consistency and availability [109].

In a day-ahead market arrangement, Proof of Inherent Intelligence CM was proposed to empower Blockchain-based TE and to facilitate an equitable energy-pool market trading system [18]. In the proposed framework, the execution efficiency for registration was 2.34 s; trading negotiations, 112.23 s; trading transaction, 42.19 s; power balancing, 17.79 s; and payment to seller, 20.12 s. The method's limitation is that it can only be utilized when the details relative to the optimization problem are obtainable. Zhang et al. [108] exploit consortium blockchain and Directed Acyclic Graph (DAG) to mitigate security and privacy challenges in large-scale P2P energy trading implementation. The authors formulated an iterative double auction-based micro-transactions scheme to address the energy pricing and the optimal amount of shared energy. Security analysis shows that the proposed spectrum-energy chain is secure for energy trading and rises with the increasing residential users' participation ratio.

5.4. Blockchain technology for TES

BT has emerged as the most effective platform for TE implementations attributable to its robust cryptographic security features and ability to withstand FDIA [110]. In the energy market, two transactive nodes engage in random-order electricity trading based on the pay-as-bid mechanism, the most popular auction structure for selling Treasury securities. The following is the operational scenario presented in [22]:

i. Random pairing of buyers with sellers in each scheduled time slot until the buyer can find a seller who can fully satisfy his electricity demand (connection with every potential prosumer),
ii. When the consumer's bid meets or surpasses the prosumer's asking price, they are paired,
iii. The consumer pays the bid price and receives the desired quantity of electricity, and
iv. When the electricity quantity demand is beyond the P2P market, it is obtained from the main grid at the grid electricity price.

In a deregulated power environment, an auction is the main pricing mechanism used in the various fragments of the energy market. Ref. [36] proposed a 7-layer TES architecture to capture the functionalities in the energy transaction operation. The layers presented are User, Network, System Operator, Market, DLT, Communication, and Regulation. Laszka et al. [111] designed and implemented a blockchain-based transactive decentralized platform, TRANSAX, for forward-trading energy exchange for resource administration, fault resilience, and security. The proposed solution encourages prosumers to trade energy without fear of compromising privacy and safety systems. Taouil et al. [51] presented a P2P energy exchange framework for Swarm electrification. The validation tests show that the approach is efficient in achieving peak shaving and minimizes prosumer production losses to the tune of 16 % for the entire PV production. Zerka et al. [112] suggested a proportional-fair energy exchange architecture in a prosumer MG setup with consideration for buyers' trading/market preferences using the Knapsack approach and the Last Diminisher protocol. The evaluation and the validation of the approach in simulation prove its efficiency in fair energy exchange.

5.5. Computing approaches for energy trading

Decentralized power systems exhibit benefits by avoiding huge investments and losses associated with long-distance power transmission through enhanced DER utilization. BT can be used to facilitate decentralized distributed computing in an energy trading environment where trust is lacking [113]. Intelligent Energy management was proposed by integrating advanced technologies (6 G IoT, AI, and BT) for grid stability in [114]. ML models (decision trees, XGBoost, Support Vector Machines) were utilized to predict load fluctuations during the peak demand periods. To enhance planning for energy consumption, the authors applied the Recurrent Neural Networks technique to examine weather data and forecast solar energy production, while BT was used to verify transactions. An accuracy of 97.99 % was achieved through the method and the P2P energy trading mechanism was reported to complement existing energy management techniques in the transition to clean energy. Ref. [90] reported that the recent advancement in cutting-edge solutions (AI, ML, and IoT) offers a dynamic interaction for power and information exchanges, thereby facilitating P2P energy-sharing and trading systems [22]. The primary aim of energy sharing is to bridge the energy demand gap within buildings in the neighbourhood excess energy from a geographically different building using RES [43].

Dynamic P2P involves energy sharing, price mechanisms, and decision-making, and collaboration among participants for mutual economic benefit [115]. Adopting an optimally designed P2P energy trading platform improves system efficiency, facilitates renewable penetration, boosts congestion management, enhances fair energy distribution, minimizes reliance on retailers, and reduces stress on the power grid [116]. P2P energy trading allows consumers to trade electricity with peers without complete reliance on utilities. It is a more stable platform for energy trade that facilitates the exchange of excess energy from the prosumers to consumers [117]. This innovation promotes the penetration and utilization of RES domestically. Tan et al. [118] adopted the scenario-based stochastic programming method and the two-settlement technique to evaluate the uncertainties from price PV output and loads to implement the energy-sharing mechanism and IDR. The obtained results show that the suggested model is economical and eco-friendly.

Transaction costs and the balance between energy trading price and the quantity of energy transacted steer the P2P energy trading platform. In addition, the P2P energy trading price depends on the excess renewable energy, demand shortfall, and the real transacted energy among peers. Similarly, the real transacted energy between peers depends on the dynamic P2P energy trading price. Hence, quantity and price-based dynamic iterations are imperative for decision-making on P2P power trading flows. TES's economic stability depends on participants' credibility [119]. Yang et al. [29] presented an energy trading model using a two-level pricing mechanism to determine the energy trading price. The authors further enhanced the P2P market quality through a credit rating system (CRS) to prevent malicious operations while the traders' data were secured using a blockchain framework. The CRS mechanism is a system designed to secure the legal behaviour of participants or peers for an optimal energy trading environment. That is, traders with good behaviour have the highest CRS score while those with bad behaviour have decreased scores or points and may be denied access to offers.

Mussadiq et al. [120] applied behavioural control theory and psychological models to facilitate prosumers' participation. The researchers used a Norm Activation Theory to regulate peers' behaviour in facilitating participation while a coalition-based game theory was used to enhance trustworthiness among participants. The results obtained show minimized carbon emissions and a reduction in energy expenses. Ref. [121] proposed Large Language Models, Scikit-llm, and zero-shot classifiers appraise some specific scenarios. The authors employ different data inputs and processes to optimize energy usage and trading decisions for prosumers using ML. The researchers discovered that Predictive analytics for RES production and P2P energy trading platforms are essential in improving financial and environmental efficiency. Raza et al. [117] developed a P2P energy trading model using a robust forecasting and scheduling framework. The proposed technique involves the integration of a cluster of models: a Wild Horse Optimization model for the summarization of the quality of the historical records, a Bi- Long Short-Term Memory (LSTM) technique for the prediction of the demand and generation values, and a Grasshopper optimization algorithm for the enhancement of the model's hyperparameters. Niaei et al. [35], Proposed a P2P-TE sharing architecture using smart demand response programming under uncertainty and line outage contingency. The results obtained from the proposed technique reduce the price of consumed energy (9.86 %) while maximizing the owners' revenue (9.86 %). Fig. 4 represents the framework for BT-based P2P energy trading.

5.6. DLT for decentralized transactions

The P2P energy market is the technique of trading energy without the intervention of intermediaries, to improve the power systems' reliability [27]. It enhances the smooth integration of microgrids (MGs), lowers corruption, increases transparency, and provides a payment platform for energy trading. The blockchain-based P2P market enables energy trading through SC to post auction orders for energy transactions that are instant, automatic, and robust trading [98]. It is a direct mechanism for energy trading amongst prosumers. Prosumers are consumers with the capacity to produce energy through small-scale DERs and trade their excess to their peers during peak periods to recoup portions of their investment [31]. However, it cannot be used without a software platform, facilitates P2P information sharing, and helps system managers monitor and manage the distribution network [122]. Hence, BT integration in designing the P2P platform for energy trading. A blockchain aid decentralized market platform that permits participants within the electricity network to directly enter the market and swap energy with other participants without supervision from a centralized entity.

DLT is a safe technique for transferring and documenting digital assets without requiring a central authority. It is a distributed system that allows the sharing and synchronization of the ledger between participants within a network. Transactions in DLT are done in a way that is cryptographically linked, secured and accessible to all participants in almost real-time. This DL means that each node has a duplicate of the transactions from other nodes. The most popular DLT is the Blockchain, which is widely used for cryptocurrencies such as Bitcoin [19]. While not all DLTs are Blockchains, all Blockchains are DLTs. Other types of DLT include Hashgraph, Holochain, Tempo, and DAG [123]. DLs do not require the introduction of a trusted authority; instead, verification of transactions is via a consensus protocol, and the transaction block is cryptographically linked to the previous block. and any alteration will notify other users [124]. Once users have reached a consensus over the history, they can proceed with a fresh transaction. Based on access and authorization, DLT architecture can be classified into permissioned and permissionless [125]. In authorized ledgers, transactions are through

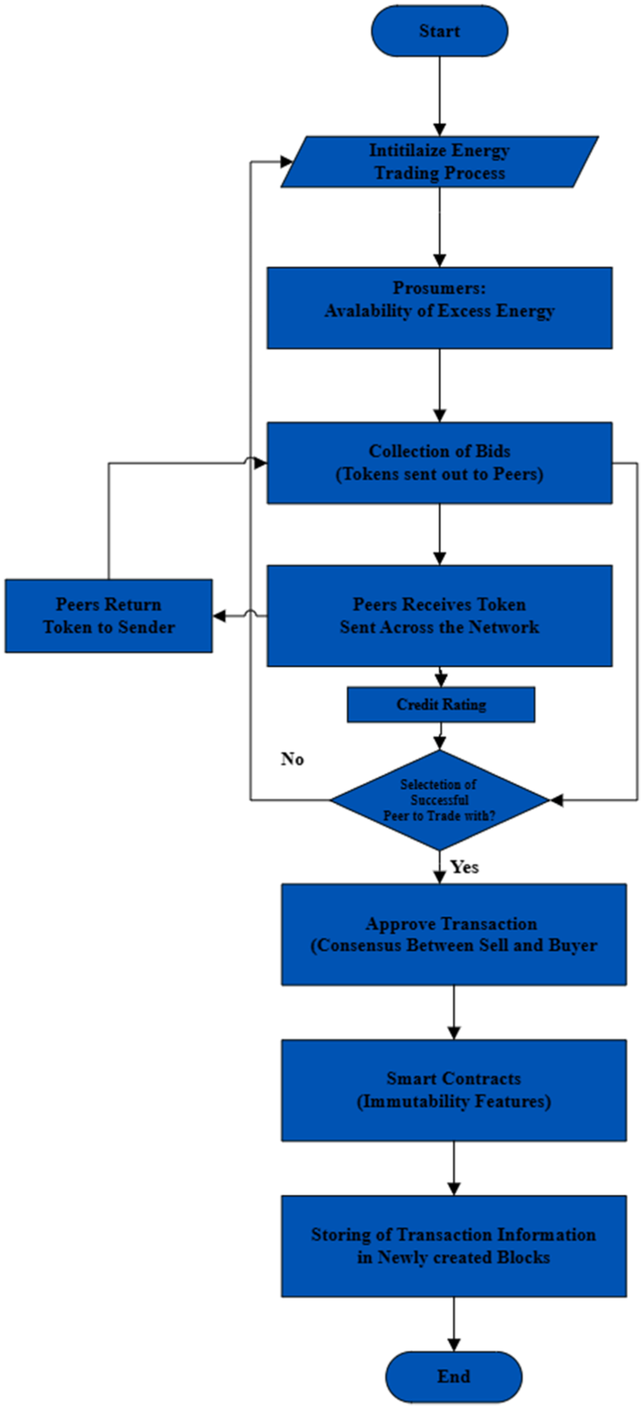

Fig. 4. BT framework for P2p energy trading.

trustworthy users only (which may or may not be made public). An example of this is Hyperledger Fabric. Unauthorized ledgers permit all participants to perform transactions; these types of ledgers are public. Examples are Ethereum, Ripple, and Litecoin. The use cases of DLT are cryptocurrencies, which represent digital representations of value.

6. Decentralized energy trading in BT-based TES: market, pricing, mechanisms, and associated complexities

The decentralization of energy trading arrangements gives more access to electricity at reduced costs or tariffs [115]. To calculate the energy price, emphasis is first placed on the capital investment expended on the RES installation. The estimation considers the highest price for a unit of energy since the investment capital varies. The expression for the calculation is expressed in [22] as:

$$IB = \frac{CI + IC + MC}{AV_{PG}} \quad (1)$$

6.1. Blockchain-based TE market

TES offers market-based control and coordination techniques to harness DERs to perform grid support functions [16]. In TES, value exchange is the mechanism used to facilitate energy flow at the distribution layer, enhancing the commercialization of energy among prosumers in a decentralized method [126]. Although TESs are effective in grid support, there are still some underlying issues with privacy, security, and data integrity [127]. For instance, the legality of bids made by participants in the TE market is essential for effective operation. The correct implementation of pricing infrastructure is a prerequisite for customer satisfaction, as a poor energy pricing technique can lead to confusion and fallout between customers and energy utilities. Implementing a decentralized TES requires transactions between participants in the network to be executed swiftly while maintaining a high degree of data security [45]. A robust energy pricing system should incorporate segments such as time of the year, time of the day, and consumption choice. This approach is better when compared with the conventional electricity rates, which are time of use, critical peak pricing, variable peak pricing, and real-time pricing [26]. Blockchain's features of immutability, distributed consensus, and cryptography make it a reliable method for protecting availability, confidentiality, and data integrity in the TES energy market. Similarly, a Deep RL-assisted Stackelberg Game algorithm was utilized for a blockchain-based framework to secure the energy trading market [128]. The researchers employed a single-leader, multi-follower Stackelberg game approach to resolve the energy trading challenges among the electricity market and EV charging operators. The authors further recommended incorporating a pruning technique to optimize its computing power efficiency. The limitation of the approach is that it only considers a single leader while neglecting the multi-leader Stackelberg game approach. Both methods are economically efficient in the researchers' theoretical evaluation of the auction mechanisms.

6.2. Dynamic energy pricing (DEP) strategy

In the work of Yang and Liu [33], Stackelberg's game theory approach was applied to the pricing strategy of a multi-energy provider (EP). The authors developed a bi-level programming model to achieve game equilibrium and obtained MEPs for the third scenario, thereby achieving a 12.29 % reduction in energy prices for residential users. Lin et al. [32] considered a double-level game model for DEP strategy to improve energy utilization efficiency. Comparing the approaches of Refs. [33] and [32] employed the Stackelberg Game theory (bi-level model) for their DEP strategy, but differed in the targeted beneficiary of their applications. Where the first focuses on multi-energy providers and residential users, the latter focuses on the operators and payoff users. Ma et al. [89] investigated DEP for community IES. The authors presented a distributed gradient (projection iterative algorithm) to determine the participants' dynamic energy prices and optimal operation strategies. The proposed energy pricing algorithm was to influence the stability and convergence of the system. Ref. [129] probes P2P multi-energy scheduling and trading using dynamically updated loss factors for a decentralized electric-heat system. Ref. [41] presents a dynamic pricing framework to manage congestion and voltage issues in distribution networks. Also, the TES concept was used to manage network constraints. The results demonstrate that the allocated incentive is a function of energy prices. Wang et al. [130] designed a bi-level bidding model (the upper level is the optimal decision-making, and the lower-level is the distribution market-clearing) to form alliances through the cooperative game. A 7.3 % revenue enhancement was achieved through the alliance.

Zhang et al. [68] presented a bi-level stochastic real-time pricing (RTP) model (a modified dynamic pricing approach) using the RL technique in a multi-energy generation setup. RL was used to learn and extract the best operational information from historical data via continuous interaction with the system environment. The researchers evaluated the performance of the proposed real-time selling and real-time buyback pricing (RSRB) pricing strategy with two other conventional pricing thresholds: real-time selling with flat buyback (RSFB) and flat SFB (FSFB) pricing. The results show that the proposed pricing technique has the smallest peak-to-average ratio, reducing the average payment for every user in each time slot. However, it can be observed from the obtained results that FSFB generates a better average profit for the power plants and SW in every time slot. The proposed RSFB model minimizes the average payment of every energy user in each time slot to $8.51 compared to FSFB with $8.67. The research limitation is that the authors failed to investigate how to enhance pricing efficiency, stochastic generation system issues, or generation forecast errors.

The reviewed articles show that the Stackelberg game model is a widely used approach for DEP. In energy trading, DEP is a type of energy tariff that changes hourly in a day-ahead energy market (DEM), allowing energy buyers and sellers to agree on prices and quantities of energy a day before delivery. Hence, the next Sub-section establishes a nexus between DEP and the Day-ahead energy market.

6.3. Day-ahead energy market

In energy markets, the day-ahead energy system is crucial to stakeholders in facilitating performance. In the arrangement, participants are allowed to bid for energy based on the concepts of self-utility maximization, where the system manager determines an energy pre-allocation for the operating day and charges the participants [131]. Participants who default day-ahead commitments are penalized by incurring fines [132]. Ref. [133] utilized a Convolutional Neural Network (CNN)-based LSTM learning model to enhance day-ahead electricity prices. The proposed multi-dimensional approach of the model facilitates robustness and prediction accuracy. The authors applied the Ensemble learning technique to minimize the uncertainty features of neural networks, enhancing prediction accuracy. The model achieved performance metrics of R^2 (0.787), MAE (1.936 JPY/kWh) and RMSE (2.630 JPY/kWh) within a month (March 2023). Zhu et al. [91] considered day-ahead energy pricing and management techniques under multi-energy DRs for regional IES. The researchers applied a bilevel Stackelberg game optimization technique where the upper level considers profit maximization for the EP while the lower-level deals with cost reduction in EC. Ref. [134] proposed P2P energy trading using a day-ahead optimization mechanism for real-time variations in demand and generation. The numerical results show that the proposed methods ensure energy sellers make gains during the day, for the time intervals. Energy trading in a multi-energy system was proposed to maximize SW using two auction mechanisms (day-ahead and real-time markets) [131]. The evaluation of the proposed multi-energy system's performance with real data for experimentation recorded the highest SW using both auctions (day-ahead and real-time). It was observed to be economically efficient. Also, Wang et al. [135] deployed an improved distributed adaptive robust optimization technique to minimize social cost in a TE Sharing arrangement. The authors presented two settlements in the TE Market, Day-ahead and Real-time, as an incentive to stimulate participation in energy sharing. The TES was said to be tested using 1000 scenarios to validate for high efficiency, robustness, and prevention of uncertainties. A three-stage optimization technique was proposed for EV-integrated MGs for P2P transactions [136]. The authors transformed the problem into three sub-problems using Lagrangian relaxation. The approach demonstrates a reduction in operational cost and enhancement of economic efficiency for the participating MGs in P2P transactions.

In summation, researchers used CNN-LSTM to enhance day-ahead pricing, the Stackelberg game optimization technique and the optimization mechanism under a real-time variation approach for day-ahead. In terms of similarity in technique, Ref. [131] and [135] combination of day-ahead and real-time actions. The former used the technique to maximize SW while the latter used it to stimulate participation in energy sharing to minimize social cost. In the energy market, MCP is important in forecasting the balance between energy demanded and energy supplied, which depends on weather conditions and economic activity. Based on this premise the next section will make clear the importance of MCP to TES.

6.4. Market clearing price in TES

The MCP is the price at which the energy demanded matches the quantity supplied in the day-ahead market. In TES, energy trading and sharing is done by finding market equilibrium at MCPs using bids and offers [127]. According to the study presented in [6], classified market-clearing techniques for a TES into (i) distribution locational marginal pricing (DLMP), (ii) auction, and (iii) game theory techniques. DLMPs hang on the participation of an independent system operator such as a Distribution System operator while auction-based technique requires a bidding process to obtain the participants' information. The game theory-based requires knowing the participants' preferences to determine the payoff functions. The auction technique was further grouped into single-auction and double-auction. Yu et al. [137] presented a pricing strategy for maximizing profit using the Ethereum blockchain in a multi-energy system. The authors compared and evaluated three pricing strategies: zero intelligence, inverse production, and game-theory pricing. According to their reservation price, identifying the amount of energy that can be traded, the demand and supply are sorted based on their reservation prices. Furthermore, determining the MCP involves consumers' bids for energy. Consequently, the MCP price is picked to maximize the amount of tradeable energy [39]. The coming to light of prosumers necessitated the creation of a trading platform to allow participants to exchange energy among participants [31].

6.5. Mechanism for matching prosumers with consumers for P2P-TES

Prosumers in the blockchain-based energy distribution market transmit tokens to consumers or participants in exchange for energy. Therefore, a mechanism is necessary to match the producers and consumers in a TE energy arrangement and is done in advance to permit the scheduled power transfer. There are three major stages in the trading operations: finding compatible offers, matching buying offers to selling offers (which may be automatic or by each consumer), and energy transactions and financial transactions (which are handled later) [111]. The diagram presented in Fig. 5 describes the mechanism for matching prosumers with consumers in TES architecture. However, the limitation observed from the Figure shows that the approach is not price-driven, and Prosumer N was not incentivized for shifting time slot allocation. The authors are of the view that there should be compensation for having ESS.

Furthermore, an optimum P2P energy trading aids energy efficiency, minimizes energy wastage, and reduces dependencies on the grid through TE [134]. Internal trade pricing strategies or mechanisms in a P2P arrangement were classified into (i) supply-to-demand ratio (ii) mid-market (iii) bill sharing, and (iv) auction theory-based pricing bargaining mechanisms in [138]. Similarly, Mussadiq et al. [120] classified P2P energy trading models into auction-based, bilateral contract-based, and decentralized blockchain-based models. According to Sun et al. [139], various vital parameters must be considered in P2P pricing mechanisms. Ignoring these elements will result in inaccurate pricing that either overestimates or underestimates the financial gains

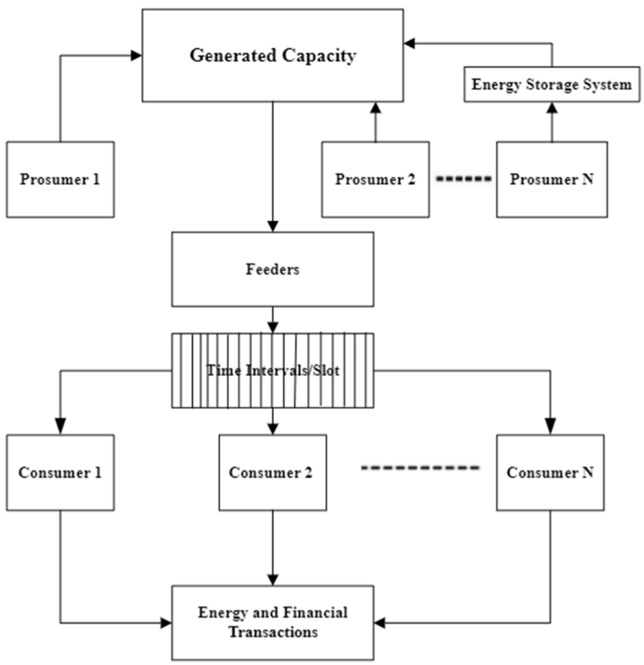

Fig. 5. Mechanism for matching producers with consumers.

for each participant. These factors include the depreciation of renewable energy systems, transmission loss, associated infrastructures, and battery degradation/cycling aging. The battery cycling aging has been linked to the electrode's active materials deterioration, changes in the electrolyte, and the formation of an insulating layer called the solid-electrolyte interphase. Ref. [4] proposed a hierarchical P2P energy trading model integrated with an energy management strategy for multi-microgrid systems. This was done to identify efficient and effective results in the energy trading market. A blockchain-based electricity trading platform was designed for prosumers with Electric Vehicles [113]. The designed system architecture facilitates a P2P energy distribution solution, focusing on operating a decentralized network to incentivize energy generation and distribution participants. A P2P energy trading model (Decentralized Multi-Criteria Ranked Prosumers) was introduced to address the privacy and security challenges of participants' data in energy trading [58]. The validation and verification of transactions were done via DLT's consensus.

Wang et al. [88] designed a reconfigurable multi-carrier energy system for TE trading. The author applied the Nash bargaining theory to decompose the bargaining problem into two sub-problems, to minimize computational complexity. A distributed transaction system has a wide range of participants. The proposed system's participants include general users (GU), ESS, MGs, and main-grid (PG) users. The GU is free to issue power purchase requests to the market, while ESS can flexibly act as producers or consumers according to their actual conditions. To realize profits in the energy market, the main grid will charge the ESS at night and sell at a higher price during the day. Also, the grid/utility may opt not to purchase energy from ESS if the price it sells to the energy market during the day is higher than the electricity price sold through the utilities. The variables for all the equations in this article are defined in Table 4.

In a foundation laid in [31] for the designed transaction model for the SW, maximization is expressed with the following equations (where welfare is the difference between the benefit and the cost)

$$Max_{P_b,P_d} \sum_{n=1}^{L_b} \gamma_{b,m} P_{d,n} - \sum_{m=1}^{L_d} \gamma_{d,m} P_{d,m} \tag{2}$$

Table 4
Description of symbols and variables for mathematical formulations.

S/N	Symbol	Variable	S/N	Symbol	Variable
1	$\beth_L{}^{su}/\beth_L{}^{sl}$	Time preference interval for Upper/Lower limits	19	$P_{sp,g}(t)$	Natural gas retail rate
2	$\gamma_l{}^s$	Working Period Demanded	20	$P_{ep,e}(t)$	Retail electric power
3	$M^s_{L,t}$	Shifted Load	21	$P_{ep,h}(t)$	Retail heat power
4	T^{hw}_t	Temperature of Hot Water	22	$P_{so,g}(t)$	Wholesale natural gas
5	T^{cw}	Temperature of Injected Cold Water	23	$P_{sp,g}(t)$	Retail natural gas rate, e(t)
6	$H_t{}^{hw}$	Heating Energy (to heat water)	24	$P_{so,e}(t)$	Electric energy wholesale price
7	$\delta^w/\ \varphi^w$	Density/ Specific Heat Capacity of Water	25	$P_{so,g}(t)$	Natural gas wholesale price
8	θ^{cw}_t	Injected Cold Water Volume	26	$P_{ee,es,min}/P_{ee,es,max}$	The lower/ upper limit of the electric energy rate
9	θ^w	Hot Water Storage Tank Volume	27	$\gamma_{b,n}$	Quotation for General (GU) users in $\boldsymbol{n^{th}}$
10	Υ^{air}	Air-Specific Heat Capacity	28	$\gamma_{d,m}$	Quotation for Energy Storage System (ESS) users for $\boldsymbol{m^{th}}$ ESS
11	$H_t{}^{in}/H_t{}^{out}$	Indoor/ Outdoor Temperature	29	$\gamma_{f,k}$	Quotation for Microgrid (MG) users for $\boldsymbol{k^{th}}$ MG
12	R_t	Thermal Resistance	30	$\gamma_{p,i}$, $\gamma_{p,j}$	Electricity prices from the Utility Grid during the day and night
13	$E_t{}^{in}$	Provided Cooling	31	$P_{d,n}$, $P_{d,m}$, $P_{f,k}$	Winning Scalar of the $\boldsymbol{n^{th}}$, $\boldsymbol{m^{th}}$, and $\boldsymbol{k^{th}}$ users
14	ω^r_t/C^s_t	Parameters of Cost Function	32	L_bL_d	Number of GU and ESS, respectively
15	$E^r_t/(E^s_t)$	Electricity Supplied/ Power Purchased from Integrated Energy	33	$P^{max}_{b,n}, P^{max}_{d,m}$	Maximum trading quantity for $\boldsymbol{n^{th}}$ and $\boldsymbol{m^{th}}$ users
16	$G^r_t/(G^s_t)$	Gas Supplied/ Gas Purchased from Integrated Energy	34	$P^{bid}_{b,n}, P^{bid}_{d,m} P^{bid}_{f,k}$	Bid amounts for ESS
17	$P_{sp,e(t)}$	Electric energy retail price	35	$T_{b,n}, T_{d,m}, T_{f,k}$	Tradable power limited by the networks (maximum)

(*continued on next page*)

Table 4 (*continued*)

S/N	Symbol	Variable	S/N	Symbol	Variable
18	$P_{ep,h,min}/P_{ep,h,max}$	The lower/upper limit of the thermal energy retail rate	36	$\gamma_{m,n}, P_{mn}$	Matching Price and matching amount among users (n and m)

$$\sum_{n=1}^{L_b} P_{d,n} = \sum_{m=1}^{L_d} P_{d,n} \tag{3}$$

$$0 \le P_{f,k} \le P_{f,k}^{max} 0 \le P_{d,m} \le P_{d,m}^{max}, \text{ and } 0 \le P_{b,n} \le P_{b,n}^{max} \tag{4}$$

$$P_{b,n}^{max} = min\left(T_{b,n},\ P_{b,n}^{bid}\right),\ P_{d,m}^{max} = min\left(T_{d,m},\ P_{d,m}^{bid}\right), \text{ and } P_{f,k}^{max} = min\left(T_{f,k},\ P_{f,k}^{bid}\right) \tag{5}$$

The cost reduction amounts for user $\boldsymbol{n}$ and the gain for ESS $\boldsymbol{m}$ is expressed as

$$Y_{b,n} = \gamma_{p,b} \sum_{n=1}^{L_b} P_{mn} - \sum_{m=1}^{L_d} \gamma_{mn} \tag{6}$$

$$Y_{d,m} = \sum_{n=1}^{L_b} \gamma_{m,n} P_{mn} - \gamma_{p,l} \sum_{m=1}^{L_d} \gamma_{nm} \tag{7}$$

6.6. Complexities associated with the application of BT in TES

BT facilitates energy trading among peers and can potentially drive future solutions to provide a more secure, distributed, and sustainable power infrastructure [16]. Presently, prosumers can only access the block channel via the gateway node. This results in high computation complexity and limited storage associated with the consensus protocol in BT. However, the challenge is that adversaries can launch a Denial-of-Service attack against the gateway node, isolating prosumers from TES. This is done to prevent some bids from the energy market from causing instability.

Extensive research has been done on the application of BT to the energy market. Little effort has been recorded on engineering impediments such as TES frameworks needed to develop scalable solutions for energy markets using BT. However, more emphasis is not placed on SC algorithms in the energy market structure. Another complexity recorded in [16] the energy-trading algorithm was used to determine the MCP and difficulties surrounding cybersecurity requirements needed to support effective market operations. Additionally, sustaining the legal behaviours of participants and how to punish malicious operations is challenging. There exist reported cases of manipulation of clearing price bids and the trade-off between decentralization and transaction speed [140]. The vulnerability of TES to cyber threats induced by the financial motives of stakeholders affects the system's operation [141]

7. Mathematical formulations

Load modelling is important in determining consumer energy usage patterns and TES implementation. Yang et al. [33] classified residential loads into fixed and flexible loads; although Zhang et al. [68] classified loads into must-run and controllable loads. The authors further divided flexible loads into shiftable and thermal loads. The fixed loads are those whose working phase and output cannot be determined (refrigerators, lighting appliances, televisions, and computers). Shiftable are dynamic, the operation time can be altered depending on energy price and consumer comfort (air conditioner, washing machine, and cloth dryer). Thermal loads are temperature-dependent and account for the largest residential load demands (water heater and cooling system). Generally, power consumption tends to rise when prices decrease and vice versa.

Shiftable loads are modelled with the expression in [68] as;

$$\gamma_L{}^s = \sum_{t=\beth_L{}^{Sl}}^{\beth_l{}^{Su}} M_{L,t}{}^s \tag{8}$$

$$0 \le M^s_{l,t+\gamma_l^s-1} - \left(M^s_{l,t} - M^s_{l,t-1}\right),\ \forall t \in \left\{\beth_l{}^{sl}, \beth_l{}^{su} - \gamma_l{}^s + 1\right\} \tag{9}$$

$$M^s_{L,t} = 0, \forall t \in \left\{1, \beth_L{}^{sl} - 1\right\} \cup \left\{\beth_L{}^{su} + 1, T\right\} \tag{10}$$

The temperature in a hot water storage tank was modelled in [33] as:

$$T^{hw}_{t+1} = T^{hw}_t + \frac{H_t{}^{hw}\Delta t}{\delta^w \varphi^w \theta^w} + \frac{\theta_t^{cw}\left[T^{cw} - T_t{}^{hw}\right]}{\theta^w} \tag{11}$$

The indoor temperature determines the thermal power:

$$Y^{air}\frac{dH_t{}^{in}}{dt} = \frac{H_t{}^{out} - H_t{}^{in}}{R_t} + E_t{}^{in} \tag{12}$$

7.1. Utility function

The utility function describes the satisfaction end users derived from energy consumption which varies with different time slots. The widely accepted utility function in quadratic form is presented in [68,89] is expressed as:

$$U(p,q) = \begin{cases} qp - \frac{\sigma}{2}p^2, & 0 \le p \le \frac{q}{\sigma} \\ \frac{q^2}{2\sigma}, & x > \frac{q}{\sigma}, \end{cases} \tag{13}$$

The system operators' target is to maintain the energy supply-demand balance, thereby enhancing the SW of the community [29]. Ma et al. [89] described SW as the difference between the consumers' total utilities and the total costs of energy providers. This was formulated with the equation:

$$SW = \sum_{t \in T}\left\{\sum_{s=1}^{S}\left[\omega_t^r(E_t^r) + \omega_t^r(G_t^r)\right] - \sum_{r=1}^{R}\left[C_t^s(E_t^s) + \omega_t^s(G_t^s)\right]\right\} \tag{14}$$

7.2. Pricing constraints

As illustrated in [91] he hourly retail rates of electric energy, thermal energy, and natural gas are depicted in Eqs. (15)–(17). The pricing constraints are given as follows:

$$min\left[P_{so,e}(t)\right] \le \left[P_{ep,e}(t)\right] \le max\left[P_{so,e}(t)\right] \tag{15}$$

$$\frac{\sum_{t=1}^{T} P_{sp,e(t)}}{T} = \frac{\sum_{t=1}^{T} P_{so,g(t)}}{T} \tag{16}$$

$$min\left[P_{so,g}(t)\right] \le \left[P_{ep,g}(t)\right] \le max\left[P_{so,g}(t)\right] \tag{17}$$

The wholesale rates for natural gas, upper and lower levels, are given as;

$$\left[P_{ep,h,min}\right] \le \left[P_{ep,h}(t)\right] \le \left[P_{ep,h,max}\right] \tag{18}$$

$$\left[P_{ee,es,min}\right] \le \left[P_{ee,es}(t)\right] \le \left[P_{ee,es,max}\right] \tag{19}$$

8. Performance evaluation of BT-based energy trading system

The performance evaluation of BT-based systems is critical in analyzing the network size to determine its capability in processing transactions. It gives room to identify the system's limitations beforehand. Numerous studies have been carried out to evaluate blockchain performance and risk reduction by applying multiple techniques. According to a study in [19], classified existing approaches for evaluating blockchain into five. These are queuing models, the Markov process (basic mathematical tool), the Markov Decision Process (a discrete-time stochastic method), Random Walks (a stochastic mathematical model), and emulations. On the other hand, Ferré-queralt et al. [142] give the parameters for the performance evaluation of blockchain as hash-chain structure, scalability, energy use, transaction volume, transaction fee, latency/process time, popularity, and security. There are different perspectives for analyzing the performance of BT-based systems. The most common among them include usability, block analysis, functional testing, security validation, integration, SCs, decentralized applications (dApps), and networks. The authors further classified metrics for the evaluation of the performance of BT operation into three: (i) blockchain, (ii) P2P network me, and (iii) system node metrics. Similarly, Abdennadher et al. [95] used the performance index of (i) process time and (ii) cycle time to evaluate the accuracy and consistency measurements.

8.1. Implementation barriers in TES-based energy trading platform

Technology is a significant barrier to energy trading implementation in TES. Hence, each country is required to roll out strategies to address this limitation. This is necessary to ensure the remodelling of the electrical grid infrastructure to support the implementation. Kumar et al. [11] identified information flow and communication among the peers as barriers impeding its full implementation. Furthermore, an inadequate communication infrastructure to support the transmission of data necessary for exchanging commands and information among the various segments of the networks. A resilient communication infrastructure facilitates interactions, fostering dynamic energy management that adapts to variable tariffs while aiding in the shift to a more resilient and adaptive energy grid [143]. The seamless communication systems and interoperability in BT-TES depend on the protocol standardization, real-time data exchange, latency minimization, reduced bandwidth usage, and communication interfaces [144]. Typically, BT-TES uses wireless communication protocols, which have a limited data rate compared to wired protocols [145]. Some of the identified limitations in the BT-TES communication system involve situations where different blockchain platforms use various protocols and standards, making it difficult for these platforms to communicate and share data. However, the challenge is that real-time monitoring of BT-TES usage requires higher data rates. According to the Ref. [146], efforts are ongoing to perfect the development of cross-chain interoperability solutions (like sidechains and atomic swaps), with feature capabilities that allow for smooth interoperability among different blockchain platforms.

Additionally, there is a huge gap between the academic studies and the implementation of the BT-TES energy trading system. Other issues include balancing economic costs and technical constraints to enhance reliability [147]. Ref. [148] assessed the implementation challenge of P2P energy trading through public power networks and identified network charging regulations as the primary barrier. This shows that substantial consideration should be paid to integrating reliability, resilience, and security features into the design and implementation of TES.

8.2. Scalability and adaptability of TES across different energy markets and grid infrastructures

Scalability is crucial when designing the energy trading system in TES, given various market configurations [149]. One essential feature of a TE system that allows scaling to large numbers of interacting parties is the separation of concerns and responsibilities [150]. The approach breaks down the complex system problem into numerous smaller issues that can be handled concurrently. The TES concept includes features that ensure the optimization of energy consumption, which helps minimize load profile deviations and enhances economic benefits for participants [143]. The Pacific Northwest National Laboratory (PNNL) survey/interview on strategies for scaling TES programmes to a broader market reveals that researchers focus more on technical rather than economic efficiencies [151]. Additionally, it was observed that scaling TE deployments will require a more sophisticated understanding of marketplace challenges and opportunities. Furthermore, in the interview, most respondents preferred focusing on regulatory, rate design, and standards for device communication over market/business model enhancement. There is a need to establish a specific framework in TES to identify the main barriers to scaling up and assess scalability.

Ultimately, a collaborative strategy promotes an adaptable energy grid, fostering sustainable energy practices within the distribution layer. The IEEE 2030.5, an established communication standard, was proposed to be adapted to the TES [152]. Additionally, the authors suggest that adapting BT to the requirements of TES is promising for supporting energy markets and grid infrastructures.

8.3. Cyber threats, efficiency, and cost reduction in BT-based TES

Owing to the various reported security breaches in energy trading, which pose significant challenges, it is essential to secure the trading process. Notable cyberattacks on power grids, such as the one recorded in Ukraine in 2015, have raised concerns about the susceptibility of the electrical grid [10]. Implementing TES without effective cybersecurity measures can expose the system to cyberattacks, which may compromise its integrity, leading to grid instability and energy consumption data manipulation. In the modern period, the vast use of electronic devices, social media, and automation has resulted in generation of a vast amount of data per second. This simultaneously makes systems more susceptible to increased cyber-attacks such as FDIA, phishing, replay attacks, Sybil attacks, identity thefts, and data breach attacks [23]. The integration of cybersecurity systems is crucial in preventing malicious activities and unauthorized access to the bi-directional flow of information on the power grid [11]. It averts scenarios where attackers infiltrate the system to obtain participants' consumption data and trading patterns within the network. A successful FDIA attack can potentially reduce prosumers' profit, which may discourage consumers from becoming prosumers. Attackers can maliciously modify bid information and prices offered between market players to cause financial losses and create disturbances in the market process. These and many more reasons necessitate an urgent need for robust solutions to combat these attacks.

An analytic approach was presented to monitor the security of the cyber-physical features of TES in [15]. The authors developed different attack models integrated with a deep learning technique (Deep Stacked Autoencoder) for cyber threat detection. The results show that the normal data detection rate for component outage events and attack rule was 79 % and 96.9 %, respectively. The unsupervised approach indicates satisfactory anomaly detection performance in an end-to-end TES-based testbed. Mohammadi et al. [153] used real datasets to explore the application of instance-based ML for detecting FDIA in P2P energy trading systems under two threat scenarios. The experimental results demonstrate detection and accuracy rates of 96.1 % and 96.18 %, respectively.

A BT-based network-constrained Self Adaptive Self-Tuning Fast-Alternative Direction Method of Multipliers (SASTF-ADMM) technique was employed to accelerate the P2P TE model to enhance security and ensure transaction transparency within the energy trading framework [106]. The security analysis revealed that the studied blockchain network can withstand Sybil attacks and 51 % of attacks in the PoS protocol. A stochastic cooperation-based TES for multi-carrier networked energy hubs was introduced to minimize operational costs through four case studies [154]. The simulation analysis of the proposed scheme shows that one of the case studies recorded a 38.72 % reduction in operational cost. In implementing TES, integrating Third Generation (GEN-3)-based BT, for the security and efficiency of P2P energy trading among participants, the simulation outcomes of the proposed model exhibit an average electricity bill reduction of 11 % for the participants [64]. A real-life scenario, consisting of 52 households within a neighbourhood in Norway, was presented to analyse P2P energy trading [155]. The approach recorded savings for the end-user, resulting in a 70 % increase in P2P trading among consumers and grid loss reduction of 20.7 %.

A good BT-based TES should have features that swiftly detect security violations and notify peers of impending danger to ensure system integrity. Therefore, the data should be secured against theft and loss.

8.4. Regulatory implications, role of government and international bodies enabling/hindering adoption of BT-based TES

Regulatory bodies must establish a comprehensive framework that addresses the unique challenges and opportunities associated with employing BT-based TES. Additionally, formulating and evaluating policy strategies that support the integration of BT in TES are crucial. The government's role includes creating economic incentives for all stakeholders [156]. Currently, ongoing research at the PNNL in the United States is exploring a research approach on BT-based TES, mapping the engineering requirements of a TES application to BT based on its obtainable features and constraints [157]. This entails exploring how BT could assist with fault-tolerant grid operations. The international organization, such as IEEE, has proposed a Standard for Blockchain in Energy, IEEE P2418.5 [158]. The participation of countries and international professional bodies underscores the benefits and transformative potential of BT-based TES in fostering clean and affordable decentralized generation in the energy sector. Factors hindering the adoption of this solution include: a lack of awareness, the necessary policies and regulations needed to support its implementation in developing countries, and insufficient incentives for businesses and individuals to invest in BT-based TES.

9. Discussion, findings, and recommendations

9.1. Discussion and findings

The TES concept can potentially be the future of distribution systems in providing resilience and energy exchange with other entities across the network. The application of Blockchain and digital communication technologies enhances various features of TES, such as data storage, security, transparency, reliability, resilience, stability, and trackable digital transactions. It was discovered that the blockchain application in TES plays a role in implementing data verification and market-clearing techniques. For instance, SCs can transfer assets between peers and enforce agreements. It was deduced from the work that the attribute of blockchain-based TES has the strength to sustain market integrity by preventing bid tampering and disruption of the market-clearing mechanisms. The arrangement in BT is that the adversary may have to compromise the majority of blockchain nodes for successful operations. On the other hand, attackers' activities may degrade the system's operation. Another noted complexity is that the robustness of transactions across the nodes in a P2P network depends on the consensus algorithms of the blockchain for transaction validation.

Transitioning to BT-enabled TES in energy trading will offer economic and operational benefits and challenges for stakeholders, including prosumers, consumers, utilities, and governments. However, the bottom line is that all participants must be adequately incentivised depending on their investment level to sustain their involvement in a functioning LEM [159]. This development will enhance prosumers' economic value, provided they are willing to trade their surplus energy [160]. Additionally, it will delay the need for utility capacity expansion as the TES can support them by supplying energy to neighbours during the peak period, thereby minimizing cost. The adoption of BT-enabled TES will help the government make energy more affordable. Consequently, this will enhance energy security, transform the economy, and facilitate a sustainable environment. On the flip side, power generation through conventional means will decrease, resulting in job losses in the sector as power stations may be decommissioned with the shift toward investing in DERs.

In this paper, the connection in centralized TES is identical to conventional energy networks, making integrating the system into existing networks easier. However, it is less secure and involves high computational expenses. Although the decentralized structure of BT-based TES is complex during the integration into existing networks, it is scalable and more secure. It was discovered that the Markov process model is the most used approach for evaluating the reliability features of blockchain protocols. Furthermore, it was observed that Blockchains rely heavily on real-time data transmission. SC has a feature to facilitate efficiency, but there are still bottlenecks in standardization regarding regulation. Acknowledging from the literature that extensive research has been carried out on the BT benefit. This is contrary to issues on clearing, which involve transaction records comparison and settlement of account balances. Regardless of the enormous satisfaction inherent in energy trading using BT, some challenges underscore the importance of a comprehensive threat mitigation strategy. These include cybersecurity threats, operational complexities, research deficits, and inadequately skilled personnel to provide the technical know-how needed for the BT-TES implementation. Authors have discovered that the decentralizing TES infrastructure encourages energy democracy, stimulates universal access to clean and affordable energy, improves RES utilization, and advocates for local energy ownership from corporate to community-owned power infrastructure.

Blockchain is currently the best-known technology in terms of trust, as it is much harder to manipulate in comparison with the central system [161]. Even so, the technology is not entirely perfect in its dependence on the democratic approach in making decisions. For instance, an action can be validated or approved by a majority. However, energy trading activities can be manipulated if most participants are dishonest, as they can come together to break blockchain rules through the manipulation of data records, which honest participants may detect, but cannot disable the existing arrangement. This is the main limitation of blockchain.

Another discovery is that PoW consensus protocol in blockchain is burdened with the issues of throughput, scalability, a large amount of energy consumption for micro-transactions verification, and computationally demanding (leading to huge operation overhead) [162]. These factors impede the application of traditional blockchain for executing a huge number of micro-transactions [108]. Recent advancements in ledger technology favoured the DAG-based IOTA distributed ledger in replacing the generic blockchain. It can simultaneously process huge micro-transactions in P2P networks with much improved security and privacy of non-trusting participants in TES.

A comparison analysis of Blockchain and DAG technologies for Bitcoin, Ethereum, and DAG technologies, based on efficiency (measured using latency) in [163], shows that despite the robustness of Bitcoin, it was discovered from the research that it is prone to latency, with inclusion times exceeding 700 s while Ethereum demonstrates inclusion times varying between 12.9 and 35.8 s. However, DAG has lower inclusion times ranging from 4.3 to 22.3 s. These results highlight its suitability for real-time applications and outmatch traditional BTs regarding transaction inclusion times and scalability. This was further corroborated in [164], that DAG-based blockchain addresses major shortcomings of conventional blockchains. These findings underscore the suitability of DAG as a viable solution for applications requiring high-frequency data validation and low-latency processing, such as the BT-TES energy trading system.

9.2. Recommendations

The BT-based peer rating mechanism should be adopted in the energy trading network to enhance the participants' commitment to their reputation in the market. This mechanism gives peers with better ratings an edge or priority over competitors with lower scores during transactions. Peers with lower ratings may end up purchasing the expensive bids left in the energy market, as a penalty for their poor reputation (higher purchase prices and limited trading options). This will encourage the lawful behaviour among participants within the network. The resilience and reliability of the BT-based TES communication system for energy trading are essential for preventing natural, physical, and cyberattacks. Failure to achieve this will impact the TES operation, making it susceptible to price manipulation. Blockchain and Artificial Intelligence integration should be encouraged to tackle complex challenges in energy trading. This aims to leverage the complementary benefits of both technologies and address challenges in a synergetic manner. The authors recommend an incremental implementation approach for accomplished BT-based energy trading in TES. This can be achieved by breaking down the implementation phase into segments to verify reliability and performance. This approach facilitates the identification and resolution of faults on a small scale. Although efforts are underway to develop frameworks for the standardization of TES, notably among them is IEEE's P825. Experts within industries, institutions, and government agencies need to do more through collaboration to solve the identified challenge of standardization in TES. The authors also suggest incorporating analytical modelling for performance evaluation.

10. Conclusion, limitations, and outlook on future research

Transitioning to sustainable development through renewable energy generation that is green, clean, and affordable is the thing of the day. This is one of the United Nations' targets for Sustainable Development Goal (SDG) Seven: to produce clean and affordable energy by 2030. The work showcased how the TES framework supports realizing these targets (SDG goals) in energy distribution, such as economic efficiency, Reliability, Scalability, and Adaptability. Besides this, this systematic review offers a detailed perspective on recent research approaches to BT applications to alleviate the security risks linked to energy trading in TES. Also, the review established the importance of BT for TES as a viable scientific approach, against being a coincidence, to secure energy trading, enhance robustness and facilitate an energy trading system that is secure, efficient, and transparent.

The authors' investigation reveals that eliminating third parties or intermediaries in BT-based TES notably facilitates energy trading and reduces costs. Additionally, it was discovered that adopting fast computing techniques will enhance digital and intelligent operations in TES. Furthermore, scaling TES deployments will require a more sophisticated understanding of marketplace challenges and opportunities. Another finding is that the DAG-based distributed ledger is replacing the generic blockchain because it can simultaneously process large micro-transactions in P2P networks with significantly improved security and privacy of the non-trusting participants in TES. This finding underscores the suitability of DAG as a viable solution for applications requiring high-frequency data validation and low-latency processing, such as the BT-TES energy trading system. It was uncovered that the IEEE 2030.5 communication standard is the only existing standard that can be readily adapted to TES. Moreover, increasing local generation improves payoffs (profits) for the participants and reduces MCPs. The review emphasizes how crucial it is to further explore the application of BT in advancing TES to avoid unnecessary complexities during the implementation stage and enhance energy efficiency and electrical grid flexibility, which subsequently minimizes operating costs to support clean and affordable energy. The limitation of this research is that communication systems in BT-based TES, through which energy trading or transactions are processed, were not adequately covered. In the future, authors wish to uncover this area further and identify more advanced technology to support BT-enabled TES for enhanced communication features. Additionally, explore an analytical modelling approach to evaluate the performance and to understand complex components of the BT-enabled TES energy solution. Lastly, investigate how multiple energy carriers, such as electricity, heat, and gas, can be traded via a singular grid infrastructure.

CRediT authorship contribution statement

Oluwaseun O. Tooki: Writing – original draft, Visualization, Validation. **Olawale M. Popoola:** Conceptualization.

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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Data availability

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

References

[1] O.O. Tooki, O.M. Popoola, A comprehensive review on recent advances in transactive energy system: concepts, models, metrics, technologies, challenges, policies and future, Renew. Energy Focus 50 (June) (2024) 1–19, https://doi.org/10.1016/j.ref.2024.100596.
[2] M.B. Mollah, et al., Blockchain for future Smart grid: a comprehensive survey, IEEE Internet Things J. 8 (1) (2021) 18–43, https://doi.org/10.1109/JIOT.2020.2993601.
[3] O. Elma, A. Taşçıkaraoğlu, A. Tahir İnce, U.S. Selamoğulları, Implementation of a dynamic energy management system using real time pricing and local renewable energy generation forecasts, Energy 134 (2017) 206–220, https://doi.org/10.1016/j.energy.2017.06.011.
[4] K. Lokeshgupta, B. Ravivarma, A peer to peer energy trading model for community microgrids with energy management, Peer Peer Netw. Appl. 17 (2024) 2538–2554, https://doi.org/10.1007/s12083-024-01722-x.
[5] H. Trung, S. Battula, R. Reddy, Z. Wang, L. Tesfatsion, An integrated transmission and distribution test system for evaluation of transactive energy designs, Appl. Energy 240 (November 2018) (2019) 666–679, https://doi.org/10.1016/j.apenergy.2019.01.178.
[6] Y. Zou, Y. Xu, X. Feng, R.T. Naayagi, B.H. Soong, Transactive energy systems in active distribution networks: a comprehensive review, CSEE J. Power Energy Syst. 8 (5) (2022) 1302–1317, https://doi.org/10.17775/CSEEJPES.2021.03290.
[7] W. Dan, Y. Zhou, L. Nian, Q. Meysam, B. Rohit, A. Sahban, Planning, operation, and trading mechanisms of transactive energy systems in the context of carbon neutrality, Energy Convers. Econ. (2022) 3–5, https://doi.org/10.1049/enc2.12060.
[8] C. Fan, H. Khazaei, P. Musilek, BPET: a unified blockchain-based framework for peer-to-peer energy trading, Future Internet (2024) 1–19, https://doi.org/10.3390/fi16050162.
[9] S. Xu, X. Wu, J. Shen, H. Hua, Low-carbon collaborative dual-layer optimization for energy station considering joint electricity and heat demand response, Front. Energy (2024), https://doi.org/10.1007/s11708-024-0958-0.
[10] O.O. Tooki, O.M. Popoola, A critical review on intelligent-based techniques for detection and mitigation of cyberthreats and cascaded failures in cyber-physical power systems, Renew. Energy Focus 51 (August) (2024), https://doi.org/10.1016/j.ref.2024.100628.
[11] N.M. Kumar, et al., Distributed energy resources and the application of AI, IoT, and blockchain in smart grids, Energies 13 (5739) (2020), https://doi.org/10.3390/en13215739 (Basel).
[12] J. Yuan, C. Cui, Z. Xiao, C. Zhang, W. Gang, Performance analysis of thermal energy storage in distributed energy system under di ff erent load pro fi les, Energy Convers. Manage 208 (November 2019) (2020), https://doi.org/10.1016/j.enconman.2020.112596.

[13] S. Nizami, W. Tushar, M.J. Hossain, C. Yuen, T. Saha, H.V. Poor, Transactive energy for low voltage residential networks: a review, Appl. Energy 323 (July) (2022), https://doi.org/10.1016/j.apenergy.2022.119556.

[14] T.M. Fernandez-Carames, P. Fraga-Lamas, A review on the application of blockchain to the next generation of cybersecure industry 4.0 smart factories, IEEE Access 7 (2019) 45201–45218, https://doi.org/10.1109/ACCESS.2019.2908780.

[15] Y. Zhang, et al., Cyber physical security analytics for transactive energy systems, IEEE Trans. Smart Grid 11 (2) (2020) 931–941, https://doi.org/10.1109/TSG.2019.2928168.

[16] S. Nikhil, et al., Blockchain smart contract reference framework and program logic architecture for transactive energy systems ☆, Appl. Energy 304 (March) (2021) https://doi.org/10.1016/j.apenergy.2021.117860.

[17] M.F. Zia, E. Elbouchikhi, M. Benbouzid, and J.M. Guerrero, "Microgrid transactive energy systems: a perspective on design, technologies, and energy markets," pp. 5795–5800, 2019.

[18] I. Hussain, H. Ashiq Hussain, N. Ullah, S. Misak, Proof of inherent intelligence consensus mechanism empowering blockchain-enabled transactive energy, IEEE Access 13 (December 2024) (2025) 5042–5055, https://doi.org/10.1109/ACCESS.2024.3525416.

[19] S. Smetanin, A. Ometov, M. Komarov, P. Masek, Y. Koucheryavy, Blockchain evaluation approaches: state-of-the-art and future perspective, Sensors 20 (12) (2020) 1–20, https://doi.org/10.3390/s20123358 (Switzerland).

[20] M. Lezzi, V. Del Vecchio, Using blockchain technology for sustainability and secure data management in the energy industry: implications and future research directions, Sustainability 16 (2024), https://doi.org/10.3390/su16187949.

[21] M.K. Hasan, et al., Blockchain technology on smart grid, energy trading, and big data: security issues, challenges, and recommendations, Wirel. Commun. Mob. Comput. 2022 (2022), https://doi.org/10.1155/2022/9065768.

[22] H.S.V.S.K. Nunna, Y. Amanbek, B. Satuyeva, S. Doolla, A decentralized transactive energy trading framework for prosumers in a microgrid cluster, in: Proceedings of the 2019 IEEE PES GTD Grand International Conference and Exposition Asia (GTD Asia), Bangkok, Thailand, IEEE Xplore, 2019, pp. 824–830, https://doi.org/10.1109/GTDAsia.2019.8715872.

[23] R. Shinde, S. Patil, K. Kotecha, K. Ruikar, Blockchain for securing AI applications and open innovations, J. Open Innov. Technol. Mark. Complex. 7 (2021) 1–38, https://doi.org/10.3390/joitmc7030189.

[24] T. Renduchintala, H. Alfauri, Z. Yang, R. Di Pietro, R. Jain, A survey of blockchain applications in the FinTech sector, J. Open Innov. Technol. Mark. Complex. (2022) 1–44, https://doi.org/10.3390/joitmc8040185.

[25] K. Yung, H. Huin, Blockchain technology for distributed generation: a review of current development, challenges and future prospect, Renew. Sustain. Energy Rev. 175 (January) (2023), https://doi.org/10.1016/j.rser.2023.113170.

[26] J.C. Olivares-rojas, E. Reyes-archundia, J.A. Gutiérrez-Gnecchi, I. Molina-moreno, J. Cerda-Jacobo, A. Mendez-Patino, A transactive energy model for smart metering systems using blockchain, CSEE J. Power Energy Syst. 7 (5) (2021) 943–953, https://doi.org/10.17775/CSEEJPES.2020.05670.

[27] C. Barreto, T. Eghtesad, S. Eisele, A. Laszka, A. Dubey, X. Koutsoukos, Cyber-attacks and mitigation in blockchain based transactive energy systems, in: Proceedings of the 3rd IEEE International Conference on Industrial Cyber-Physical Systems (ICPS 2020), 2020, https://doi.org/10.1109/ICPS48405.2020.9274708.

[28] G. Gurjar, M.D. Nikose, Smart contract framework for secure and efficient P2P energy trading with blockchain, J. Electr. Eng. Technol. 20 (1) (2024) 255–269, https://doi.org/10.1007/s42835-024-02043-y.

[29] J. Yang, A. Paudel, H.B. Gooi, Blockchain framework for peer-to-peer energy trading with credit rating, in: Proceedings of the 2019 IEEE Power & Energy Society General Meeting (PESGM), Atlanta, GA, USA, IEEE, 2020, pp. 1–5, https://doi.org/10.1109/PESGM40551.2019.8973709.

[30] L.L. Delina, R. Yi, H. Lam, W. Shun, T. Ka, Y. Wong, Mapping the actor landscape of a future fintech funded renewable energy ecosystem in Hong Kong, J. Environ. Stud. Sci. 13 (2023) 419–427, https://doi.org/10.1007/s13412-023-00839-4.

[31] C. Mu, T. Ding, M. Yang, Y. Huang, W. Jia, X. Shen, Peer-to-peer energy trading based on a hybrid blockchain system, Energy Rep. 9 (September) (2023) 124–128, https://doi.org/10.1016/j.egyr.2023.09.123.

[32] L. Lin, J. Bao, J. Zheng, G. Huang, J. Du, N. Huang, Capacity planning of micro energy grid using double-level game model of environment-economic considering dynamic energy pricing strategy, IEEE Access 8 (2020) 103924–103940, https://doi.org/10.1109/ACCESS.2020.2999373.

[33] Z. Yang, M. Ni, H. Liu, Pricing strategy of Multi-energy provider considering integrated demand response, IEEE Access 8 (2020) 149041–149051, https://doi.org/10.1109/ACCESS.2020.3016005.

[34] J. Xue, J. Ding, L. Zhao, D. Zhu, L. Li, An option pricing model based on a renewable energy price index, Energy 239 (2022), https://doi.org/10.1016/j.energy.2021.122117.

[35] H. Niaei, A. Masoumi, A. Reza, M. Marzband, Smart peer-to-peer and transactive energy sharing architecture considering incentive-based demand response programming under joint uncertainty and line outage contingency, Energy Convers. Prod. 363 (May) (2022), https://doi.org/10.1016/j.jclepro.2022.132403.

[36] M.F. Zia, M. Benbouzid, E. Elbouchikhi, S.M. MUYEEN, K. Techato, J. M. Guerrero, Microgrid transactive energy: review, architectures, distributed ledger technologies, and market analysis, IEEE Access 8 (2020), https://doi.org/10.1109/ACCESS.2020.2968402.

[37] Y. Xinyi, Z. Yi, Y. He, Technical characteristics and model of blockchain, in: Proceedings of the 2018 10th International Conference on Communication Software and Networks, ICCSN 2018, 2018, pp. 562–566, https://doi.org/10.1109/ICCSN.2018.8488289.

[38] P. Siano, G.D. Marco, A. Rolan, V. Loia, A survey and evaluation of the potentials of distributed ledger technology for peer-to-peer transactive energy exchanges in local energy markets, IEEE Syst. J. 13 (3) (2019) 1–13, https://doi.org/10.1109/JSYST.2019.2903172.

[39] K. Christidis, D. Sikeridis, Y. Wang, M. Devetsikiotis, A framework for designing and evaluating realistic blockchain-based local energy markets, Appl. Energy 281 (2020) 2021, https://doi.org/10.1016/j.apenergy.2020.115963.

[40] S. Saha, N. Ravi, K. Hreinsson, J. Baek, A. Scaglione, N.G. Johnson, A secure distributed ledger for transactive energy: the electron volt exchange (EVE) blockchain, Appl. Energy 282 (2020) 2021, https://doi.org/10.1016/j.apenergy.2020.116208.

[41] S.Z. Althaher, S.W. Alnaser, Transactive energy system for distribution network management: procuring residential flexibility services under dynamic pricing, IEEE Access (September) (2022), https://doi.org/10.1109/ACCESS.2022.3208690.

[42] J. Yang, Y. Li, Y. Cao, Y. Tan, C. Rehtanz, Transactive energy system: a review of cyber- physical infrastructure and optimal scheduling, IET Gener. Transm. Distrib. Rev. (2019) 173–179, https://doi.org/10.1049/iet-gtd.2018.6554.

[43] Y. Xia, Q. Xu, S. Li, R. Tang, P. Du, Reviewing the peer-to-peer transactive energy market: trading environment, optimization methodology, and relevant resources, J. Clean. Prod. 383 (November 2022) (2023) 135441, https://doi.org/10.1016/j.jclepro.2022.135441.

[44] E. Kusatake, M. Imahori, N. Shinomiya, A peer-to-peer energy trading model for optimizing both efficiency and fairness, Energies 16 (14) (2023), https://doi.org/10.3390/en16145501 (Basel).

[45] K. Krawiec, O. Kraft, R. Jahn, A comparative analysis of using distributed ledger technologies for transactive energy systems, in: Proceedings of the International Youth Conference on Energy (IYCE), 2022, https://doi.org/10.1109/IYCE54153.2022.9857518.

[46] M.I. Ismail, N.A. Yunus, H. Hashim, Peer-to-Peer control strategy for the optimal trading price of integrated solar thermal systems, Chem. Eng. Trans. 106 (September) (2023) 631–636, https://doi.org/10.3303/CET23106106.

[47] M. Imran, N. Alafiza, M. Nurariffudin, M. Idris, Peer-to-peer economic decision analysis model for integrated thermal energy trading, Chem. Eng. Trans. 97 (October) (2022) 253–258, https://doi.org/10.3303/CET2297043.

[48] L. Chang, X. Wang, Transactive energy scheme based on multi-factor evaluation and contract net protocol for distribution network with high penetration of DERs, in: Proceedings of the 2017 Chinese Automation Congress (CAC), Jinan, China, IEEE, 2017, https://doi.org/10.1109/CAC.2017.8244066.

[49] J. Tan, Y. Li, X. Zhang, Optimization and trading of district multi-energy system in university community considering carbon emission, Int. J. Electr. Power Energy Syst. 137 (April 2021) (2022), https://doi.org/10.1016/j.ijepes.2021.107450.

[50] C. Hurtado, A Feasibility Analysis of Transactive Energy Systems in Ontario, York University, Toronto, Ontario, Canada, 2019. http://hdl.handle.net/10315/36863.

[51] K. Taouil, R. Aloulou, B. Salma;, A. Gassara, M.W. Kharrat, P2P Energy exchange architecture for swarm electrification-driven PV communities, Energies 17 (2024), https://doi.org/10.3390/en17153680 (Basel).

[52] S. Ali, S. Mojtaba, S. Amirali, Computationally efficient peer to peer energy trading mechanisms for autonomous agents considering network constraints and privacy preservation, Peer Peer Netw. Appl. 16 (2023) 1088–1105, https://doi.org/10.1007/s12083-023-01456-2.

[53] P. Chen, Y. Ye, H. Wang, S. Bu, Y. Tang, G. Strbac, Holistic coordination of transactive energy and carbon emission right trading for heterogenous networked multi-energy microgrids: a fully distributed adaptive consensus ADMM approach, Sustain. Energy Technol. Assess. 64 (November 2023) (2024), https://doi.org/10.1016/j.seta.2024.103729.

[54] H. Taherdoost, Blockchain integration and its impact on renewable energy, Computers 13 (4) (2024), https://doi.org/10.3390/computers13040107.

[55] B.P. Framework, Carbon and energy trading integration within a blockchain-powered peer-to-peer framework, Energies 17 (2024), https://doi.org/10.3390/en17112473 (Basel).

[56] G. Nicolae and C.V. Marian, "DLT and blockchain technology outlook," IEEE Blockchain Technical Brief, pp. 1–3, 2024.

[57] J.Y. Shi, B. Szymanski, L.S. Ramachandran, and I. Bashir, "A peek into the blockchain technology developments," IEEE Blockchain Technical Brief, no. c, pp. 5–8, 2023.

[58] N.N. Devi, S. Thokchom, G. Srivastava, R.H. Jhaveri, D. Sinha, Demcrp et: decentralized multi criteria ranked prosumers energy trading using distributed ledger technology, Peer Peer Netw. Appl. 17 (2024) 549–565, https://doi.org/10.1007/s12083-023-01599-2.

[59] R.V. Tkachuk, D. Ilie, R. Robert, V. Kebande, K. Tutschku, On the performance and scalability of consensus mechanisms in privacy enabled decentralized renewable energy marketplace, Ann. Telecommun. 79 (2024) 271–288, https://doi.org/10.1007/s12243-023-00973-8.

[60] S.L. Arun, Enhancing transactive energy trading framework for residential end users, IEEE Access (March) (2024), https://doi.org/10.1109/ACCESS.2024.3377129. Enhancing.

[61] S. Saxena, H.E.Z. Farag, H. Turesson, H. Kim, Blockchain based transactive energy systems for voltage regulation in active distribution networks, Inst. Eng. Technol. 3 (5) (2020) 646–656, https://doi.org/10.1049/iet-stg.2019.0286.

[62] L. Chen, L. Xu, Z. Gao, Y. Lu, W. Shi, Tyranny of the majority: on the (Im) possibility of correctness of smart contracts, IEEE Secur. Priv. 16 (4) (2018) 30–37, https://doi.org/10.1109/MSP.2018.3111240.
[63] A.M.A. Daiyan Kaif, K.S. Alam, S.K. Das, G. Chen, S. Islam, S.M. Muyeen, Blockchain-integrated cyber-physical smart meter design and implementation for secured energy trading in virtual power plants, IEEE Trans. Autom. Sci. Eng. 22 (2025) 15083–15093, https://doi.org/10.1109/TASE.2025.3566938.
[64] L. Ali, M.I. Azim, J. Peters, N.B. Ojha, M.G. Simoes, S.M. Muyeen, Integrating Gen3 blockchain into a transactive energy market for DERs orchestration, IEEE Trans. Ind. Appl. 61 (3) (2024) 5103–5115, https://doi.org/10.1109/AIE61866.2024.10561267.
[65] I. Papersonline, M. Sivianes, P. Velarde, M. Sivianes, P. Velarde, and M. Sivianes, “Uncertainty management in management in energy trading based on blockchain and distributed model predictive control,” in IFACPapersOnLine, 2023, pp. 7102–7107.
[66] A. Tabares, P. Cortes, Using stochastic dual dynamic programming to solve the multi-stage energy management problem in microgrids, Energies 17 (2024), https://doi.org/10.3390/en17112628 (Basel).
[67] J. Abushnaf, A. Rassau, W. Górnisiewicz, Impact of dynamic energy pricing schemes on a novel multi-user home energy management system, Electr. Power Syst. Res. 125 (2015) 124–132, https://doi.org/10.1016/j.epsr.2015.04.003.
[68] L. Zhang, Y. Gao, H. Zhu, L. Tao, Bi-level stochastic real-time pricing model in multi-energy generation system: a reinforcement learning approach, Energy 239 (2022), https://doi.org/10.1016/j.energy.2021.121926.
[69] M.F. Zia, E. Elbouchikhi, M. Benbouzid, J.M. Guerrero, Microgrid transactive energy systems: a perspective on design, technologies, and energy markets, in: Proceedings of the IECON 2019 - 45th Annual Conference of the IEEE Industrial Electronics Society 1, 2019, pp. 5795–5800.
[70] K. Rowe, G. Mokryani, K. Cooke, F. Campean, T. Chambers, Bi-level optimal sizing, siting and operation of utility-scale multi-energy storage system to reduce power losses with peer-to-peer trading in an electricity /heat / gas integrated network, J. Energy Storage 83 (2024), https://doi.org/10.1016/j.est.2024.110738.
[71] X. Zhao, W. Gao, F. Qian, J. Ge, Electricity cost comparison of dynamic pricing model based on load forecasting in home energy management system, Energy 229 (2021), https://doi.org/10.1016/j.energy.2021.120538.
[72] M. Mohiti, M. Mazidi, N. Oggioni, D. Steen, L.A. Tuan, An IGDT-based energy management system for local energy communities considering phase-change thermal energy storage, IEEE Trans. Ind. Appl. 60 (3) (2024) 4470–4481, https://doi.org/10.1109/EEEIC/ICPSEurope54979.2022.9854642.
[73] Y. Lin, J. Wang, Realizing the transactive energy future with local energy market: an overview, Curr. Sustain./Renew. Energy Rep. 9 (2022) 1–14, https://doi.org/10.1007/s40518-021-00198-0.
[74] Z. Bao, et al., Toward green and efficient blockchain for energy trading: a noncooperative game approach, IEEE Internet Things J. 10 (22) (2023) 20021–20032, https://doi.org/10.1109/JIOT.2023.3283412. Digital Object Identifier.
[75] A. Hafid, A.S. Hafid, M. Samih, New mathematical model to analyze security of sharding-based blockchain protocols, IEEE Access 7 (2019) 185447–185457, https://doi.org/10.1109/ACCESS.2019.2961065.
[76] Y. Wang, X. Wang, C. Shao, N. Gong, Distributed energy trading for an integrated energy system and electric vehicle charging stations: a Nash bargaining game approach, Renew. Energy 155 (2020) 513–530, https://doi.org/10.1016/j.renene.2020.03.006.
[77] L. Wang, Z. Zhang, J. Fan, S. Zeng, S. Pan, H. Chen, Blockchain-based joint auction model for distributed energy in industrial park microgrids, Energies 17 (2024) 1–15, https://doi.org/10.3390/en17133140 (Basel).
[78] W. Zhao, S. Zhang, L. Xue, T. Chang, L. Wang, Research on model of micro grid green power transaction based on blockchain technology and double auction mechanism, J. Electr. Eng. Technol. (2024) 133–145, https://doi.org/10.1007/s42835-023-01541-9.
[79] M. Rashed, H. Polas, A.I. Kabir, A.S. Sohel-uz-zaman, Blockchain technology as a game changer for green innovation: green entrepreneurship as a roadmap to green economic sustainability in Peru, J. Open Innov. Technol. Mark. Complex. (2022), https://doi.org/10.3390/joitmc8020062.
[80] M.J. Page, et al., The PRISMA 2020 statement: an updated guideline for reporting systematic reviews, Int. J. Surg. 88 (March) (2021), https://doi.org/10.1016/j.ijsu.2021.105906.
[81] D. Moher, A. Liberati, J. Tetzlaff, D.G. Altman, and T. Prisma, “Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement,” vol. 8, 2010, doi: 10.1016/j.ijsu.2010.02.007.
[82] University of Wollongong Australia, “Five other types of systematic review - systematic review - guides at University of Wollongong Library.” Accessed: Jun. 07, 2025. [Online]. Available: https://uow.libguides.com/systematic-review/types-of-systematic-reviews.
[83] S. Agrawal, P. Oza, R. Kakkar, S. Tanwar, V. Jetani, Analysis and recommendation system-based on PRISMA checklist to write systematic review, Assess. Writ. 61 (January) (2024), https://doi.org/10.1016/j.asw.2024.100866.
[84] A. Leles, L. Zaina, J.R. Cardoso, L. Member, Challenge-based learning for competency development in engineering education, a prisma-based systematic literature review, IEEE Trans. Ed. 67 (5) (2024) 746–757, https://doi.org/10.1109/TE.2024.3417908.
[85] J. Nazir, P.K. Das, A systematic literature review on factors of perception impacting entrepreneurial success based on PRISMA framework, J. Innov. Entrep. (2025), https://doi.org/10.1186/s13731-025-00491-y.
[86] S.A. Mengiste, K. Antypas, M.R. Johannessen, J. Klein, eHealth policy framework in low and lower middle income countries; a PRISMA systematic review and analysis, BMC Health Serv. Res. 7 (2023) 1–15.
[87] B. Tedja, M. Al Musadieq, A. Kusumawati, E. Yulianto, Systematic literature review using PRISMA: exploring the influence of service quality and perceived value on satisfaction and intention to continue relationship, Future Bus. J. 10 (1) (2024) 1–9, https://doi.org/10.1186/s43093-024-00326-4.
[88] Y. Wang, Z. Huang, Z. Li, X. Wu, L.L. Lai, F. Xu, Transactive energy trading in reconfigurable multi-carrier energy systems, J. Mod. Power Syst. Clean Energy 8 (1) (2020) 67–76, https://doi.org/10.35833/MPCE.2018.000832.
[89] T. Ma, W. Pei, H. Xiao, L. Kong, Y. Mu, T. Pu, The energy management strategies based on dynamic energy pricing for community integrated energy system considering the interactions between suppliers and users, Energy 211 (2020), https://doi.org/10.1016/j.energy.2020.118677.
[90] Y. Zhou, P.D. Lund, Peer-to-peer energy sharing and trading of renewable energy in smart communities — trading pricing models, decision-making and agent-based collaboration, Renew. Energy 207 (November 2022) (2023) 177–193, https://doi.org/10.1016/j.renene.2023.02.125.
[91] X. Zhu, et al., Day-ahead energy pricing and management method for regional integrated energy systems considering multi-energy demand responses, Energy 251 (2022), https://doi.org/10.1016/j.energy.2022.123914.
[92] S. Nojavan, K. Zare, Optimal energy pricing for consumers by electricity retailer, Int. J. Electr. Power Energy Syst. 102 (April) (2018) 401–412, https://doi.org/10.1016/j.ijepes.2018.05.013.
[93] M.D. Abdulrahaman, N. Faruk, A.A. Oloyede, N.T. Surajudeen-bakinde, and L.A. Olawoyin, “Multimedia tools in the teaching and learning processes: a systematic review,” vol. 6, no. February 2020.
[94] S. Agrawal, P. Oza, R. Kakkar, S. Tanwar, V. Jetani, Analysis and recommendation system-based on PRISMA checklist to write systematic review, Assess. Writ. 61 (June) (2024), https://doi.org/10.1016/j.asw.2024.100866.
[95] S. Abdennadher, W. Cheffi, A. Hudaya, M. Amin, M. Naveed, Performance analysis of a blockchain process modeling: application of distributed ledger technology in trading, clearing and settlement processes, J. Open Innov. Technol. Mark. Complex. 10 (July) (2024), https://doi.org/10.1016/j.joitmc.2024.100348.
[96] T.B. Malla, A. Bhattarai, A. Parajuli, A. Shrestha, Status, challenges and future directions of blockchain technology in power system: a state of art review, Energies 15 (8571) (2022), https://doi.org/10.3390/en15228571 (Basel).
[97] Y. Li, et al., A non-transferable trade scheme of green power based on blockchain, Energies 17 (2024), https://doi.org/10.3390/en17164002 (Basel).
[98] J. Yang, Blockchain For peer to Peer Energy Trading, Nanyang Technological University, 2020, https://doi.org/10.32657/10356/139944.
[99] W. Hu, Y.W. Hu, W. H, W.Q. Yao, H.H. Lu, Li, Z.W. Lv, A blockchain - based smart contract trading mechanism for energy power supply and demand network, Adv. Prod. Eng. Manag. 14 (3) (2019) 284–296, https://doi.org/10.14743/apem2019.3.328.
[100] M.N. El-din, N.M.M. Ramos, J.P. Martins, F.P. Pereira, The role of blockchain-secured digital twins in promoting smart energy performance-based contracts for buildings, Energies 17 (2024), https://doi.org/10.3390/en17143392 (Basel).
[101] G. Gurjar, M.D. Nikose, Smart contract framework for secure and efficient P2P energy trading with blockchain, J. Electr. Eng. Technol. (2024), https://doi.org/10.1007/s42835-024-02043-y.
[102] S. Bouraga, A taxonomy of blockchain consensus protocols: a survey and classification framework, Expert Syst. Appl. 168 (November 2020) (2021), https://doi.org/10.1016/j.eswa.2020.114384.
[103] F. Michalopoulos, S. Vavilis, H. Niavis, K. Loupos, Global Internet of Things and Edge Computing Summit, Springer, First. Brussels, Belgium, 2025, https://doi.org/10.1007/978-3-031-78572-6_12. Communications in Computer and Information Science.
[104] J. Powell, A. McCafferty-Leroux, W. Hilal, S.A. Gadsden, Smart grids: a comprehensive survey of challenges, industry applications, and future trends, Energy Rep. 11 (May) (2024) 5760–5785, https://doi.org/10.1016/j.egyr.2024.05.051.
[105] A.K. Jain, N. Gupta, B.B. Gupta, A survey on scalable consensus algorithms for blockchain technology, Cyber Secur. Appl. 3 (2024) 2025, https://doi.org/10.1016/j.csa.2024.100065.
[106] H. Chabok, A. Moeini, I. Kamwa, A fair and efficient transactive energy trading framework hosting distributed ledger technology, IEEE Trans. Industr. Inform. 21 (4) (2025) 2977–2986, https://doi.org/10.1109/TII.2024.3514208.
[107] D. Galeano-Suárez, D. Toquica, N. Henao, K. Agbossou, J.C. Oviedo-Cepeda, M. Fournier, Technical assessment framework for cost-sharing agreements in transactive energy systems, Comput. Electr. Eng. 124 (April) (2025), https://doi.org/10.1016/j.compeleceng.2025.110356.
[108] Z. Zhang, M. Zhang, Y. Li, B. Fan, L. Jiang, Directed acyclic graph blockchain for secure spectrum sharing and energy trading in power IoT, China Commun. 20 (5) (2023) 182–197, https://doi.org/10.23919/JCC.2023.00.013.
[109] A.K. Yadav, K. Singh, A.H. Amin, L. Almutairi, T.R. Alsenani, A. Ahmadian, A comparative study on consensus mechanism with security threats and future scopes: blockchain, Comput. Commun. 201 (October 2022) (2023) 102–115, https://doi.org/10.1016/j.comcom.2023.01.018.
[110] D. Sousa-Dias, D. Amyot, A. Rahimi-Kian, J. Mylopoulos, Enhancing trust in transactive energy with individually linkable pseudonymous trading using smart contracts, Energies 17 (2024) 1–20, https://doi.org/10.3390/en17143568 (Basel).
[111] A. Laszka, K. Kvaternik, TRANSAX: a blockchain-based decentralized forward-trading energy exchange for transactive microgrids, in: Proceedings of the IEEE

24th International Conference on Parallel and Distributed Systems (ICPADS), Singapore, IEEE, 2018, pp. 918–927, https://doi.org/10.1109/ICPADS.2018.00123.
[112] Z. Ayoub, M. Ouassaid, M. Maaroufi, R. Rabeh, Energy exchange management in a prosumer microgrid cluster: a piece of cake, Energy Syst. (0123456789) (2024), https://doi.org/10.1007/s12667-024-00670-y.
[113] K. Mehboob, K. Junaid, A. Darakhshan, S. Mohammed, A. Shabir, TruPro: a blockchain-based decentralised prosumer electricity trading platform for electrical vehicles (EVs), Clust. Comput. 5 (2024) 13871–13896, https://doi.org/10.1007/s10586-024-04639-5, 3456789.-volV)(0123456789.,- volV).
[114] S. Smart, et al., IoT intelligent energy management across smart grids deploying, IoT 5 (2024) 560–591, https://doi.org/10.3390/iot5030025.
[115] A. Das, S.D. Peu, M.A.M. Akanda, A.R.M.T. Islam, Peer-to-Peer energy trading pricing mechanisms: towards a comprehensive analysis of energy and network service pricing (NSP) mechanisms to get sustainable enviro-economical energy sector, Energies 16 (5) (2023), https://doi.org/10.3390/en16052198 (Basel).
[116] M. Massaoudi, K.R. Davis, K.A. Haque, Analysis and quantification of demand flexibility for resilient distribution networks: a systematic review, IEEE Access 13 (February) (2025), https://doi.org/10.1109/ACCESS.2025.3548526.
[117] A. Raza, L. Jingzhao, M. Adnan, M. Sajid, Transforming smart homes via P2P energy trading using robust forecasting and scheduling framework HEM LS, Results Eng. 23 (August) (2024), https://doi.org/10.1016/j.rineng.2024.102766.
[118] J. Tan, W. Pan, Y. Li, H. Hu, C. Zhang, Energy-sharing operation strategy of multi-district integrated energy systems considering carbon and renewable energy certificate trading, Appl. Energy 339 (March) (2023), https://doi.org/10.1016/j.apenergy.2023.120835.
[119] V. Anil, S.L. Arun, Credit rating-based transactive energy system with uncertainties in energy behavior, IEEE Access (November) (2023), https://doi.org/10.1109/ACCESS.2023.3336400. Credit.
[120] U. Mussadiq, A. Mahmood, S. Ahmed, S. Razzaq, I. Koo, Economic and climatic impacts of different peer-to-peer game theoretic – based energy trading systems, IEEE Access 8 (2020), https://doi.org/10.1109/ACCESS.2020.3033811.
[121] S. Oprea, A. Bâra, A recommendation system for prosumers based on large language models, Sensors 24 (2024), https://doi.org/10.3390/s24113530.
[122] C. Sabillon, A.A. Mohamed, A. Golriz, B. Venkatesh, Comprehensive platform for distribution transactive energy markets, IET Gener. Transm. Distrib. (February) (2021) 2344–2355, https://doi.org/10.1049/gtd2.12182.
[123] B.A. Jnr, W. Sylva, J.K. Watat, S. Misra, A framework for standardization of distributed ledger technologies for interoperable data integration and alignment in sustainable smart cities, J. Knowl. Econ. 15 (2023) 12053–12096, https://doi.org/10.1007/s13132-023-01554-9.
[124] GAO-19-704SP, Blockchain and distributed energy technologies, GAO Sci. Technol. Assess. Anal. (September) (2019).
[125] D.D.F. Maesa, M. Loporchio, F. Tietze, Privacy-preserving and automated intellectual property license agreements over heterogeneous blockchain networks, Blockchain Res. Appl. 100288 (2025), https://doi.org/10.1016/j.bcra.2025.100288.
[126] Q. Huang, et al., Simulation-based valuation of transactive energy systems, IEEE Trans. Power Syst. 34 (5) (2019) 4138–4147, https://doi.org/10.1109/TPWRS.2018.2838111.
[127] Y. Lu, J. Lian, M. Zhu, K. Ma, Transactive energy system deployment over insecure communication links, IEEE Trans. Autom. Sci. Eng. 21 (3) (2024) 2677–2688, https://doi.org/10.1109/TASE.2023.3267034.
[128] Y. Xiao, et al., Blockchain-assisted secure energy trading in electricity markets: a tiny deep reinforcement learning-based Stackelberg game approach, Electronics 13 (2024), https://doi.org/10.3390/electronics13183647 (Basel).
[129] C. Sun, Y. Liu, Y. Li, S. Lin, H. Gooi, J. Zhu, Network-aware P2P multi-energy trading in decentralized electric-heat systems, Appl. Energy 345 (April) (2023), https://doi.org/10.1016/j.apenergy.2023.121298.
[130] Jing; Fu C. Wang, J. Xing, Y. Wang, Z. Xu, X. Benjie, L. Haoming, Bidding strategy for the alliance of prosumer aggregators in the distribution market, Energies 17 (2024) 1–17, https://doi.org/10.3390/en17195006 (Basel).
[131] W. Zhong, K. Xie, Y. Liu, C. Yang, S. Xie, Auction mechanisms for energy trading in Multi-energy systems, IEEE Trans. Industr. Inform. 14 (4) (2018) 1511–1521, https://doi.org/10.1109/TII.2017.2787751.
[132] W. Bao-ying, X. Yu, J. Karimpoor, A novel forecasting method based on the economic and demand response for FC/WT/PV unit and a 3 in 1 TES energy storage, Int. J. Hydrog. Energy 6 (2021), https://doi.org/10.1016/j.ijhydene.2021.07.074.
[133] Z. Wang, M. Mae, T. Yamane, M. Ajisaka, T. Nakata, R. Matsuhashi, Convolutional neural network – Long short-term memory ensemble learning approach with multimodal data integration, Energies 17 (2024) 1–17, https://doi.org/10.3390/en17112687 (Basel).
[134] K. Ajai, K.P. Pancholi, S.N. Islam, A. Anwar, A.M.T. Oo, Rolling horizon optimisation based peer to peer energy trading under real time variations in demand and generation, Energy Syst. (2023) 541–565, https://doi.org/10.1007/s12667-022-00511-w.
[135] B. Wang, C. Zhang, C. Li, Transactive energy sharing in a microgrid via an enhanced distributed adaptive robust optimization approach, IEEE Trans. Smart Grid 13 (3) (2022) 2279–2293, https://doi.org/10.1109/TSG.2022.3152221.
[136] S. Tian, et al., An optimization strategy for EV-integrated microgrids considering peer-to-peer transactions, Sustainability 16 (2024), https://doi.org/10.3390/su16208955.
[137] Q. Yu, A. Meeuw, F. Wortmann, Design and implementation of a blockchain multi-energy system, Energy Inform. 1 (17) (2018), https://doi.org/10.1186/s42162-018-0040-4.
[138] W. Zhou, J. Lai, X. Li, Z. Zeng, A novel dynamic peer-to-peer carbon right sharing scheme for microgrid clusters, IEEE Trans. Smart Grid (2025) 1–12, https://doi.org/10.1109/TSG.2025.3555305.
[139] Z. Sun, Z. Li, Y. Xue, X. Chang, H. Li, J.H. Zheng, Price-function-free energy pricing in Bilevel peer-to-peer energy markets considering network security, Appl. Energy 391 (April) (2025), https://doi.org/10.1016/j.apenergy.2025.125864.
[140] O. Tooki, O. Popoola, Intelligent-based techniques for detection, identification and mitigation of cyberattacks in cyber-physical power systems: a review, in: Proceedings of the 11th IEEE PES & IAS Power Africa Conference (PAC 2024) "Towards Ensuring Energy Security in Africa, Johannesburg, South Africa, October 7 –11, 2024, 2024, https://doi.org/10.1109/PowerAfrica61624.2024.10759370.
[141] O. Tooki, O. Popoola, Application of cyber-physical system models in detection and mitigation of cyberattacks in a transactive energy system: a review, in: Proceedings of the 2024 International Conference On Emerging Trends In Networks And Computer Communications (ETNCC) July 23 - 25, 2024, Windhoek, Namibia, 2024, https://doi.org/10.1109/ETNCC63262.2024.10767560.
[142] J. Ferré-queralt, J. Castellà-roca, A. Viejo, Blockchain-based hierarchical smart contracts to prevent user profiling in decentralized energy trading systems, Sustain. Energy Grids Netw. 43 (March) (2025), https://doi.org/10.1016/j.segan.2025.101762.
[143] N.A. Abdul, A. Salih, S. Golshannavaz, T. Ghanizadeh-bolandi, A local transactive energy market for microgrids considering techno-economic interactions with distribution system, J. Energy Manag. Technol. (JEMT) 9 (1) (2024) 40–54.
[144] A.A. Ardebili et al., Enhancing resilience in complex energy systems through real-time anomaly detection: a systematic literature review, vol. 7, no. 1. 2024. doi:10.1186/s42162-024-00401-8.
[145] M.I. El-Afifi, B.E. Sedhom, S. Padmanaban, A.A. Eladl, A review of IoT-enabled smart energy hub systems: rising, applications, challenges, and future prospects, Renew. Energy Focus 51 (September) (2024), https://doi.org/10.1016/j.ref.2024.100634.
[146] A. Boumaiza, Design and implementation of a blockchain-enabled transactive energy market, IEEE Access 12 (October) (2024), https://doi.org/10.1109/ACCESS.2024.3440180.
[147] A.J. Onumanyi, S.J. Isaac, Transactive energy: state-of-the-art in control strategies, architectures, and simulators, IEEE Access 9 (2021), https://doi.org/10.1109/ACCESS.2021.3115154.
[148] Y. Zhou, J. Wu, W. Gan, P2P energy trading via public power networks: practical challenges, emerging solutions, and the way forward, Front. Energy 17 (2) (2023) 189–197, https://doi.org/10.1007/s11708-023-0873-9.
[149] A. Gorbatcheva, Scalability of Peer-To-Peer Energy Trading markets: A case-Based Approach, University College London, 2025.
[150] S.C. Doumen, D.S. Boff, S.E. Widergren, J.K. Kok, Taming the wild edge of smart grid – Lessons from transactive energy market deployments, Electr. J. 36 (2–3) (2023), https://doi.org/10.1016/j.tej.2023.107253.
[151] D. Boff, A. Somani, S. Widergren, Transactive Energy Practices Survey, Pacific Northwest National Lab. (PNNL, 2022.
[152] S.N. Gourisetti et al., "Blockchain smart contracts for transactive energy systems," 2019.
[153] S. Mohammadi, F. Eliassen, Y. Zhang, H.A. Jacobsen, Detecting false data injection attacks in peer to peer energy trading using machine learning, IEEE Trans. Dependable Secure Comput. 19 (5) (2022) 3417–3431, https://doi.org/10.1109/TDSC.2021.3096213.
[154] S. Tiwari, J.G. Singh, A cooperation based transactive energy management for networked energy hubs considering improved payoff allocation mechanism, Sustain. Energy Technol. Assess. 65 (August 2022) (2024), https://doi.org/10.1016/j.seta.2024.103777.
[155] M.F. Dynge, P. Crespo del Granado, N. Hashemipour, M. Korpås, Impact of local electricity markets and peer-to-peer trading on low-voltage grid operations, Appl. Energy 301 (December 2020) (2021), https://doi.org/10.1016/j.apenergy.2021.117404.
[156] M. Parhamfar, I. Sadeghkhani, A.M. Adeli, Towards the net zero carbon future: a review of blockchain-enabled peer-to-peer carbon trading, Energy Sci. Eng. 12 (3) (2024) 1242–1264, https://doi.org/10.1002/ese3.1697.
[157] P. N. N. Laboratory, "Blockchain | PNNL." Accessed: Jun. 15, 2025. [Online]. Available: https://www.pnnl.gov/projects/transactive-systems-program/blockchain.
[158] IEEE, "IEEE Sa - IEEE P2418.5." Accessed: Jun. 15, 2025. [Online]. Available: https://standards.ieee.org/ieee/2418.5/11217/.
[159] Y.S.A. Kwateng, D. Qiu, G. Strbac, Incentivising peers in local transactive energy markets: a case study for consumers, prosumers and prosumagers, IET Smart Grid (November 2023) (2024) 672–694, https://doi.org/10.1049/stg2.12166.
[160] S. Credle, et al., Blockchain research and development activities sponsored by the U.S. Department of Energy and Utility Sector, Energies 18 (3) (2025) 1–48, https://doi.org/10.3390/en18030611 (Basel).
[161] S. Chen, J. Ping, Z. Yan, J. Li, Z. Huang, Blockchain in energy systems: values, opportunities, and limitations, Front. Energy 16 (1) (2022) 9–18, https://doi.org/10.1007/s11708-022-0818-8.

[162] X.S. Song, S.Y. Li, Performance analysis of DAG-based blockchain systems based on markovian arrival process, IEEE Access 13 (November 2024) (2025), https://doi.org/10.1109/ACCESS.2025.3529739.

[163] A. Villafranca, et al., Comparing blockchain and DAG technologies for smart agriculture traceability in terms of efficiency and latency, Simul. Model. Pract. Theory 142 (May) (2025), https://doi.org/10.1016/j.simpat.2025.103131.

[164] Y. Bai, S. Lee, S.H. Seo, A survey on directed acyclic graph-based blockchain in smart mobility, Sensors 25 (4) (2025) 1–43, https://doi.org/10.3390/s25041108.