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Microgrid Transactive Energy: Review, Architectures, Distributed Ledger Technologies, and Market Analysis

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ABSTRACT Prosumer concept and digitilization offer the exciting potential of microgrid transactive energy systems at distribution level for reducing transmission losses, decreasing electric infrastructure expenditure, improving reliability, enhancing local energy use, and minimizing customers' electricity bills. Distributed energy resources, demand response, distributed ledger technologies, and local energy markets are integral parts of transaction energy system for emergence of decentralized smart grid system. Hence, this paper discusses transactive energy concept and proposes seven functional layers architecture for designing transactive energy system. The proposed architecture is compared with practical case study of Brooklyn microgrid. Moreover, this paper reviews the existing architectures and explains the widely known distributed ledger technologies (blockchain, directed acyclic graph, hashgraph, holochain, and tempo) alongwith their advantages and challenges. The local energy market concept is presented and critically analyzed for energy trade within a transactive energy system. This paper also reviews the potential and challenges of peer-to-peer and community-based energy markets. Proposed architecture and analytical review of distributed ledger technologies and local energy markets pave the way for advanced research and industrialization of transactive energy systems.

INDEX TERMS Blockchain, decentralization, demand response, distributed ledger technologies, energy trading, local energy market, microgrid, peer-to-peer market, prosumer, renewable energy sources, smart grid, system architectures, transactive energy.

I. INTRODUCTION

Conventional power system uses mainly diesel, coal, and natural gas–based generation units for producing electric energy. However, these conventional generation sources (CGSs) heavily contributes in greenhouse gas emissions (GHGs), which leads to increased global warming and abrupt climate changes. Hence, CGSs capacity cannot be indefinitely increased to meet increasing global energy demand. The alternative green energy solutions are renewable energy sources (RESs). Researchers, academics, and industrialists have been working on technical advancements and deployment of these RESs worldwide. PV systems and wind turbines are the most deployed RESs due to their high technology maturity level and energy potential [1].

As small scale RESs are locally being installed in distribution systems, they are also referred as distributed energy resources (DERs). DERs are potentially helping in improving reliability and power quality of power system as they are installed close to load ends and they can meet energy demand locally. However, wind turbines and PV systems produce intermittent electric power, which is also uncertain.

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Moreover, they are non–dispatchable DERs. Hence, management and control of DERs require Microgrid (MG) system for their smooth operation and effective integration into power system [2]–[4]. MGs face power balancing problems due to non-dispatchable and intermittent nature of RESs [5]. Energy storage systems and/or CGSs can be used to resolve this balancing issue [6], [7]. However, alternative solutions are also needed as CGSs cause high GHG emissions, which lead to global warming, and ESSs alone cannot mitigate the balancing problem. Demand response and prosumers are the best emerging solutions that can help in balancing power demand locally [8], [9].

Demand response is defined as a tariff or program established to motivate changes in electric consumption by end-use customers in response to changes in the price of electricity over time [10]. Prosumer is defined as a customer that can both produce and consume energy with the possible potential of demand response capabilities [11]. In traditional power systems, customers can only consume energy at fixed price or time-of-use price rates. However, prosumers can sell surplus energy into local markets and neighboring prosumers/consumers. They aim to reduce their energy bills by selling excess energy to other prosumers and consumers. The smart home–based prosumers market is expected to be \$53 billion by 2022 and the annual growth rate of prosumers–based households can reach 14.5% between 2017 and 2022 [12]. Prosumers and consumers also take advantage of demand response capabilities with the advancement in intelligent responsive load devices (IRLDs). IRLDs can auto-regulate the power consumption by responding to price control signals, thus ensuring power quality and reliability of the distribution system and decreased energy bills for consumers. To this end, Internet of things (IoTs) based smart meters are required for real–time communication among all users [13].

Distributed generation and prosumers are changing the way the revenue owes in the energy value chain and changing the value chain itself. Moreover, some countries have also taken initiatives in promoting local energy production and consumption [14]. Hence, prosumers can actively participate to the growing energy economy in the near future [15]. The integration number of prosumers naturally implies the requirement of establishing an electricity trading mechanism for prosumers to trade electricity with each other. In this regard, transactive energy (TE) concept has been proposed in the literature to achieve all the aforementioned objectives [16].

TE is a system comprised of coordinated participants that use automation tools to communicate and exchange energy based on value and grid reliability constraints. TE uses market–based economic transactions and control functionality for energy trading and sharing among prosumers, renewable and conventional power producers, storage systems, and active consumers within an electric power system [17]. With transactive energy system (TES), energy is becoming a commodity for customers. They can trade their surplus energy either in real–time or on a deferred basis. For the latter case, energy storage systems are required [18]. Distributed ledger technology (DLT) and local energy market (LEM) are integral parts in decentralized TES realization.

TESs maintain system reliability and control with optimal integration of DERs and prosumers. They provide scalable, adaptable, and extensible, highly automated platform across a number of devices, participants, and geographic extents. They ensure coordinated self-optimization for distributed energy trade among participants. They also provide non-discriminatory participation by qualified participants. Finally, they also ensure that all transacting parties are accountable for standards of performance

Microgrid TES (MG-TES) is an information and communication technology–based ecosystem that uses communication technologies, Internet, and mobile networks–based hardware/software platform to trade energy among power producers, prosumers, and consumers [19]. The energy trading and sharing process is achieved by determining market equilibrium at market clearing price (MCP) using real–time information of bids and offers. The energy management objectives of an MG-TES can be dynamic demand supply balance, profit maximization of power producers, reduced GHG emissions, cost minimization of MG system and prosumers, and congestion management among others. MG-TESs are practically implemented and tested in various practical projects, such as Brooklyn MG [20], South Australian residential MG [21], Allgau MG [22], and other projects as mentioned in [23]–[25].

Few reviews exist in the literature in the framework of transactive energy systems. TE and demand response were reviewed in terms of their characteristics, industry practices, potentials, and challenges in [26]. However, functional framework and DLTs are not discussed. In [27], TE concepts were presented alongwith the details of its pilot projects and transactive control approaches. However, DLTs and LEMs, which are integral parts of decentralized TES, are not discussed. A survey on peer-to-peer (P2P) transactive energy exchange in LEMs was presented in [28]. Blockchain potentials and challenges were highlighted for decentralized TES implementation. A 3-layer DLT-based transactive management infrastructure was introduced for managing LEMs. A permissioned blockchain with a proof of energy, a simplified proof of stake version, consensus mechanism was presented for reducing energy demand as compared to Bitcoin proof of work consensus mechanism and promoting social behavior based on circular economy. However, only permissioned blockchain was discussed in this survey among all DLTs, which lacks customer transparency as it is more inclined to centralized transaction system. Moreover, the potentials and challenges of other DLTs should also be reported for selecting suitable DLT for transaction energy-based power system operation.

This paper addresses the importance of MG-TES in particular and TES in general. The supervisory control

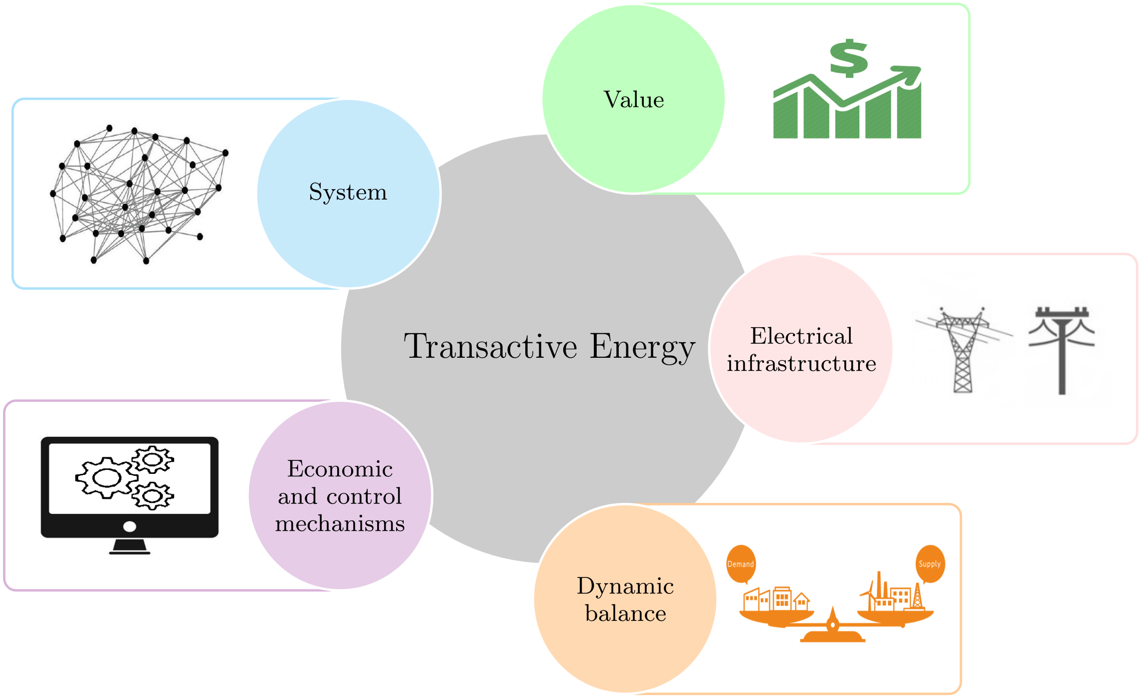


FIGURE 1. Transactive energy concept.

of MG-TES are presented to highlight the advantages of decentralized MG-TES. Decentralized MG-TES lacks comprehensive architecture in terms of functional components or layers. Hence, seven functional layers have been proposed for designing a novel decentralized MG-TES architecture that represents its working characteristics and standardization. The proposed seven functional layers are then evaluated with practical example of the Brooklyn MG. Furthermore, widely known DLTs are reviewed and explored including their advantages and challenges. These DLTs are blockchain, directed acyclic graph, hashgraph, holochain, and tempo. They are evaluated on the basis of key performance parameters such as hash-chain structure, scalability, energy use, transaction fee, latency, popularity, and security. This paper also discusses concept and challenges of LEM. Finally, P2P and community-based energy market are summarized including their strengths and limitations.

The rest of the paper is organized as follows. Section II describes the transactive energy concept and supervisory control of MG-TES. Section III introduces 3-layers and 5-layers architectures and proposes 7-layers architecture for decentralized MG-TES. Section IV explains widely known DLTs, blockchain, directed acyclic graph, hashgraph, holochain, and tempo, and provides comparison of their characteristics. Section V illustrates concept and challenges of local energy market alongwith discussion on its two main types; peer-to-peer and community-based energy market. Finally, the concluding remarks and recommendations are presented in section VI.

II. MICROGRID TRANSACTIVE ENERGY SYSTEM

A. TRANSACTIVE ENERGY CONCEPT

Prosumers are gaining increased awareness in benefits of using IRLDs and RESs. With RESs, prosumers can have surplus energy, which has evolved the concept of prosumers participation in energy market. They can bid their surplus energy with competing prices, which helps them in energy bills reduction or profit increase. This active involvement of prosumers causes bi-directional power flow in MG system. Therefore, MG system requires bi-directional power flow management to ensure smooth energy transactions among all users. Hence, TE concepts have been defined in the literature for achieving bi-directional energy transactions in an effective market-driven system. TE uses economic, automation and control tools to exchange energy based on economic value and operational constraints, as shown in Fig. 1.

Transactive energy is defined by the GridWise Architecture Council [16] as "a system of economic and control mechanisms that allows the dynamic balance of supply and demand across the entire electrical infrastructure using value as a key operational parameter." In this definition, the system refers to a network of multiple participants having individual and/or social goals and following common set of rules. Economic and control mechanisms ensure that the coordination and control among all participants is achieved without technical constraints violation of market-driven system. Dynamic balance of supply and demand refers to the fact that supply and demand are continuously changing that needs constant balancing for avoiding any unstable equilibrium and ensuring entire electrical infrastructure safety. The value refers to the

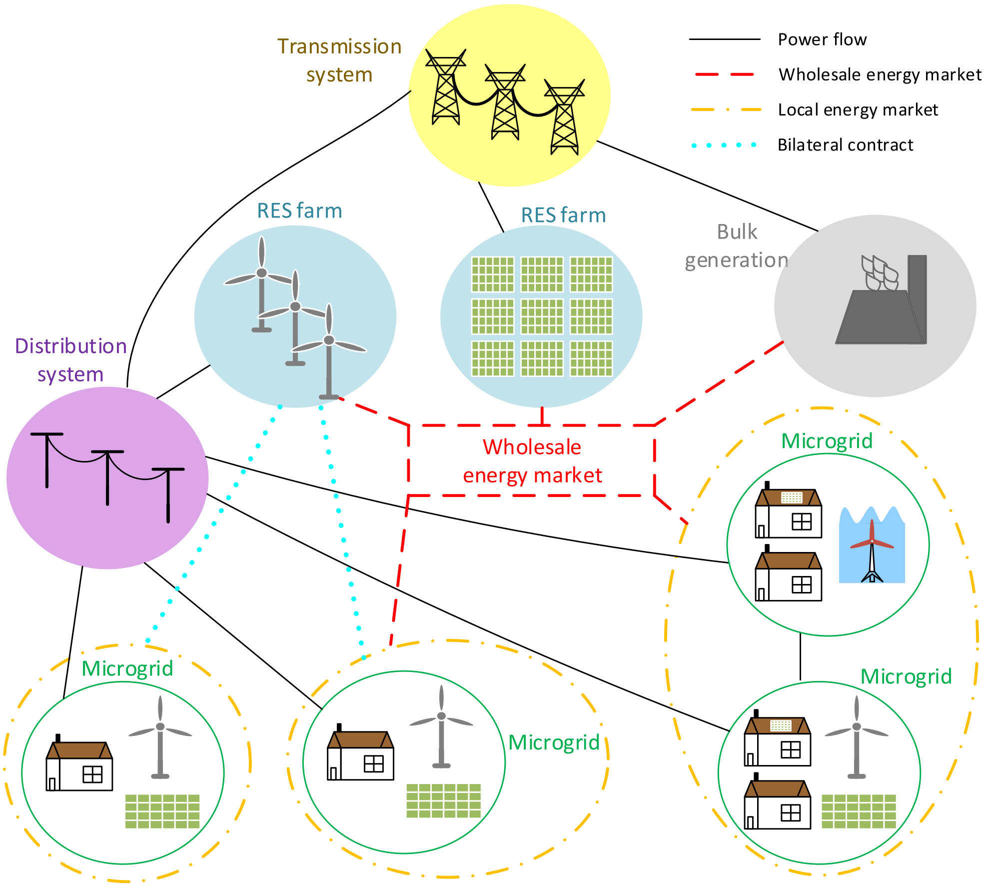


FIGURE 2. Schematic representation of transactive power system.

MCP for system participants to trade and consume energy in a win-win approach, which means all the participants are getting fair incentives. MCP is the key for operating the market and realizing a TES. MCP is defined as a short term locational marginal price of per unit energy transaction, which should be transparent to all participants. Moreover, all the energy transaction decisions within a TES are based on these price signals.

Figure 2 presents a general illustration of TE-based power system. LEMs of MGs are a platform that helps residential and commercial prosumers to participate and trade their energy for monetary benefits. The participation of these small prosumers in LEMs eventually help in realization of a TE-based power system. In this system, power producers and LEMs are transacting energy based on the price signals determined by wholesale energy markets. Wholesale energy market collects the bids and offers of all participants. It also receives the cost signals for the use of transmission and distribution system for power exchange to determine MCP. Large MGs can also have long and short duration bilateral contracts with power producers and they are represented by dotted blue line. Small MGs may also prefer buying and selling energy at fixed or time-of-use energy price instead of participating in wholesale energy markets. An LEM can be operated for only one MG as well as a group of community MGs. Hence, wholesale and local energy markets play important roles in achieving an efficient TES in a smart grid perspective. Moreover, small prosumers are essential entities in successful realization of transactive power system, which can be achieved by integrating these prosumers in a transactive energy-based MG system.

B. SUPERVISORY CONTROL

Supervisory control ensures smooth and efficient operation of MG transactive energy system. All participants send information to either central controller or local controllers for collecting and analyzing informations or data to determine necessary optimal decision strategies for each participant. Participants refer to electric equipments and devices, whose operational preferences are set by consumers, prosumers and producers. Hence, MG-TES can have centralized or local supervisory control. Therefore, it is classified into two main categories; centralized MG-TES and decentralized MG-TES. The comparison between centralized and decentralized MG-TESs is presented in Table 1.

1) CENTRALIZED MG-TES

Centralized system uses a single authority to control all operations on the system. A conventional power system is a centralized system in which all participants are dependent on a

TABLE 1. MG-TESs comparison.

MG-TES	Centralized	Decentralized
Scalability	Low	High
Transparency	Low	High
Reliability	Low	High
Computational cost	High	Low
Communication cost	High	Low
Customer centricity	Low	High
Implementation difficulty	Low	High

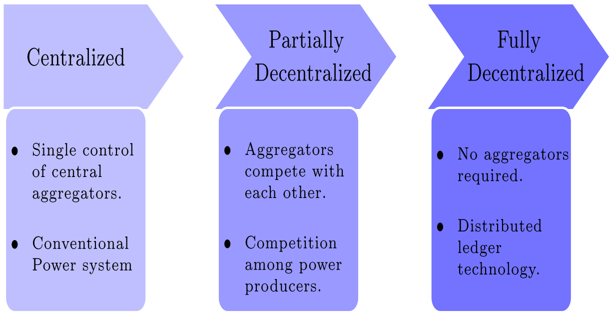


FIGURE 3. Decentralization stages.

single source of control. In a centralized MG-TES, microgrid operator (MGO) acts as a central controller and market operator. All MG participants sends their energy bids and offers to MGO using cloud infrastructure. MGO aggregates all the bids and offers to determine MCP, while satisfying technical and operational constraints. MGO then sends back this price signal to all participants to initiate energy transactions.

A centralized MG-TES was proposed in [29] for smart grid system realization. Cloud infrastructure is used for data and informations exchange among central controller and participants. The centralized energy trading model minimizes overall energy cost of MG system, which includes energy cost of households, disutility cost due to time delay in IRLDs operation, and energy trading cost with utility grid (UG). In [30], a centralized TES has been developed by Sonnen-Community for realization of a P2P energy trading project among smart homes. This centralized TES achieves supply demand balance without violating any operational constraint. In [12], energy cost is minimized for MG smart homes using cloud environment. Pareto optimality concept is used for fair cost distribution among participants. Cloud-based TES is presented in [31] to minimize energy cost of prosumers and maximize profit of DERs.

A centralized energy management system was developed for optimal economic operation of grid-connected multiple home MG system [32]. It consists of prosumers and consumers that have profit maximization and cost minimization objectives, respectively. The developed multi-objective energy management problem determines optimal MCP and decision strategies for homes using Nikaido-Isoda relaxation algorithm. In [33], a two-stage TES is developed for maximizing net profit. The proposed TES is analyzed in a co-optimized energy and ancillary services market framework. First stage performs a day-ahead decision, while second stage is related to real-time balancing scheme for transactive energy.

Centralized MG-TES has a biggest problem of scalability due to growing integration of prosumers and IRLDs into electrical infrastructure and having difficulty in accommodating users' diverse objectives. Besides, it also experiences high risks of cyber-attacks and security threats as all the sensitive information is transferred to a central platform. Centralized MG-TES has higher communication cost as compared to a decentralized one, due to constant data and information sharing among participants and central controller. Finally, big player may influence on local MCP, which results in unfair energy trading. Hence, decentralized MG-TES is preferred due to scalability, fair price competition, and privacy benefits [34]. Therefore, the rest of the paper shall cover solely decentralized MG-TES.

2) DECENTRALIZED MG-TES

In a decentralized system, participants or nodes are not dependent on a single source of control. Instead, it is distributed among many nodes. Fig. 3 presents various stages of decentralization process [35]. A conventional approach is shown on left-hand side in which system is centrally controlled just like a conventional power system. In a partially decentralized stage, participants select third party intermediaries, like energy brokers and aggregators, based on their performances and incentives. Intermediaries negotiate competitive prices with power producers on behalf of their participants. On right-side, a fully decentralized approach is shown in which no aggregators are required for energy transactions and negotiations. A fully decentralized energy system can be practically realized by using DLT, as it is used in Bitcoin for achieving decentralized financial system [36].

Decentralized MG-TES provides secure and transparent energy transactions process. It uses DLT for this purpose, which also provides an added advantage of scalability property. Each MG participant acts simultaneously as server and client and stores the same copy of data. Once the consensus is reached among participants, transaction is validated and new data is stored. Hence, it reduces cyber-attacks risk and improves transparency.

III. DECENTRALIZED TES ARCHITECTURE

Decentralized TES aims to achieve specified economic and operational objectives related to the coordinated integration of prosumers, power producers, and DERs. It can overcome intermittency problems of RESs by engaging more prosumers and active consumers in energy transaction, which is the key feature of TES. A general setup of decentralized MG-TES is presented in Fig. 4. All the power producers, network operator, prosumers, and active consumers share energy bids and offers through a transactive trading platform based on

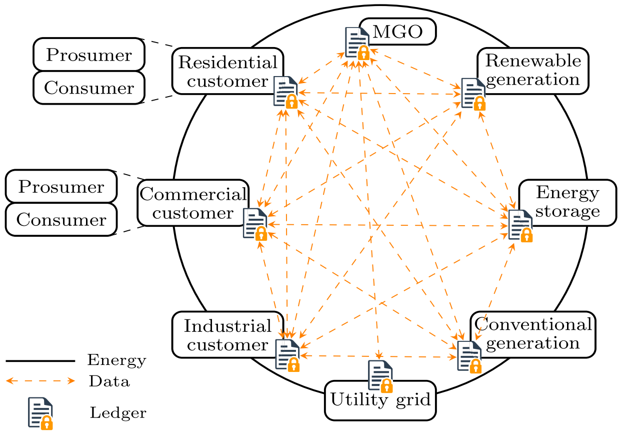


FIGURE 4. Example of microgrid transactive energy system setup.

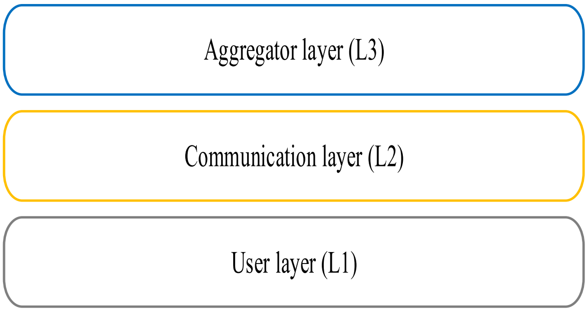


FIGURE 5. 3-layer transactive energy system architecture [28].

dynamically changing preferences. The operational objectives can be mutual economic benefit, reduced energy cost, environment sustainability, and system efficieny and reliability among others. Various TES architectures are explained in the following sections.

A. 3-LAYER TES ARCHITECTURE

Siano et *al.* has proposed a 3-layer architecture of transactive management infrastructure for enabling P2P energy transactions, which can also be used for MG-TES and an aggregator acts as an MGO [28]. The 3-layer architecture is shown in Fig. III-A. These layers are aggregator layer (L3), communication layer (L2), and user layer (L1), respectively.

In user layer (L1), all participants perform the necessary energy transaction operations. The participants are IRLDs and surplus energy from DERs, whose preferences and objectives are set by users. Participants exchange information with aggregators through IT infrastructure.

Communication layer (L2) ensures reliable communication among servers and participants. The communication platform can be internet cloud, or wired and wireless communication technologies for digital information flow. The selection of these technologies depends on TES requirements.

In aggregator layer (L3), aggregator owns data-center, which is controlled by either aggregator, MGO, or distribution system operator. It stores and analyzes data to accomplish virtual energy exchange process. It does not monitor validations and storage of energy transactions, which are managed by the DLT. The core components of this layer are publish-subscribe servers, smart meters database, and analytics component. Publish-subscribe servers are used to achieve ubiquitous and asynchronous communication among MG participants. Smart meters database contains participants' energy data, which are received from their smart meters. The analytics component performs the tasks of storing TE data for analysis and interpretation of TE operations.

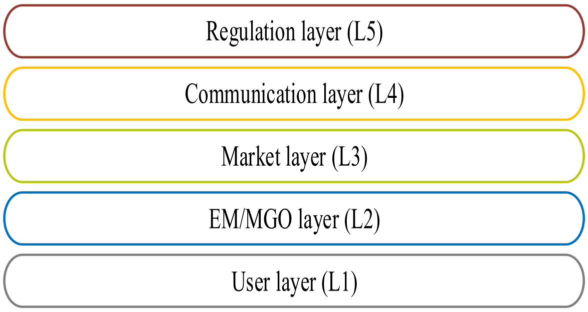


FIGURE 6. 5-layer architecture for transactive energy system [37].

The 3-layer architecture is informative but too simplistic to explain the TES mechanism. It does not include many stages like regulation and energy price determination. Moreover, electrical power network layers are also not mentioned to consider network losses, voltages deviations, and frequency deviation among others.

B. 5-LAYER TES ARCHITECTURE

Authors presented a 5-layer architecture for illustration of MG-TES mechanism, which is shown in Fig. III-B [37]. These layers are users layer (L1), MG operator (MGO)/energy management (EM) layer (L4), market layer (L5), communication layer (L6), and regulation layer (L7), respectively.

In user layer (L1), all participants send their bids and offers through DLT and communication devices. The bids and offers are sent with time stamps and key signatures for privacy and security. Home/building energy management systems (HEMSs/BEMSs) receives local MCP signals, which is used to start energy transactions and adjust power consumption and time-shift of IRLDs.

MGO/EM layer (L2) refers to MGO that optimizes economic and operation objectives of MG system. These objectives can be reduction in system losses, minimization of voltage and frequency deviations, improvement in system reliability, and congestion management among others. It also ensures dynamic supply demand balance. It performs analysis on participants' informations and data for more customer engagement in energy transactions.

Market layer (L3) reflects the decision strategies for determining local MCP. Market layer collects all energy bids and aggregates them to find optimum local MCP. It forwards MCP to participants for initiating energy transactions. For centralized TES, it uses cloud infrastructure. While, DLT is used for decentralized TES operations.

Communication layer (L4) is very important for reliable and fast information exchange among MG participants. Various wired and wireless communication platforms exist nowadays. However, their selection depends on various factors like geographical area, data-rate, and investment cost [2], [38].

The top layer is regulation layer, which is responsible for defining governance and regulation procedures for TES operation. These procedures and policies are necessary for smooth and transparent energy transactions among MG participants.

The 5-layer architecture is more extensive in explaining TES stages as compared to 3-layers architecture. However, it also does not include electrical network layer separately for determining congestion and losses effects of transmission and distribution lines on local MCP. Moreover, DLT layer should be defined to discuss DLTs architecture, smart contracts, and their implementation in TES framework. Hence, authors propose a 7-layer TES architecture in the following subsection.

C. PROPOSED 7-LAYER TES ARCHITECTURE

TES has various functionalities and operations in energy transactions mechanism. These functionalities have been divided into seven main layers, which are shown in Fig. III-C.2. These layers are categorized as user layer (L1), network layer (L2), system operator layer (L3), market layer (L4), distributed ledger layer (L5), communication layer (L6), and regulation layer (L7), respectively.

1) USER LAYER (L1)

User layer consists of MG participants and their hardware platforms that exchange data with other participants using DLT-based secured information system. All participants must have clear objective for their energy trade, which are usually selected by customers based on their preferences. Moreover, specific procedures and requirements must be defined that need to be satisfied by new participants for entrance and integration into an existing TES.

The energy trading forms must also be clearly defined like electricity trading, heat trading, or both. Each participant pursue its own individual objectives, and they are often conflicting objectives [39]. Sufficient number of MG participants, both prosumers and consumers, are needed for LEM to determine MCP effectively.

2) NETWORK LAYER (L2)

The network reflects the MG setup that MG is using either traditional UG network or its own physical electric infrastructure. Moreover, MG is grid-connected or stand-alone. In case of stand-alone MG system, all load demand must be supplied by local energy sources and system flexibility (energy storage and demand response). The energy supply is usually available from local DERs and prosumers. Flexibility can be provided in the form of IRLDs and energy storage systems [40].

For a grid-connected MG, dynamic supply demand balance is met with the help of UG. It can have several connection points with UG and energy exchange is measured with smart meters. In case of UG failure or disturbances, grid-connected MG operates in an islanded mode and uses local generation capacity and flexibility sources to maintain appropriate levels of supply security and resiliency. In Grid-connected MG-TES, MCP may increase due to additive factors of UG congestion cost and UG surcharges for using its network.

3) SYSTEM OPERATOR LAYER (L3)

This layer is responsible for storing and analyzing data for monitoring the operation of electrical power system during energy transactions. For a smart grid, this layer can be represented by transmission or independent system operator for handling data storage, data analytics, and voltage and frequency quality analysis of power system. In MG-TES, this layer is represented by MGO. It is responsible for meeting supply security objective for each MG participant. It must have a real-time access to aggregated demand supply data of all of its participants for data storage and analysis. It also performs statistical analysis on participants' aggregated data to encourage more customers to integrate and participate in energy trading process.

MGO/EMS can have various, often conflicting, objectives like emission, reliability, security, stability, power quality, and resiliency objectives. Customers can have objective of using more green energy, maximizing revenue or minimizing energy cost. MGO/EMS ensures that participants receive their required energy supply and their objectives are also met at the same time. In case of grid-connected operation, MGO/EMS also provides UG congestion cost and network usage cost information to market operator. It is different from central MGO/EMS in the sense that it neither collects all the participant's information nor performs energy trading tasks anymore. Hence, a transparent system leads to increased social acceptance of MG-TES, P2P and community energy markets. [41].

4) MARKET LAYER (L4)

Market layer is also very important layer in TES as it determines MCP for energy transactions among participants. Market collects all bids and offers from participants. Moreover, it also collects UG network congestion and usage cost from system operator. It aggregates all the bids and offers to determine optimal bidding strategy or MCP [42]. It is necessary for market operator to have access to participants' DLT accounts to collect bids and offers data only.

LEMs can also be divided into various stages like electricity market. These stages can be classified as day-ahead, real-time balancing, ancillary services, and bilateral contracts. Day-ahead stage can be same as of electricity market in which MGO participates to determine day-ahead bidding strategies. Real-time balancing stage is very important due to small power contributions of prosumers. It determines intra-day MCPs after a specified time step for achieving the tasks of energy allocation and real-time balancing. Ancillary services market stage can also be considered to control voltage and frequency deviations of MG system in real-time.

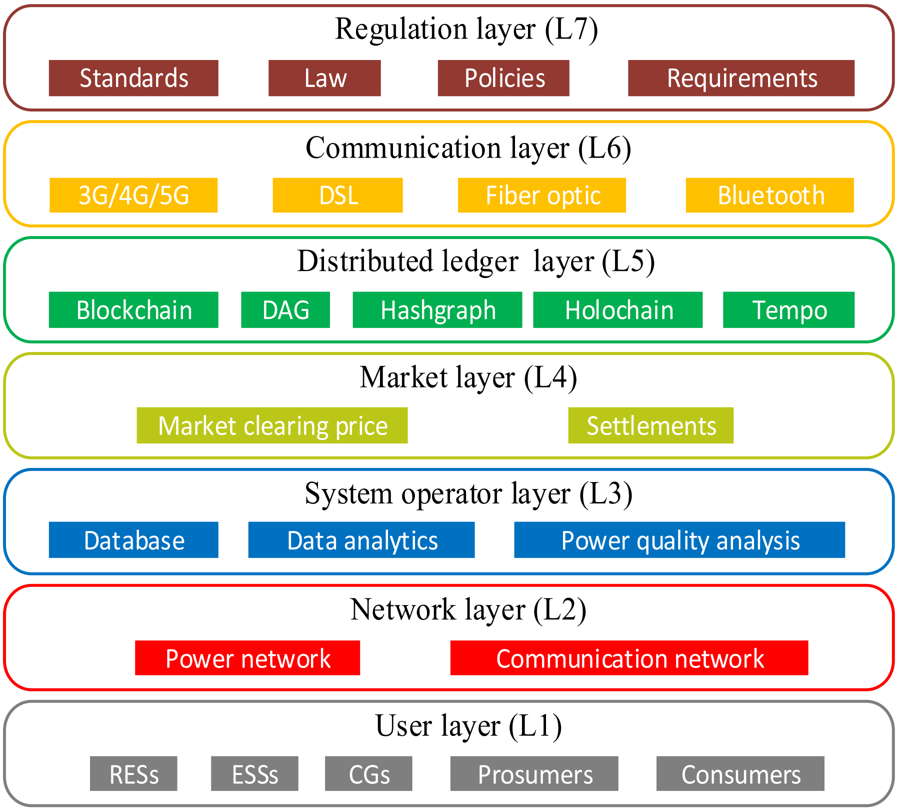


FIGURE 7. **7-layer model for decentralized transactive energy system.**

In bilateral contracts, participants negotiate price against a specified energy offer for over an extended period of time.

Market layer is also responsible for defining penalty mechanism for participants in case of contract violations. Participants can avoid these plenty prices by having nearly perfect consumption and generation predictions or using bilateral contracts. Plenty prices should neither be too high to discourage customers nor should it be too low to ensure system stability.

LEMs provides economic benefits to its participants because local MCP is normally lower than UG energy price, which also encourages participants to actively participate. However, if social objectives are given more value than economic gains, like minimization of GHG emissions, local MCP can go higher than UG energy price in such cases.

5) DISTRIBUTED LEDGER LAYER (L5)

It is the most important layer of TES for realization of a decentralized TES operation. DLTs provide digital platform to each participant to exchange their information among themselves for both energy and economic transactions validation. The data is not stored centrally, but it is distributed and recorded among multiple participants at the same time.

The main parts of DLT are ledgers, smart contracts, and consensus protocols. Ledger is used to record participants' key information and data. Smart contracts define user preferences and ensure implementation of agreed terms between two or more parties. Consensus protocols are used for transactions validation. Various types of DLTs are extensively discussed in section IV.

6) COMMUNICATION LAYER (L6)

This layer reflects fast, secure, and reliable communication infrastructure for information exchange among participants. DLT ledgers are transmitted using communication technologies. Communication system is essential for smooth operation of TES. The efficiency of TES operation is adversely affected by using poor communication infrastructure. The selection of communication technology in HEMSs and BEMSs is also important to control operations of their IRLDs and to monitor their energy generation and consumption data with smart meters [43].

Communication system in TES must meet some specific requirements based on bandwidth, coverage area, reliability, deployment cost, security, and latency [44]. However, the selection of communication system is difficult in MG-TES and smart grid applications due to different interoperability requirements among various components. Nonetheless, some articles have discussed the characteristics and traffic requirements of different communication technologies in the literature [45], [46]. In [2], the comparison among various wireless and wired communication

TABLE 2. Matching Brooklyn MG against 7-layer TES architecture.

Layer	Status	Remarks
L1	✓	Brooklyn MG aims to increase local supply security and RESs utilization. Customers are divided into consumers and prosumers.
L2	✓	Brooklyn MG is a grid-connected MG-TES, which uses UG electrical infrastructure for energy flow.
L3	✓	Customers set their price limits for local RESs and provide details on their socio-economic preferences.
L4	✓	Double-auction mechanism is used to determine local MCP after a fixed time step.
L5	✓	Blockchain-based DLT structure is used for energy transactions among Brooklyn MG participants.
L6	✓	A reliable and secure communication system exists for data monitoring, data storage, and transactions validation.
L7	✗	Brooklyn MG is working with regional utility company to define legislative policies for legal implementation of MG-TES.

technologies is presented for possible use in MG energy management applications.

7) REGULATION LAYER (L7)

Regulation layer is important for practical physical implementation of TES. TES regulatory policies must be defined for successful evolution from traditional to decentralized power system. The legislative rules and regulatory polices are necessary for providing framework for LEM design and its integration with other electricity markets and electrical network. Moreover, taxes and surcharges policies must also be defined for TESs. Governments can also introduce such incentive schemes for MG-TESs that increase customer willingness in participation and use of local RESs for reduced GHG emissions. However, they may also discourage implementation of MG-TESs for having negative effects on traditional power system [47].

D. BROOKLYN MICROGRID: CASE STUDY

Brooklyn MG is a practical example of decentralized MG-TES, which is implemented by LO3 Energy as a pilot project in Brooklyn, US [20]. PV owned prosumers can sell their surpulis energy to consumers and other prosumers. They use P2P market structure for energy transactions among participants. Smart meters are used to monitor customers' bi-directional energy flow data. They use blockchain-based DLT network for storage and validation of energy transactions in a P2P environment.

Table 2 presents functionalities mapping of brooklyn MG on the 7-layer MG-TES architecture, introduced in section 3.3. First three layers are fully implemented. Users (L1) consists of consumers and prosumers to empower community participation. Local producers are also encouraged to participate in MG-TES for having more local generation mix. Brooklyn MG is using existing UG electrical network (L2) and achieving supply demand balance with the help of UG. MGO/EM (L3) is partially implemented to determine strategies for more active participation of local community. However, it lacks the study of what will be the impacts of high energy generation or consumption on network losses at a particular node and how can it be incorporated into local MCP. Moreover, other important factors such as reliability, supply security, and resilience need to be improved by analyzing aggregated energy generation and consumption data of MG-TES.

Market (L4) uses double auction mechanism. However, small number of prosumers and consumers are actively participating in LEM. Hence, practical success of LEM is still underway. Private blockchain-based DTL network (L5) is fully implemented for recording and validating energy transactions among participants. Communication system (L6) is assumed to be based on internet or utility own communication infrastructure. However, more research and practical implementation are needed to select the communication system based on system and applications requirements. Regulation policies (L7) are still being studied. For now, no third party is involved in regulating P2P energy trading between two participants. However, MGO, UG, or distribution system operator can act as an independent system operator to regulate P2P LEM mechansim.

IV. DISTRIBUTED LEDGER TECHNOLOGY

DLT is a fundamental part of decentralized MG-TES. It is an information system that uses protocols for accessing, validating, updating, and storing records in a transparent and secure manner across a decentralized P2P network of computers, which may spread over multiple locations [48]. DLT solves the problem of third party need or central data-center. It is also more secure as information is shared in a distributed manner [49]. DLT is currently being used in many applications such as finance [50], smart cities [51], [52], supply chain [53], [54], public sector [55], healthcare [56], [57], vehicular network [58], and Internet-of-Things [59].

The key components that characterize DLT are distributed ledger, smart contract, cryptography, and consensus mechanism. Ledger is simply defined as a log of an ordered list of transactions such as financial, supply chain, and energy transactions [60]. Distributed ledger is a replicated identical data structure, which is received by all system nodes and updated through consensus among nodes.

Smart contract is a digital contract, in which terms of the contract are preprogrammed with self-execution and

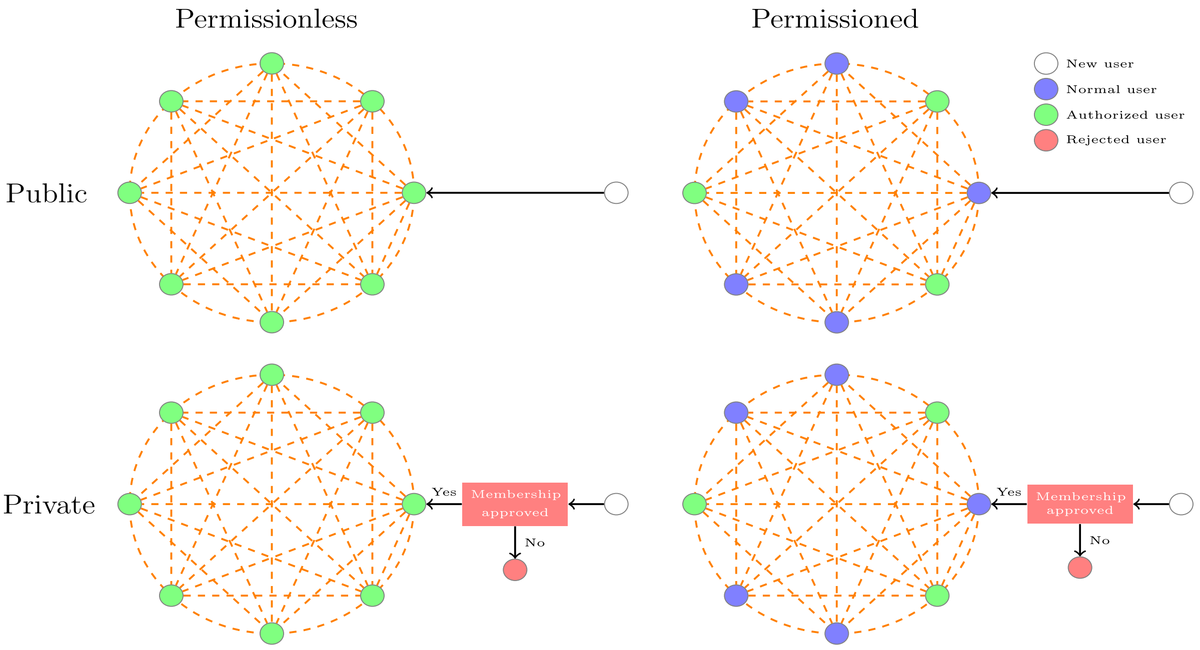


FIGURE 8. Classification of DLT architectures based on network access and authorization.

self-enforcement features [36]. Smart contract is a set of logical rules that define the procedure for reaching an agreement [61]. It enables autonomous trade and business operation between two participants without involving a third party intermediary.

Cryptography ensures data and information security against cyber-attacks. Cryptography is divided into main categories in terms of secret key, which are symmteric-cryptography and asymmetric-cryptography. In symmetric-cryptography, each node receives only one secret key to encrypt and decrypt message process. In asymmetric-cryptography, each node receives two secrete keys: public-key and private-key. Public-key is used by other nodes for message encryption, while private-key is used for message decryption. Asymmetric-cryptography provides more security against malicious attacks as compared to symmetric-cryptography [62].

Consensus mechanism refers to the process of reaching an agreement amongst all nodes in a decentralized way, which implies that every node accepts and supports the same decision. It is also known as a concensus protocol that verifies and validates information to be added to a distributed ledger according to pre-defined state transitions and rules. It must be fault-tolerant and resilient to network latency, system partitions, and corruption [63].

It is important to mention that DLT is not always the best solution for MG-TESs. If customers do not have ledger copies or they trust third party intermediary to use conventional database, centralized or partially decentralized MG-TES would be a better approach here. However, DLT-based fully decentralized MG-TES must be adopted if customers demands transparency, immutability, and no third party involvement.

DLTs are divided into different categories based on rights to access decentralized network and to validate transactions. They are defined as public and private DLTs in respect of rights to access network. While, they are differentiated between permissionless and permissioned DLTs based on authorization for transactions verification and validation. Figure 8 represents the illustrative comparison between public permissionless, public permissioned, private permissionless, and private permissoned DLTs. Public Permissionless DLT is an example of fully decentralized system, while others come in the category of partially decentralized systems.

Public Permissionless DLT: In this type of DLT, any user can access the network at any time and all users participate in verification, validation and recording of transactions. Public permissionless DLTs are highly transparent, immutable, and secure. However, they are less efficient in terms of performance and computation cost.

Public Permissioned DLT: It allows users to have free access to its network without any registration process. However, specified users are allowed to validate transactions. Such type of DLT is more efficient in terms of performance and computation cost as compared to public permissionless DLT. However, it is less efficient in transparency, immutability, and security.

Private Permissionless DLT: This DLT have a membership process for users to access the network. Users are not allowed to use the network before signing membership contract. Once they sign the contract, they can initiate the transactions. In terms of authorization, it allows all of its users to participate in transactions validation process. It has high performance and less computation cost, but at the cost of transparency, immutability, and security.

Private Permissioned DLT: It is the most restricted DLT type in which user must have to sign membership contract beforing accessing the decentralized DLT network and only limited users have privileges to accept and verify transactions. Like private permissionless DLT, it is highly efficient in term of performance and computation cost. But it lacks transparency, immutability, and security features.

Nowadays, various DLTs exist for realization of decentralization operation of MG-TES and they can be differeniated based on principles and data structure. However, the most popular DLTs are blockchain, directed acylic graph (DAG), hashgraph, holochain, and tempo, which are explained in the following.

A. BLOCKCHAIN

Blockchain is the most popular and widely used DLT in various real-life applications [64], [65]. Bitcoin, a digital currency, is the real-life blockchain example in financial sector [66]. Blockchain provides a trust-less P2P environment for Bitcoin to perform digital financial transactions in a decentralized way [67]. Blockchain is divided into three generations based on its technology evolution. Blockhain 1.0 enables digital cryptocurrency transactions, while blockhain 2.0 includes smart contracts and few applications beyond cryptocurrency. The latest blockhain 3.0 introduces decentralized applications in various areas, such as energy, healthcare, Internet-of-Things, and government [68]–[70].

In general, blockchain reflects the linked list data structure of growing blocks that contain transactions information [71]. Blocks are replicated and transmitted to all network nodes to avoid their modification or deletion. New data entry in block is allowed by majority consensus among connected nodes. Blockchain facilitates decentralized operation with added features of transparency, integrity, reliability, immutability, and scalability. Various programming languages can be used for implementation of blockchain. However, the primary programming language is Solidity, a high-level object-oriented programming language, which is currently being adopted and used by many blockchain developers for decentralization applications [72].

1) BLOCKCHAIN STRUCTURE

Blockchain consists of a chain of blocks that contains transactions information. Figure 9 illustrates the general blockchain structure. Genesis block is the first block in every blockchain that makes the foundation of the chain [73], [74]. Each new block then connects with the preceding block in the chain.

Each block header contains previous header hash, which is used for security of the information. Cryptographic algorithms are used to create hash for unique identification of each block. Therefore, any modification in block's contents results in creating a new hash each time. Block becomes invalid once hash is modified by external threat, which also disconnects all the following blocks. Hence, hash plays a vital role in ensuring blockchain security [75].

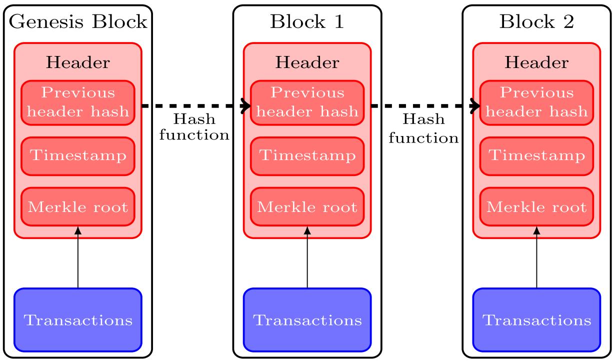


FIGURE 9. Basic structure of blockchain.

Timestamp represents the time when a block is created. As each node has different validation periods for each block, timestamp helps in fixing the order of a block in the chain. Merkle root is a hash of the Merkel tree of a block's transactions. Merkle tree is used for validation and verification of all transactions in the block. In a Merkle tree, hashes of child nodes are used to create hash for a parent node and this process continues until a single hash value, also called Merkle root, is obtained.

Each block stores a transaction counter, which represents total number of transactions, as well as all transactions information. Each transaction includes senders' address, receivers' address, and value. Each transaction is distributed throughout the network for independent verification and validation.

2) CONSENSUS ALGORITHMS

Blockchain uses a consensus algorithm for verification and validation of transactions by each authorized node. Various consensus algorithms exists in the literature for blockchain applications. However, the most well-known consensus algorithms are proof of work, proof of stake, and Byzantine fault tolerance.

Proof of Work: It is the most widely used consensus algorithm in various blockchain applications. It involves a computational puzzle to be solved by a node for creation of a new block. Each node passes through numerous guesses to verify hash value of a transaction. Bitcoin is the most popular cryptocurrency that utilizes proof of work as a consensus algorithm. Proof of work provides the advantages of transparency, scalability, and immutability at the cost of high power consumption. In [76], the author predicted Bitcoin electricity consumption to be equal to Denmark by 2020.

Proof of Stake: Proof of stake is developed to solve the high power consumption problem of proof of work algorithm. It uses stake values of nodes to decide which newly created block is to be added to the chain. Similarly, a node with high stake values can validate the transaction and its stake values are decreased in case of validating fraudulent transaction. To avoid monopoly of high stakes holder node, the selection of node is decided using a randomization method. Proof of stake is more prone to cyber attacks as compared to proof of work [77].

Practical Byzantine Fault Tolerance: In this consensus algorithm, Byzantine faults are avoided using a stat machine replication approach. It tolerates at most 33% faulty replicas at the same time [78]. It involves primary and secondary stages like master-slave approach. The decisions of primary stage are constantly evaluated by secondary stage to provide safety against fraudulent attacks [79].

Various consensus algorithms also exist in the literature other than aforementioned algorithms. The comparison analysis of these algorithms is provided in [80], [81]. In [82], the characteristics and working principles of all existing consensus protocols are provided. Moreover, the performances of these protocols are compared in terms of anonymity, suitability, transparency, efficiency, incentive, and network control.

3) BLOCKCHAIN-BASED MG-TES

Blockhcain revolutionizes conventional centralized power system for consumers to actively participate in TES and receive incentives in return. In this context, Ahl *et al.* [83] have presented holistic view of practical implications of blockhain-based MG system. They conducted expert interviews and literature review for developing an analytic framework for blockhain-based MG-TES in terms of five domains, which are economic, technical, social, institutional, and environmental.

In [73], interconnected MGs achieved improvements in efficiency, resiliency, and sustainability by using decentralized TES. This TES used four permissioned blockhains for initiating LEM, trading energy, balancing real-time deviations, and settling LEM transactions, respectively. Blockchain-based TES was developed in [84] for MG prosumers that applied Vickery auction algorithm for determining local MCP. Contribution metric criterion was used to reward benefits. Prosumers received more benefits and consumed less energy when their contributions were higher in terms of energy trading.

Hahn *et al.* [85] utilized smart contracts in blockchain for demonstration of a decentralized TES. They used Vickery second price auction algorithm to determine local MCP. It was shown that the energy transaction process was smooth and transparent for MG participants. In [86], blockhcain potential was studied for energy trading among rooftop PV prosumers in a neighborhood. Blockchain-based TES was developed in [87] that incorporated participants' reputation factor in optimizing emission trading operation of an islanded MG.

In [88], blockchain-based islanded MG-TES was proposed that also includes power flow losses in determining local MCP for energy transactions. Mengelkamp *et al.* [89] have provided various components for MG energy markets design. They also explain them using practical case study of Brooklyn microgrid. A mixed complementarity problem was developed in [90] to incentive customers for shifting RLDs into high local generation periods. A generator produces energy token for load shifting and its value decreases with time. Consumer buys this energy token to minimize consumption bill.

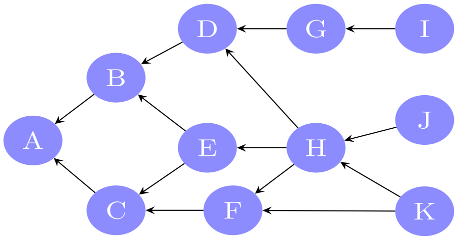


FIGURE 10. Basic structure of directed acyclic graph [97].

Power losses attribution concept was introduced in [91] to compute practical accurate local MCP for energy transactions within a physical network constrained MG system. A collaborative intrusion detection approach was developed in [92] to secure MG against physical damages or failures due to cyber attacks. Two-phase optimization problem was developed in [93] for blockchain-enabled TES. First phase determines optimal day-ahead decision strategies, while second phase is responsible for real-time operation and adjustments.

In [94], Blockchain-enabled networked MGs used unscented transform method in energy management model to minimize their overall costs. Blockchain ensures enhanced security and privacy in energy transactions among networked MGs. A decentralized MG-TES was proposed in [95] for prosumers to trade energy and maximize their revenue. Blockchain was used in [96] for developing decentralized TES to obtain fair energy transactions among interconnected MGs.

Blockchain is still in developing phase for practical implementation in businesses to have positive economic impacts on society [69]. However, It suffers from bandwidth issues with the increase in transaction volumes and they are all linked to one chain only. Moreover, it has high transaction fees.

B. DIRECTED ACYCLIC GRAPH

DAG is the second most popular DLT type after blockchain. It does not consist of blocks like blockchain. Instead, it uses nodes to store transactions, where each node stores single transaction. DAG provides advantages in scalability and transaction fees, which public blockchain lacks [98]. The general structure of DAG is shown in Fig. 10, in which nodes represent stored transactions. In general, DAG consensus mechanism ensures that each transaction validates at least two transactions before its own validation [99]. The edges represent approval of transactions and they connect transactions such that DAG could not make a directed cycle. Hence, no transaction can trace back to itself. Transaction G directly validates transaction D, while it indirectly validates transaction B.

In DAG, a branch represent a chain of transactions and its length determines weight of an associated transaction. Higher the branch length, more work will be done on each new transaction. Any member can validate its own transactions, which results in corruption and centralization. To avoid such deceitful actions, random selection algorithm is used to pick one transaction from a pool of new transactions for validation. DAG work efficiently in case of high transaction volumes. However, it is more prone to cyber attacks if a system processes a low volume of transactions. Hence, DAG must be adopted for such systems that ensure high transaction volumes [100].

IOTA Tangle is the most popular DAG instance for Internet-of-Things application [97]. It has main features of low energy consumption and no transaction fee unlike blockchain. In IOTA, each new transaction validates preceding two transactions for its own validation by a subsequent transaction. Unapproved transactions are referred as tips and Markov chain Monte Carlo method is used to randomly select two tips for a new transaction to validate. Each new transaction is created by proof of work algorithm (lighter version) for security enhancement against cyber attacks.

Wang *et al.* [101] have proposed a DAG-enabled TES for secure energy transactions among networked MGs, which are categorized as residential, commercial, and hospital MGs. The energy management objective is defined to minimize overall system cost, which includes generation and energy trading costs of each MG. The unscented transform method is used to model uncertainties of RESs and load demand. DAG applicability for TES was evaluated in [102] against the objectives of providing benefits to end-users and developing P2P energy trading framework.

IOTA DAG-based DLT was proposed in [102] for P2P energy trading framework. DAG-based TES showed better results as compared to Blockchain-based TES in terms of scalability and latency. IOTA DAG-based vehicular system was presented in [103] to improve trasactions latency. It is concluded that the transactions delay in IOTA is influenced by two main factors; tip selection algorithm and proof of work. DAG-enabled TES was presented in [104] for implementing transparent energy transactions among smart homes. It is shown that transaction speed has positive linear relationship with number of new transactions, which validates the scalability improvement in DAG-enabled TES.

C. HASHGRAPH

Hashgraph is a DLT that uses DAG-structure instead of blocks and it is developed in 2016 [105]. Like DAG, each transaction is connected to other transactions in a directed way and it cannot trace back to itself. Swirlds is the popular instance of hashgraph [105]. In hashgraph, Byzantine fault tolerance consensus algorithm is used to validate transactions. Transactions information are randomly shared among all members using random gossip method that provides advantage of low bandwidth utilization.

The general structure of hashgraph is presented in Fig. 11. The vertices represent gossip events, while edges are meant for information sharing. Time increases with upward flow of the graph. Hence, lower vertices show earlier gossip events. Each gossip event contains hash of two other events and digital signature of the member who creates it. Member A creates an event (green), which contains hash of two parent events. One is the self-parent event (blue), which is created by the same member A. While, the second parent event (yellow) comes from member B. Hence, Member B gossips and shares all the information with member A at gossip event (green), which also contains a timestamp and payload of new transaction created by member A at that time. Other previous events (gray) are not stored in the green event. However these ancestor events can be determined by using a set of all cryptographic hashes. Similarly, the previous events of self-parent can be reached through self-parent event. However, white events are not reachable for green events. Random gossip method transfer different types of information in an asynchronous manner. These informations can be related to transactions, member identities, or any other valuable information to be distributed.

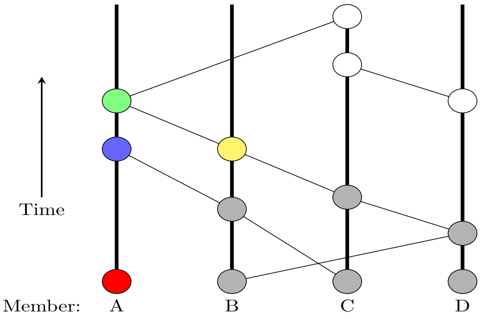


FIGURE 11. Basic structure of hashgraph [105].

The potentials of hashgraph for machine-to-machine application has been discussed in [106]. The performance of hashgraph is compared with blockhchain and DAG in terms of suitability, accessibility, transaction fee, security, and throughput. In [107], applicability of hashgraph was explored in the domain of transactive energy control. Blockchain, DAG, and hashgraph are proposed for TES and they can be used in various TES operations, like capacity planning, MCP, cost optimization, and ancillary services.

D. HOLOCHAIN

Holochain is an agent-centric DLT, unlike other DLTs, which was developed in 2017 for distributed system applications [108]. It is built to provide scalability features in distributed system. It contains cryptographic hash, digital signatures, and distributed hash tables (DHTs) to enhance integrity and security of distributed ledgers. DHT is a platform for reliable data sharing among untrusted participants. It ensures information sharing and validation even if one node goes offline as other nodes have partial copies of that information. Hence it maintains fault tolerance and provides security for critical data in case of cyber-attacks or hardware problems.

The basic architecture of holochain is presented in Fig. 12. White vertices represent users or agents and each user maintains its own private source chain of transactions, which can be merged and split. This source chain consists of headers,

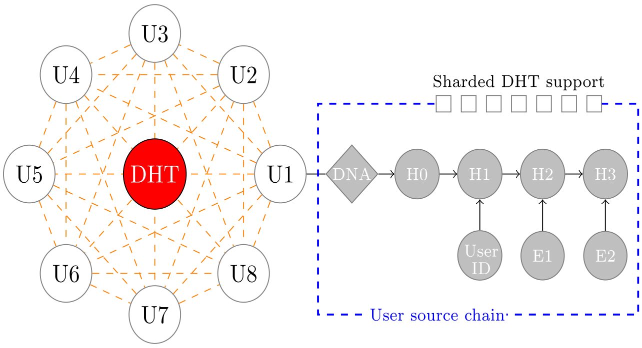


FIGURE 12. **Basic structure of holochain [111].**

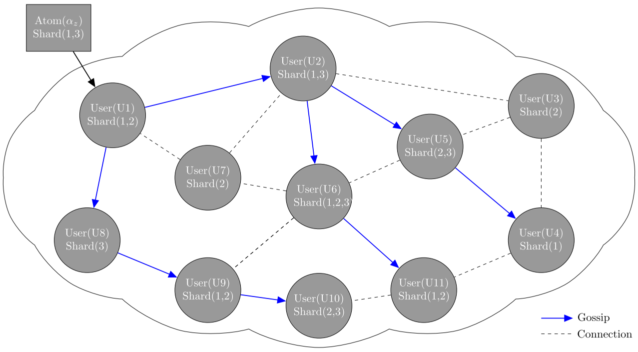


FIGURE 13. **Basic structure of Tempo [110].**

which are connected in a sequential order with previous headers and transactions. Each user establishes their own validation rules on data, which are referred as DNA of that user. DNA consists of definitions for entry types to be added, functions for decentralized applications, and system properties for setting operating parameters of the application. DNA is contained in header H0. The second header H1 constitutes the public key and identity information of corresponding user. This header can also be referred as agent identity header. Each user also shares chunks of other users' transactions and associated public metadata in its DHT shard.

Each user has a set of authorized users who hold copy of its source chain. A user must have control over significant majority of users for validation of its malicious transaction. For this purpose, holochain uses gossip protocol to share information of a user personal experience about other users' behaviors. This information of a user about other users behaviors is called world model. It helps in finding and excluding a fraudulent user who brokes the validation rules or change the transaction information. In [109], holochain was studied and proposed for decentralized operation of Internet-of-Things devices. Holochain is preferred because it requires few users to validate or share transactions instead of involving all users, like in blockchain.

E. TEMPO

Tempo is a recently developed DLT and its popular instance is radix [110]. It has completely different architecture than blockchain and DAG. It is very light-weight sharded DLT and does not require any hardware components. Sharding means dividing global ledger into segments or partitions horizontally, which are then distributed among users to enhance scalability. Tempo introduces unique concept of logical clocks for transactions validation. Logical clock of a user is an ever-increasing integer value, which is used to represent total number of transactions observed by it. Logical clock makes the distributed system temporal-proof.

Figure 13 presents the basic structure of Tempo. It assumes a universe consisting of vertices that reflect users or nodes. These users share the sharded ledger and they have unique shard IDs. The connection between users are shown by dotted line, while information is shared through gossiping represented by blue edges. The events or transactions are represented by atoms. Atom (α_z) contains an item ((α). All atoms also contain at least one destination address, which are derived from user public key. The destination address is used for transferring atom through the network. Atoms are of two types: transfer and payload atoms. Transfer atoms are used for transferring an item like currency, while payload atoms are protocol events that send instant messages for communication among users. Atoms may also include other atoms for various purposes like application meta-data, associations, and conditional destinations [110].

If an atom (α_z) is to be validated, it is sent to the users carrying associated shards as shown in Fig. 13. The item or transaction is gossiped among relevant users. User U1 has an atom (α_z), which can be shared with the users having shards 1 or 3 only. The other users with shards (1 or 3) get the knowledge of sender, recipient, and state of item (α). After the event is complete, users having shard 1 do not need to know about future changes in the item. While, users storing shard 3 are responsible for updating their record about changes in item (α_z) state.

F. DLTs Comparison and challenges

Each DLT type has its own advantages and limitations. Table 3 highlights the comparison between aforementioned DTL types in terms of has-chain structure, scalability, mining requirement, transaction cost, technology maturity, security, energy consumption, decentralized applications support, and popularity. Blockchain is the most popular DLT type but its public implementation suffers scalability and high energy consumption issues. Tempo may become the best alternative for blockchain in future.

DLTs suffer many challenges for real-life implementation. The most important challenge is the lack of technology maturity levels of all DLTs. They are still in developing stages, even if blochchain is more mature technology than other discussed DLTs. They are not yet used in energy applications to prove robustness for huge volume of transactions and interoperability standards between hardware and software components [112]. The scalability issue is the second most important technical challenge. As these DLTs are recently developed, their scalability aspects for real-life large network

TABLE 3. DLTs comparison.

	Blockchain	DAG	Hashgraph	Holochain	Tempo
Hash-chain approach	Data-centric	Data-centric	Data-centric	Agent-centric	Data-centric
Scalability	Low	High	High	High	High
Mining needed	Yes	No	No	No	No
Transaction fee	High	Low	Low	Low	Low
Technology maturity	Medium	Low	Low	Low	Low
Security	Most favorable	Favorable	Favorable	Favorable	Most favorable
Latency	High	Low	Subject to GD*	Subject to uptime and GD*	Subject to GD*
Energy usage	High	Low	Low	Low	Low
Decentralized applications support	Yes	No	No	Yes	Yes
Popularity	High	Low	Low	Low	Low
Software platform(s)	Ethereum, hyperledger	IOTA	Swirlds	Holo	Radix
Initial release	2008	2017	2016	2018	2017

*GD: Gossip delay

applications are still unexplored in detail [113]. For example, public blockchain has scalability problems, while private blockhain moves away from full decentralized operation that affects privacy and transparency.

Security and energy consumption are also very important factors in DLTs implementation. Network security and cryptographic encryptions must be strong enough to withstand cyber-attacks and make distributed energy system tamper-proof. However, public blockchain consumes high electricity to ensure system security, and it raises the question who is going to pay this electricity cost. Hence, the objective is to assure both the system security and low energy consumption for successful real-life implementation of DLTs.

Apart from technical challenges, they also lack in social awareness and global impact. It is essential to have public advertisements for society awareness about advantages of using DLTs in distributed system. Practical examples of DLTs implementation shall attract the society for their global acceptance.

Finally, regulation and governance laws are still not extensively defined for DLTs. Regulatory polices are required to define data integrity and privacy standards, energy transaction mechanism, customers' participation contract, and transparent local MCP rules. These legal issues must be addressed to facilitate MG-TES implementation at community and business levels [37].

V. LOCAL TRANSACTIVE ENERGY MARKETS

In a traditional power system, conventional wholesale and retail energy markets prevail. However, evolution of prosumers and high penetration of DERs have evolved the concept of LEM for handling energy uncertainty, volatility, and flexibility in MG-TES [114]. A LEM is defined as a platform on which prosumers and consumers trade energy supporting regional scopes such as a neighbourhood environment [115]. LEM with DLT paves the way for successful real-life realization of decentralized MG-TESs [116].

LEM can be divided into day-ahead market, intra-day market, bilateral market, and ancillary service market [117], [118]. Day-ahead market takes into account wholesale market allocation, weather forecasts, energy volumes, and biddings to determine scheduling strategies for local participations. Intra-day market is used for taking into account the imbalances in energy volumes of day-ahead market. Bilateral market is a platform for energy trade between two participants of the same MG system and also the energy trade between neighboring MGs [119]. Ancillary service market can also be introduced in LEM structure in future for voltage and frequency support of MG-TES.

MCP mechanism can be implemented in two ways: hierarchical or distributed way. In hierarchical clearing mechanism, also called double auction mechanism, participants send their energy volumes and bids to MGO that determines MCP and decision strategies for them. In distributed clearing mechanism, MGO broadcasts the initial energy price guess to all participants in MG-TES in order to receiver their energy volumes data. MGO updates the energy price and broadcast it again. This process continues until energy price converges to actual MCP. Algorithmic complexity of an hierarchical clearing mechanism commonly depends on two important factors: computational time and communication bandwidth. While algorithmic complexity of a distributed clearing mechanism has two additional measures: convergence rate and solution convergence [120].

LEM offers various advantages to MG-TES and power system, which include self-consumption, self-sufficiency, reduced transmission losses, reduced risk effects of reverse power on LV/MV transformer, strong local economy, more business and industry opportunities locally, and smart grid development support [121], [122].

In terms of consumers' preferences, LEM can be broadly classified into two types for MG-TESs: P2P and community-based energy markets.

A. P2P ENERGY MARKET

In P2P energy market, local participants iteratively share information about their energy volumes and bids for convergence towards an acceptable MCP. The information sharing is achieved through two-way communication link. Figure 14(a) presents the layout of P2P market. P2P energy market provides benefits of decentralization, adaptability, scalability, transparency, and security for individual participants in MG-TES framework.

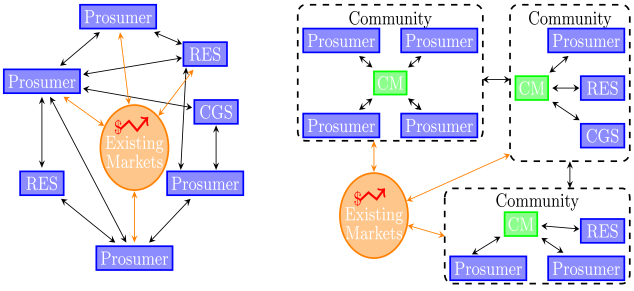
In [123], P2P energy market concept was introduced using relaxed consensus approach that achieves efficient energy trade among participants. The objective function of each participant include its production cost and trading cost. P2P energy sharing market design was proposed in [89]. Brooklyn MG is used as a case study for analyzing proposed components of market design. Liu *et al.* [8] developed an energy sharing model for MG prosumers, which optimizes a cost objective function defined in terms of participants' willingness and economic cost model. For market clearing, local MCP algorithm uses supply demand ratio criterion.

Continuous double auction P2P market was developed in [124] for energy trade among MGs. The objective is minimizing the energy cost of individual MGs. The advantages of P2P market are also highlighted in the context of DERs expansion and system reliability. Wu *et al.* [125] proposed a P2P market structure for local users. user-centric objectives are considered for their active participation. Mihail *et al.* [126] used NRGcoins as a virtual currency for energy trade among participants locally. Supply demand ratio metric is used for regulating production rate of NRGcoins and calculating local MCP.

In [127], energy trade model was developed for P2P prosumers. Blockchain is used for secure and fair energy transaction, while alternating offers method is used to determine agreed internal market price for transactions settlement. Li *et al.* [128] presented a Cournot-based risk averse energy trading model for interconnected MGs. Guerrero *et al.* [129] presented a P2P energy trading model for residential prosumers, which also incorporates network constraints to determine local MCP.

A two-stage non-cooperative game model was developed in [130] for efficient energy sharing among smart buildings, and it is solved by alternating direction method of multipliers. Decomposition approach was used in [131] to solve a distributed optimal power flow problem for efficient energy trading among peers. Bidding strategies was proposed in [132] for both risk-averse and risk-neutral peers, while taking into account the expected profit and transaction risk factors.

Cali and Cakir [133] presented a DLT-enabled P2P market model that introduces regulatory and energy policy players. Market parameters are defined in terms of players' participation and supply demand ratio. Two incentive methods, namely fixed stipend and decaying stipend, are defined for fair incentive distribution among local prosumers. Double auction method was used in [134] for P2P energy trading among electric vehicles. Prosumers preferences–based P2P energy trading model is proposed in [135] and the trading price is determined by alternating direction method of multipliers.



(a) (b)

FIGURE 14. **(a) P2P energy market (b) community-based energy market [37].**

Regulatory policies need to be defined for practical implementation and operation of P2P market. Moreover, cost-effective investment information and communication infrastructure should be developed for highly distributed network. High quality energy delivery should also be maintained at all times. Finally, convergence issues of distributed price clearing methods should also be resolved to avoid potential failure of P2P energy markets.

B. COMMUNITY-BASED ENERGY MARKET

A community manager (CM), also commonly referred as central controller, receives energy volumes from prosumers, DERs and consumers to determine community energy trade price. In general, a community consists of members that share common objectives, like decarbonization. The basic market design of community-based energy market is presented in Fig. 14(b). MG-TES can have single or multiple community-based energy markets within an MG system. In case of multiple community-based energy markets, small community groups may have their own LEMs [136]. These community groups normally consist of a combination of prosumers, consumers, and DERs, as shown in Fig. 14(b).

In [137], prosumers work in collaborative way to minimize overall energy trading cost of community with UG. Moreover, CM ensures fairness among members by imposing penalty on maximum importer. In [138], energy sharing model for nanogrid clusters was proposed and solved using Lyapunov optimization method to determine energy trade volume. Similarly, Stackelberg game method was used in [139] to determine local MCP for energy sharing within a prosumer MG. A modified auction-based method was presented in [140] to optimize energy storage sharing within a community.

Agent-based community energy market was developed in [141] to share community battery and minimize overall social cost of system. Community energy market concept was introduced in [142] to maximize local energy sharing among members. Mediwaththe *et al.* [143] presented and compared three models of non-cooperative, cooperative, nad competetive for community energy storage operator within a neighborhood area network. The performances of these models are compared in terms of cost savings, community benefits, and peak-to-average ratio.

A bi-level model was presented in [144] for solving LEM problem of a community MG. Marginal price is determined based on maximization of social welfare objective. Ye *et al.* [145] proposed a renewable energy sharing model for cooperative residential communities. The objective is to minimize overall social cost of residential community. Cooperative energy sharing model shows higher economic benefits than non-cooperative model. In [146], a bi-level problem was formulated and solved in a centralized way where the central controller gathers the global information of all participants.

Transactive energy control mechanism and pricing rule were developed in [147] for energy trade among cooperative networked MGs. The objective of central controller is to minimize overall social cost of networked MG. Nonlinear energy sharing model was developed in [148] for energy trade among DERs and prosumers. The model objective aims to minimize social cost of community MG. Various performance indicators, which include community energy cost, participation willingness index, self-consumption, self-sufficiency, and consumers' energy bill, are defined for assessing effectiveness of energy trade operation.

Fair and unbiased energy sharing is the main challenge in community-based energy market due to possible influence of big members on energy trade price. Furthermore, cost-effective information and storage infrastructure is needed for aggregation and optimization of all community members data. Finally, security of community manager is also very important to avoid cyber-attacks.

C. ENERGY TRADING METHODS

In the MG-TES framework, because of the intermittent nature of power generation sources, the energy trading algorithms have additional importance for determining MCP against demand management, profit maximization, loss reduction, and other objectives. They are categorized into auction, multi-agent, and analytical methods. The details of auction and double auction methods for TE applications are available in [85], [120], [134]. In [149], [150], multi-agent simulation method is used for energy trading among participants in TE framework. Similarly, multi-agent TE system can also be used for interconnected MGs for optimally scheduling demand response and ESSs as well as minimizing power mistaches of MGs [151]. In analytical methods, supply demand ratio and mid-market rate methods are used to define the local MCP for energy trading among MG participants [8], [148].

Recently, the game theory has been considered as a valuable analytical tool for determining MCP for efficient energy trading in MGs and DERs. The game-theoretic approach can formulate the objective function required for energy transactions in an MG system considering different MG elements as players in a game and then various optimization algorithms can help in solving the developed optimization problems with multi-objective functions [152]. A state-of-the-art literature survey on game theory along with identification of upcoming applications of game theory in modern power system are reported in [153]. Many details of the game theory approach applied to TE are available in [154]–[157]. It can also be used for cost optimization of DERs as reported in [158]–[160] and revenue maximization of interconnected autonomous MGs as detailed in [161]. In [162], game-theoretic approach is proposed for TE system, where Nash equilibrium is used to model a networked MG.

TABLE 4. Comparison of P2P and community-based energy markets.

LEM	Main potentials	Main challenges
P2P	• Decentralization • Democratization • Autonomy • Transparency • Customer-centricity	• Scalability • Convergence rate • System behavior prediction problem • High information and communication infrastructure costs • Safety and high quality energy delivery issue
Community	• More community members involvement • Social cooperation • More predictable system behavior • Additional services for utility grid, like peak shaving • Customer-centricity	• Aggregation of all community members data • Optimization of large amounts of data • Big members' influence

D. LEMs COMPARISON AND CHALLENGES

P2P and community-based energy markets are mostly presented and discussed in the literature. Table 4 highlights main potentials and challenges of both P2P and community-based energy markets [163], [164]. P2P market is focused on meeting individual objectives of each participant, while community-based energy market mainly represents cooperation and enhanced relationship among community members against common goals or objectives.

The most important challenge for LEM implementation is a lack of existing legal frameworks. Regulatory policies and government legislations are not yet extensively defined for such markets. Besides, potentials and advantages of LEMs need to be communicated with general population to increase their interest in using such market systems and technologies. In technical aspects, LEM currently suffers from high investment cost of implementing and maintaining highly distributed information and communication infrastructure.

Unbias and fair energy sharing is also very important factor for active participation of customers in LEM. The impacts of lifetime and reliability of data gathering devices and communication devices on LEM performance and operation should also be analyzed. Finally, the computation time and convergence issues of market clearing mechanism should also be analyzed and rectified.

VI. CONCLUSION AND RECOMMENDATIONS

This paper has summarized recent discussions on architectures, distributed ledger technologies, and local energy markets for realization of a microgrid transactive energy system in particular and a decentralized power system in general. Both centralized and decentralized microgrid transactive energy systems were discussed and the potential reasons for avoiding the use of centralized microgrid transactive energy system were also highlighted. Existing architectures for a decentralized transactive energy system were discussed. Seven functional layers were proposed for decentralized transactive energy system architecture design. System operator layer is represented by microgrid or energy management operator in microgrid system, and transmission or independent system operator in smart grid. The proposed seven layers architecture was compared with practical case study of Brooklyn microgrid. Most popular distributed ledger technologies, blockchain, directed acyclic graph, hashgraph, holochain, and tempo, were also extensively discussed for decentralized transactive energy system. They were evaluated and compared on the basis of key performance parameters such as hash-chain structure, scalability, energy use, transaction fee, latency, popularity, and security. The challenges of these distributed ledger technologies implementation were also highlighted. Finally, two main types of local energy markets, P2P and community-based energy markets, were presented. The challenges and potentials of these markets were also highlighted. This extensive critic review and proposed architecture could be helpful in academic research and industrial implementation of decentralized microgrid transactive energy system in the future.

Legal framework should be defined for implementation, operation, and regulation of microgrid transactive energy system. Regulatory policies are required to define data integrity and privacy standards, energy transaction mechanisms, customers' participation contract, and transparent market clearing price rules. Transactive energy systems are mainly analyzed in the framework of real-time balancing and their scope should be broadened to include day-ahead management. Moreover, they potentially need to be analyzed for ancillary services, such as voltage regulation and frequency stability. Emulation and simulation tools are also required to evaluate practical challenges of transactive energy systems and avoid the failures in their implementation stage. Information and communication infrastructure deployment should be optimal in terms of investment cost, maintenance cost, bandwidth, and coverage area, for effective energy transactions and data sharing within a distributed system. Interoperability standards should be defined for interaction among heterogeneous distributed ledger technologies. Network security and cryptographic encryptions must be strong enough to ensure data-integrity, customer privacy, and security against cyber-attacks. Therefore, security and privacy algorithms need to be improved for a tamper-proof decentralized transactive energy system realization. Finally, the impacts of lifetime of smart devices on MG-TES performance should also be investigated and analyzed. The aforementioned recommendations shall help in smooth transition of a conventional power system into a decentralized smart grid system with added advantages of scalability, resiliency, reliability, and sustainability.

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