INVITED PAPER

Application of Distributed Ledger Technology in Distribution Networks

This article presents a comprehensive review of the distributed ledger technology (DLT) applied in distribution networks.

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ABSTRACT | In the transition to a society with net-zero carbon emissions, high penetration of distributed renewable power generation and large-scale electrification of transportation and heat are driving the conventional distribution network operators (DNOs) to evolve into distribution system operators (DSOs) that manage distribution networks in a more active and flexible way. As a radical decentralized data management technology, distributed ledger technology (DLT) has the potential to support a trustworthy digital infrastructure facilitating the DNO–DSO transition. Based on a comprehensive review of worldwide research and practice, as well as the engagement of relevant industrial experts, the application of DLT in distribution networks is identified and analyzed in this article. The DLT features and DSO needs are first summarized, and the mapping relationship between them is identified. Detailed DSO functions are identified and classified into five categories (i.e., "planning," "operation," "market," "asset," and "connection") with the potential of applying DLT to various DSO functions assessed. Finally, the development of seven key DSO functions with high DLT potential is analyzed and discussed from the technical, legal, and social perspectives, including peer-to-peer energy trading, flexibility market facilitation, electric vehicle charging, network pricing, distributed generation register, data access, and investment planning.

KEYWORDS | Blockchain; distributed ledger technology (DLT); distribution network; smart contract; smart grid.

I. INTRODUCTION

The transition to a society with net-zero carbon emissions has been causing radical changes in electricity distribution networks. Distributed generators (DGs), especially renewable power generation, are rapidly connected toward a very high penetration. The transport and heat sectors are being electrified, potentially increasing the electricity demand significantly [1]. The conventional "fit and forget" approach for accommodating DGs and the network reinforcement approach for accommodating increasing demand are no longer fit-for-purpose or cost-effective. As a result, conventional distribution network operators (DNOs) are exploring to become distribution system operators (DSOs) [2], which adopt a more active way to manage distribution networks with "smart" alternative technical solutions and innovative market approaches. Note that the terms DNO and DSO are commonly used in the United Kingdom and used in this article to describe the role change of the operators of electricity distribution networks/systems before and after the transition. In some other countries, the terms DNO and DSO may not be

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distinguished in this way, and some other terms may be used such as power utilities and electricity distribution companies, but the challenges faced and transition needed for operating future distribution networks are very much common.

The transition from DNO to DSO requires a fundamental revolution of the supporting information, communication, and computing technologies, to which the emerging distributed ledger technology (DLT) could have a great contribution. DLT is a radical decentralized data management paradigm, supporting a trustworthy platform for DSOs to manage the multiple parties, assets, and devices in distribution networks.

The potential and application of DLT in supporting the transition of energy systems have been increasingly studied, as summarized in a set of review papers published in the past three years. The major areas identified include peer-to-peer (P2P) energy trading [3], [4], electric vehicles (EVs) [5], [6], microgrids [7], demand response [8], measurement and communication [9], cryptocurrencies and tokens [10], green certificate and carbon trading [11], and cybersecurity [9]. Some review papers provide a general review of DLT application in the wide energy sector [12] or smart grid [13], [14], while some review papers focus on more delicate areas, such as transactive energy [1], [3], distributed energy [4], smart communities [15] or cities [16], and cybersecurity [9].

The numerous academic studies and industrial practices, as reviewed in these papers, demonstrate the great potential of DLT in the energy sector or, more specifically, power systems. However, there is still a lack of comprehensive analysis and review on the potential application of DLT in electricity distribution networks, especially in the context of DNO–DSO transition, although some relevant functions, such as P2P energy trading, EVs, and demand response, have been briefly analyzed. This article aims to fill this gap, and the contribution of this article is summarized as follows.

1) The features of DLT are mapped with the needs of DSOs for the first time, with the features of multiple variants of DLT analyzed.
2) The DLT potential for a comprehensive set of DSO functions is assessed for the first time, with the development of several key functions analyzed in detail from the technical, regulatory, and customers' perspectives.
3) The results of this article are heavily drawn from the direct engagement of relevant industrial partners, in contrast to most existing review papers merely based on a literature survey.

II. MAPPING DLT FEATURES WITH DSO NEEDS

A. Introduction to DLT

DLT is a data management framework, where the data are stored and maintained by multiple entities in a distributed way. DLT is considered to have the potential to transform the delivery of public and private services and enhance the productivity of the human society [17].

There are several types of DLT, including blockchain [7], directed acyclic graph (DAG) [10], Hashgraph [18], Holochain [19], Cerberus [20], and so on. These types of DLT have different ledger structures—for example, blockchain stores data in a chain of blocks, while DAG adopts the DAG as its ledger structure. Blockchain is the most widely used type of DLT, originally being the underlying technology of the famous cryptocurrency "Bitcoin" started in 2008 and then applied in other sectors, such as finance, energy, entertainment, government, healthcare, and transportation [21]. Bitcoin and Ethereum are the two largest blockchain platforms across the world. Compared to the blockchain, the application of other types of DLT, such as DAG and Hashgraph, is at a tremendously smaller scale, and some types of DLT, such as Holochain and Cerberus, are still at an early development stage.

DLT can also be categorized into two categories: permissionless and permissioned DLT. Permissionless DLT, also called public DLT, is open to anyone to participate, while permissioned DLT is limited to be used within one organization (private DLT) or by a number of organizations (consortium DLT).

Even for DLT within the same category or with the same ledger structure, there are also many variants as a result of the differences in specific designs of DLT. For example, "consensus mechanisms" are the protocols used to maintain the data consistency across a DLT network, and there are tens of different consensus mechanisms, 66 of which have been surveyed in [22]. DLT with different consensus mechanisms will show different performance in various aspects, such as trustworthiness, speed, and scalability [22].

B. Features of DLT

The major technical features of DLT can be assessed from the following perspectives: 1) decentralization; 2) verifiability; 3) transparency; 4) tamper proof; 5) redundancy; 6) open source; and 7) customizability. The description of the features and how different types/categories/variants of DLT will perform with regard to each feature are detailed as follows.

1) Decentralization: Decentralization is the fundamental feature of DLT, where multiple data copies are stored in different nodes of a network, in contrast to a centralized database. Nevertheless, the decentralization level varies with different DLTs and can be assessed from different perspectives. Permissionless DLT is considered to have a higher level of decentralization than that of permissioned DLT, in the sense that permissionless DLT, such as Ethereum, is not limited to specific organizations and open to the whole world. Consensus mechanisms adopted by DLT affect the decentralization level as well. For example, for DLT with the "proof of work" consensus mechanism (where the nodes in a network race in solving a cryptographic puzzle to get the right to add data to the ledger and get remunerated, such as Bitcoin), the decentralization level is usually considered good but will also depend on the distribution of computational power across all the participants—a coalition with more than half of the total computational power could validate malicious update of the ledger (called “51% attack”).

2) Verifiability: Verifiability allows the correctness of the data on the distributed ledger to be verified. The update of the ledger is verified by the “verifiers.” For different DLTs, the verifiers may have different characteristics—e.g., for Bitcoin (a public blockchain), the verifiers are called “miners,” which should have computational power [23], while, for Fantom (a DAG), a node that wishes to be qualified as a validator should have verified at least two of the previous transactions on the ledger [24]. Besides the verifiers, other observers can also verify the change of the ledger according to the protocol of the specific DLT.

3) Transparency: Transparency refers to the observability of the data on the distributed ledger and the update of the ledger. Transparency is a prerequisite for verifiability. The level of transparency varies with different DLTs. Public DLT is open and, thus, transparent to generally anyone, while the data on and the update of the ledger are only observable to certain participants in private/consortium DLT. Some DLT-based smart contracts can encrypt the relevant data, thus affecting transparency.

4) Tamper Proof: DLT has the feature of tamper proof largely because of its feature of verifiability. Malicious updates of the ledger will be identified by the verifiers and the observers according to the DLT protocol. The level of tamper proof is associated with the level of decentralization—less decentralized DLT faces the risk of the key nodes being attacked. The level of tamper proof depends a lot on the consensus mechanisms—there is usually a compromise between the strength of tamper proof and speed, as well as scalability [22].

5) Redundancy: Redundancy is an inherent feature of DLT since a distributed ledger consists of multiple identical copies held by multiple nodes of a network.

6) Open Source: Open-source DLT refers to the relevant computer codes being publicly accessible, and anyone can see, modify, and distribute the codes. Whether a variant of DLT is open-sourced is completely case-by-case, but the most widely used variants of DLT are open-sourced, such as Bitcoin and Ethereum (as blockchains), as well as many other types of DLT, such as Fantom (an example of DAG), Hedera (a project of Hashgraph), Holochain, and Radix (a project of Cerberus).

7) Customizability: Customizability allows customizing DLT for multiple applications. The level of customizability may vary with different DLTs. For example, Bitcoin is hardly customizable and solely used as a cryptocurrency, and Polygon [25] and Algorand [26] (two other variants of blockchain) allow customization for several applications, while Ethereum supports smart contracts that are highly customizable. The customizability is also associated with the feature of open source—modifications can be made to the open-source codes to create new variants of DLT, tailored for specific applications.

C. Pros and Cons of DLT

The features of DLT presented in Section II-B are generally described from a positive perspective, while some features are actually double-edged swords. The verifiability and transparency are good for enhancing trustworthiness but may raise privacy concerns. The redundancy prevents DLT from a single point of failure but also occupies large amounts of storage and computational resources. Moreover, the open-source feature may cause some security concerns. For example, the bugs (if any) in smart contracts may be utilized by the malicious nodes to attack the system or “steal” the digital assets. A hack to the wormhole, a bridge linking Ethereum and Solana (two blockchains), happened in February 2022 and led to a loss of about \$320 million [27].

A number of measures have been proposed to overcome the disadvantages of DLT. For example, “sharding” (i.e., dividing a ledger into several partitions called “shards”) and “off-chain” solutions (e.g., processing the transactions off-chain and then synchronizing the aggregated state onto the main chain) are two measures to enhance the speediness and scalability of blockchains [10]. Different consensus mechanisms of DLT also have different compromises between trustworthiness, security, speediness, and scalability, as a conclusion of the analysis of 66 existing consensus mechanisms [22]. There is not a “silver bullet” kind of DLT that can eliminate all the disadvantages at zero cost, and therefore, proper types/categories/variants need to be selected and designed according to the specific requirements in practice, such as the suggestions given in [10] for part of applications in the energy sector and the suggestions given in [22] for some applications in the public sector.

In the rest of this article, the potential and application of DLT for future distribution networks will be analyzed. The analysis will be about what DSO functions can be empowered by DLT and to what extent, as well as the relevant technical, regulatory, and customers’ perspectives of some selected functions. The specific design of DLT for each function, such as ledger type, whether open to public and consensus mechanisms, will not be covered and is beyond the scope of this article.

D. Future Distribution Networks and DSOs

With the course of the low-carbon transition, there will be a very high penetration of distributed energy resources (DERs) in future distribution networks, including DGs (especially renewable power generation, such as photovoltaic (PV) panels and wind turbines), energy storage systems (e.g., batteries), EVs, electrified heating devices, and other flexible loads. Multiple parties, such as prosumers, energy communities, and aggregators, will further emerge to provide multiple services, such as energy trading, energy arbitrage, voltage support, frequency control, and congestion management, for end customers and the bulk power grid. The volume of various data will boost exponentially.

In this context, DNOs will have to shift their roles from passively constructing and maintaining distribution networks to actively managing the large numbers of heterogeneous parties, services, and data within the networks, becoming DSOs.

The new role of DSOs results in new needs of DSOs on their digital infrastructure in future distribution networks, which are detailed as follows.

1) Trustworthiness: In contrast to the conventional business model of distribution networks where DNOs just distribute electricity to end users, local energy and flexibility markets are expected to be established in future distribution networks [28], [29], where a number of different parties will emerge, such as prosumers, flexibility service aggregators, and P2P energy trading coordinators [30]. All these parties have their respective and even conflicting interests, and therefore, the digital platforms need to be trustworthy for facilitating the participation of various parties in future local energy and flexibility markets, alleviating the concerns such as untransparent market information and the moral hazard of platform operators [31].

2) Security: Huge amounts of data will be generated, transmitted, stored, processed, and utilized in future distribution networks, including, but not limited to, smart metering data, network measurements (such as those from distribution phasor measurement units (D-PMUs) [32]), measurements and control signals for coordinating EV charging, and biding, pricing, and settlement signals for local energy and flexibility trading. As a result, cybersecurity is of great importance for protecting the interests of all the parties and also the electricity supply security of distribution networks [33].

3) Customer Privacy: Increasing amounts of customer data will be collected for various purposes, such as local energy trading and demand response. Much private information of customers, such as location, financial situation, and human behaviors, can be inferred from these data, and thus, customer privacy is increasingly becoming an important issue in future distribution networks [34].

4) Reliability: Highly integrated cyber and physical systems with increasing new equipment, such as power electronics devices, have posed great challenges to the reliability of future distribution networks since faults in either cyber components or physical components may affect the electricity supply [35], [36].

5) Scalability: With the continuous electrification, especially for heat and transport, and the development of renewable power generation, more and more DERs will be integrated into future distribution networks. Therefore, the scalability of digital infrastructure is vital for DSOs to manage the increasing scale of DERs.

6) No Vendor Lock-In: Opening the opportunities for developing digital infrastructure in future distribution networks will be beneficial for accelerating the development to meet the urgent needs of DSOs in climate emergencies [37] and avoiding the potential issues, which would be brought by monopolies, such as higher cost and reduced service quality.

7) Flexibility: The business models of future distribution networks may change rapidly. For example, the design of P2P energy trading markets is evolving very fast in the recent few years [38]. Therefore, the digital infrastructure of future distribution networks needs to be flexible for adaptation and customization.

8) Quickness: Faster communication and data processing can support more delicate control of DERs in future distribution networks so that services with higher values can be provided with greater capability, such as dynamic frequency response service from virtual energy storage systems [39].

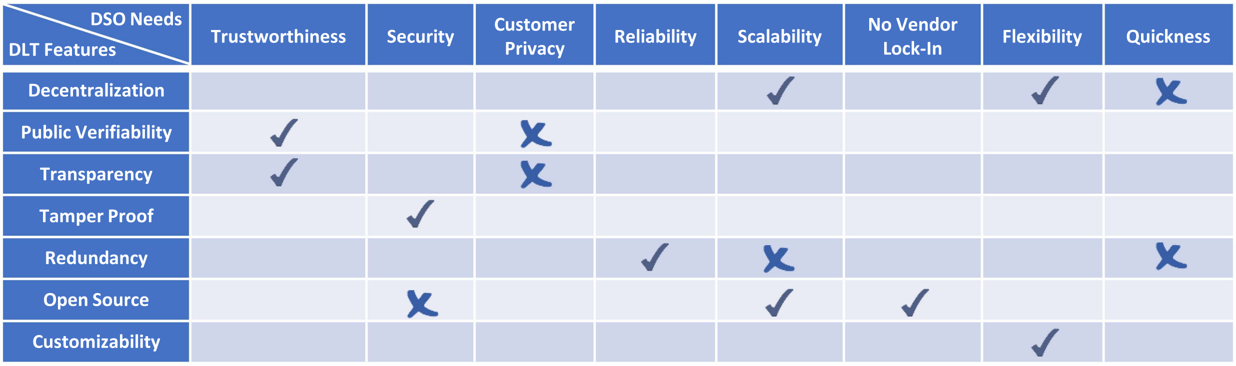
E. Mapping DLT Features With DSO Needs

The features of DLT very well match the needs of DSO in many aspects, as summarized in Fig. 1.

For providing a trustworthy infrastructure on which multiple untrusted parties in distribution networks can negotiate, trade, make agreements, and provide services with each other, DLT is an ideal solution because of its features of decentralization, verifiability, and transparency. The decentralization avoids the possibility of one single party (e.g., an aggregator) manipulating the whole process (e.g., ancillary service provision) and cheating other parties in a weaker position (e.g., small prosumers). The verifiability and transparency further make the whole process more trackable and trustful. If smart contracts are deployed based on DLT, everything will be enforced automatically, and no one will even have a chance to cheat, as long as the smart contracts are designed soundly [40].

The tamper-proof feature of DLT prevents the data from being tampered with, protecting the data security and further the cybersecurity of network equipment and operation. For example, in a blockchain, the data blocks are linked with each other sequentially using cryptographic hash algorithms. If the data stored in a block are tampered with by a malicious node, the other nodes of the blockchain network will detect and signal the “illegal” displacement in the state of the data and will immediately “fork the chain” from the block, which is tampered.

Furthermore, thanks to the decentralization feature of DLT, new participants can connect in an easy “plug and



DSO Needs DLT Features	Trustworthiness	Security	Customer Privacy	Reliability	Scalability	No Vendor Lock-In	Flexibility	Quickness
Decentralization					✓		✓	✗
Public Verifiability	✓		✗					
Transparency	✓		✗					
Tamper Proof		✓						
Redundancy				✓	✗			✗
Open Source		✗			✓	✓		
Customizability							✓	

Fig. 1. ***Matching relationship between DLT features and DSO needs. (“Ticks” and “Crosses” represent that the DLT features positively/negatively correlate with the DSO needs.)***

play” way, resulting in good scalability for DSOs to manage increasing numbers of DERs, parties, and services. The redundant data stored in multiple nodes in the decentralized network increase the reliability of the digital infrastructure, being immune from single-point failures. Many variants of DLT are open source; thus, any party that is interested can participate to develop their own products and services freely, with no vendor lock-in. The customizability feature of DLT allows a flexible framework where customized solutions can be deployed and adapted for meeting the quickly evolving DSO needs.

III. DLT POTENTIAL FOR DSO FUNCTIONS

A. Methodology

The investigation on the potential of DLT for DSOs was conducted through a state-of-the-art analysis based on the survey of existing academic studies and industrial practice, and through seeking inputs from industry experts. The experts were from three DNOs in the United Kingdom, i.e., SP Energy Networks (SPEN), Scottish and Southern Electricity Networks (SSEN), and U.K. Power Networks (UKPN). They were engaged through a series of discussions and surveys during the course of a joint project “DeDSO” from 2018 to 2020.

The overall methodology is summarized in Fig. 2—as the outcomes of the third stage “Roadmap Drafting,” the identification of DSO functions with the accordingly DLT potential will be presented in Section III, while the development and timelines of key DLT functions will be presented in Section IV.

B. Categorization of DSO Functions Supported by DLT

Synthesizing the opinions of industry experts, five categories of DSO “functions” were identified, which are “planning,” “operation,” “market,” “asset,” and “connection,” as explained in Fig. 3. The concepts of these categories and how DLT can provide support are detailed as follows.

The “planning” functions aim to identify the constraints and needs of distribution networks considering the increase in local generation and demand in the future and make corresponding investment decisions on network reinforcement or other alternative technical options, such as investing in DERs [41]. DLT-based crowdfunding provides an innovative digital financing mechanism for supporting the development of DERs. Larger numbers of small investors can be attracted through DLT-based crowdfunding compared to traditional crowdfunding platforms because of enhanced trustworthiness brought by the transparency and decentralization, the convenience brought by the automation of DLT-based smart contracts, and considerably lower transaction fees [42]. Case studies in the European countries reveal that DLT-based crowdfunding is able to reduce the financial costs and Levelized Cost of Electricity (LCOE) of solar energy projects [42]. In practice, there have been projects that use DLT-based crowdfunding for supporting distributed solar PV projects, such as those in Germany [43] and sub-Saharan Africa [44].

The “operation” functions refer to monitoring the states of distribution networks and deciding the setpoints of controllable devices in the networks (such as on-load tap changers and soft-open points) to ensure operational security, reliability, and economy of distribution networks. Research has been conducted to use DLT for tracking real-time network losses [45], supporting smart contracts enabling shared control between networks connected through dc links [46], and conducting voltage regulation services [47].

The “market” functions enable the prosumers, consumers, DER owners, aggregators, and other related parties to participate in energy trading, energy arbitrage, and provision of ancillary services [48]. DLT can establish an open, accessible, and trustworthy platform for decentralized trading, preventing both replay attacks (i.e., malicious sellers selling energy or services twice) [49] and double-spending attacks (i.e., malicious buyers spending digital currency twice) [50], through tracking the ownership of the energy, services, and currency. DLT-based smart

Fig. 2. *Methodology of investigating the application of DLT for DSOs.*

contracts can set out an auction and enable self-enforcing settlement for energy and service trading in distribution networks. Smart contracts also provide standardized trading protocols with reduced transaction fees and prevent unforeseen trading behaviors, such as violating auction protocols. There are many studies and applications in this area, such as the blockchain-based energy trading platforms presented in [51] and deployed by Power Ledger Company in Australia [52].

The "asset" functions serve both the digital assets and physical assets in distribution networks. DLT can assist the management of these assets in an accessible and reliable manner [53]. When managing digital assets using DLT, the privacy of the relevant parties is a key aspect. The pseudonyms and encryption used in many variants of DLT (such as Bitcoin) protect the real identity of the parties from being explicitly linked to their activities (e.g., financial transactions). However, there are still a number of privacy concerns on transaction linkability, private keys management and recovery, malicious smart contracts, non-erasable data, and so on [54]. Nevertheless, a number of privacy-preserving techniques have been developed as well, such as zero-knowledge proof (a method through which one party can prove the truth of specific information to another party, i.e., the verifier, without disclosing any additional information). Many application-specific schemes have also been proposed, such as those for energy trading between prosumers and EVs [55], [56]. For managing the physical assets, the collective authenticity and update of distributed ledgers can ensure traceability and cybersecurity for physical assets, such as meters. PNNL [57] piloted two use cases where the cryptographic signature was used to secure the digital information in distribution networks, and blockchain was used to continuously monitor and autonomously verify the integrity of sensors and energy sources.

Fig. 3. *Categories of DSO functions.*

The “connection” functions support the registration and integration of DERs in distribution networks. The complexity of connection depends on the connected capacity, technological types, and interactions with other stakeholders, e.g., regulators and system operators [58]. DLT-based smart contracts can reduce this complexity with automatic information exchange and standardized replicable protocols and ease the burdens for the information infrastructure in distribution networks. In [59], blockchain-based smart contracts are designed for enabling the connections of DERs. In the United Kingdom, two DNOs, i.e., UKPN and SPEN, partnered with the transmission system operator (TSO), Nation Grid and the software developer, Electron, started a project in 2019 to design and build a blockchain-based register of assets of both electricity transmission and distribution systems [60].

C. Assessment of DLT Potential for DSO Functions

Detailed DSO functions under the five categories were identified with reference to the “Future Power Systems Architecture” jointly developed by Energy Systems Catapult and the Institution of Engineering and Technology (IET) [61]. The level of potential in each detailed DSO function was evaluated based on industry experts’ opinions and a comprehensive survey of global academic studies and industrial practice with more than 100 data sources examined. Through the survey, the DLT potential was preliminarily marked with four levels by evaluating the technical possibility and the extent of existing academic research and industrial practice. Then, two technical workshops were convened, where industry experts, including a group of engineers and managers from U.K. DNOs and wider researchers and practitioners in this area, adjusted and confirmed the evaluation outcome, as illustrated in Fig. 4. The industry experts also voted for selecting several key DSO functions with high potential for more detailed analysis, as presented in Section IV.

Categories	DSO Functions	DLT Potential Level
Planning	Investment Planning	++++
	DER Planning	++++
Operation	EV Charging	++++
	Black Start & System Restoration	++++
	Network Reconfiguration	+++
	System Monitoring	+++
	Volt/VAR Control	+++
	System Coordination	+
	Outage Management	+++
	System Restoration, Supervisory Control and Data Acquisition (SCADA)	++++
	Service Optimization	++++
	Relay Protection Re -coordination	+
	Carbon Footprint	++++
Market	Peer-to-Peer Energy Trading	++++
	Distribution Market Operation	++++
	Flexibility Market Facilitation	++++
	Network Pricing	++++
	Electrical Fraud	+++
	Imbalance Management	+++
Asset	System Management	++
	Asset Management	++
	Data Access	++++
	Platform Technologies	+
	Renewable Energy Certificate	++++
Connection	Distributed Generator Register	++
	Connection Rights	+

Fig. 4. ***Evaluation of DLT-applying potential in various DSO functions. (The DLT potential level of DSO functions is marked from one plus sign “+” to four plus signs “++++,” representing the potential level from low to high. The seven functions in red are analyzed in detail in Section IV.)***

IV. DEVELOPMENT OF DSO FUNCTIONS WITH HIGH DLT POTENTIAL

Within the five categories of DSO functions, seven key functions with high DLT potential were identified, as highlighted in red in Fig. 4 for further assessment, which are “P2P energy trading,” “flexibility market facilitation,” “EV charging,” “network pricing,” “distributed generation register,” “data access,” and “investment planning.”

The future development of these DSO functions was evaluated based on the votes of the industrial experts engaged, as illustrated in Fig. 5. The future development is forecast in the short term (0–5 years), medium term (5–15 years), and long term (over 15 years). It is seen that the DLT development of some functions has started and is considered to keep developing for over 15 years, such as P2P energy trading, EV charging, and distributed generation register. By contrast, the DLT development of some functions, such as network pricing, will not start in the near term, considering that the function itself is under reform and still at an early stage. For some other functions, such as investment planning, the DLT development is only considered in the short or medium terms.

Note that the results shown in Fig. 5 just summarize the votes of industry experts engaged in the “DeDSO” project, so they might not be totally accurate in every detail but just reflect a general prediction of the trends of the DLT development regarding DSO functions. More in-depth analysis, based on a wider literature survey and with a more detailed logical reasoning, is presented in Sections IV-A–IV-G, with the analysis from the perspectives of technology, law and regulation, and customer engagement.

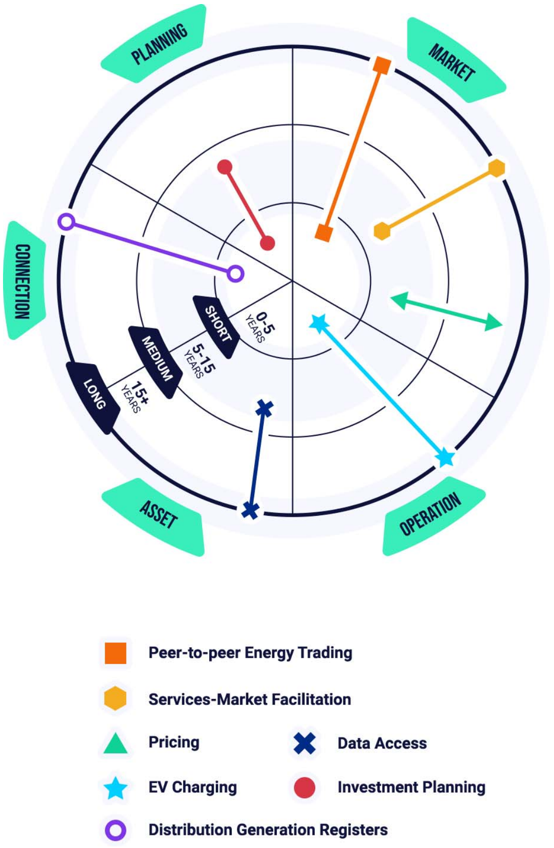


Fig. 5. ***Forecast DLT development of the selected DSO functions.***

A. P2P Energy Trading

P2P energy trading is an innovative electricity supply paradigm where prosumers with DERs, and consumers can directly trade electricity with each other [62]. A rapidly increasing number of academic studies and industrial projects have been conducted across the world to explore the use of DLT (especially blockchain) enabled platforms to support P2P energy trading [38].

From the technical perspective, DLT can provide a trustworthy P2P energy trading platform by removing the centralized trading coordinator and disabling malicious actions from trading participants using certain consensus protocols [63], [64]. Transparency, immutability, and auditability are also favorable features of DLT for P2P energy trading [65]. With proper designs, DLT-based P2P energy trading can be scalable [66], [67], secure [68], [69], and with good privacy protection as well [70]. Furthermore, DLT-based smart contracts, with the features of good reusability and automatic execution, can reduce the contracting, enforcement, and compliance costs [17], being ideal for P2P energy trading usually involved with large numbers of low-value transactions between small-scale DERs. For some types of DLT, such as public blockchain, concerns have been raised regarding throughput and latency, and therefore, some designs, such as those in [71] and [72], have been proposed for being applied for P2P energy trading.

However, significant barriers still exist in the law and regulation domain. Worldwide, there has been a lack of laws or regulations on P2P energy trading and the supporting DLT [73]. There is a lack of legal clarity on many issues, such as the legal recognition of prosumers, the protection of personal data, and the legal validity of smart contracts, although some existing legal forms (e.g., the “Co-Operative Society” and “Limited Liability Partnership” in the United Kingdom) could play some roles [74]. Efforts have been made to explore the legal and regulation framework needed for P2P energy trading through setting sandboxes (e.g., in the United Kingdom and The Netherlands) or legislation (e.g., in France and Spain). For example, the GB electricity market regulator, Ofgem, has launched the “Energy Regulation Sandbox” in 2017 to help innovators trial new mechanisms without some of the usual regulations applied [75]. One sandbox was approved for trialing blockchain-based P2P energy trading [76].

Furthermore, customers’ attitudes and willingness to accept and participate in P2P energy trading play a vital role. P2P energy trading is still a new concept to most of the customers but an online survey in the United Kingdom shows that around two-thirds of the participants would be willing to participate in DLT-enabled P2P energy trading if it were available to them [77], which is an optimistic sign.

B. Flexibility Market Facilitation

The increasing level of volatility of generation and demand in modern power systems has posed increasing requirements on the “flexibility,” which refers to the capability of an electrical device to change its power input or output pattern, given the relevant incentives, to increase its own revenue and/or support the bulk power system. DERs can provide various flexibility services (such as congestion alleviation and voltage control) for supporting the operation of distribution networks or further to the upper level transmission system (e.g., through frequency services), potentially facilitated by DLT [78].

Customized DLT-based smart contracts could be made to enable different types of flexibility services involving multiple parties in distribution networks. The technical prospects of DLT for flexibility market facilitation and P2P energy trading are similar. Therefore, many discussions have been made on establishing joint markets for P2P energy trading and flexibility services, such as those in [30] and [79].

On the law and regulation side, the prospects of flexibility markets are more optimistic than P2P energy trading. For example, in the United Kingdom, there has been a relatively mature flexibility market for the TSO to purchase flexibility services from DERs in distribution networks [80], and many ancillary services for distribution networks are being trialed [81]. There are no obvious legal obstacles to stop using DLT for enabling flexibility services although the role, responsibility, and protection of customers in DLT-enabled flexibility markets are still to be formally defined in the longer term.

From the customers' perspective, in many countries, such as the United Kingdom, customers may be more familiar with the time-of-use (ToU) pricing schemes that have been applied for years. In the medium and long terms, the awareness of customers' needs to be raised for them to participate directly or through intermedia such as aggregators.

C. EV Charging

How to manage the high electric demand brought by the electrification of transport will be a major concern of future distribution networks. The EV charging markets are currently highly fragmented with various apps and cards to access charging points and with complex IT and payment processes between EV/charging companies.

DLT is, therefore, a promising technology to provide a trustworthy platform to deal with the information exchange and payment process among multiple parties, including drivers, EV charging companies, and DSOs. Standardized smart contracts deployed on DLT can also help to cope with the problems brought by the fragmented EV charging markets with the need for the relevant laws and regulations in place as well.

Moreover, DLT can be used for establishing cost-efficient charging-record storage and management schemes [82]. With smart contracts, secure charging pile management can be achieved through DLT [83]. DLT can further be used for incentivizing charging EVs to use renewable energy [84] and facilitating energy trading between EVs through vehicle-to-vehicle (V2V) networks [85] and vehicle-to-grid (V2G) technologies [86].

D. Network Pricing

Network pricing is about how DSOs recover their operational costs and investment in reinforcing and replacing networks through collecting use of network and connection charges. The existing network pricing methods need to be reformed to accommodate new technologies and business models in future distribution networks, such as EV charging and P2P energy trading in the DNO–DSO transition [87].

DLT can be used as a platform supporting smart contracts that simultaneously integrate innovative network pricing and other related functions (such as P2P energy trading with network losses allocation and network charges considered).

Considering that innovative network pricing itself is just under discussion or trial (e.g., the electricity network access project and the Targeted Charging Review undergoing in the United Kingdom [88]) in many counties, the application of DLT for network pricing is, therefore, foreseen as a medium- to long-term development.

E. Distributed Generation Register

Currently, the information about DGs is usually not well shared among the stakeholders in power systems. For example, in GB, the TSO has limited visibility of the DGs connected to distribution networks. Therefore, a distributed generation register is needed to share the information regarding DGs within DSOs, with TSOs and other stakeholders (such as aggregators), as the first step for further managing and utilizing DGs for various purposes.

DLT, with the features of decentralized databases, is an ideal technology for establishing distributed generation register to be shared among multiple parties in the electricity supply chain with good security and scalability.

Some trials have been conducted in this area. For example, in the United Kingdom, the TSO (National Grid ESO) has been partnered with two DNOs (SPEN and UKPN) and an energy tech firm (Electron) to start a blockchain-powered DER asset register pilot since 2019 [89]. In the medium and long terms, the distributed generation register might develop from a pure register to include multiple types of information, such as flexibility and the relevant availability and prices, with a quicker updating frequency (even in real time), for supporting more advanced applications. This will require the relevant technical progress of DLT. Also, related laws and regulations will be made to ensure data security and customer privacy and specify how the data could be stored, shared, and used.

F. Data Access

Similar to the distributed generation register, this function is about the access to data but is much broader. Besides the connection of DGs, much information within distribution networks may be of value to other stakeholders, such as the network congestion information and smart metering data (note that the situation may vary in different countries—for example, in the United Kingdom, the smart metering data are handled by a state-licensed monopoly named "Data Communication Company (DCC)," while, in many states of the United States and China, the smart metering data are handled by power utilities).

DLT is also suitable for managing and sharing these types of data. Compared to distributed generation registers with relatively simple functions, more complicated structures, consensus mechanisms, and rights management need to be developed for the DLT to enable the management and sharing of multiple types of data for different purposes. Customers' awareness and laws and regulations need to be developed accordingly as well.

G. Investment Planning

Investment planning refers to the investment decisions made by DSOs for reinforcing and replacing the distribution networks and also involves coordination with other asset owners (such as DG owners) and TSOs to identify whole system investment options with higher efficiency, lower costs, and better overall effects.

DLT can be used for facilitating investment planning in multiple ways, including: 1) information sharing among multiple parties; 2) management of the supply chain regarding the investment projects; and 3) fundraising through blockchain platforms and cryptocurrency, e.g., through the "initial coin offerings (ICOs)" [90].

In the near term, from the technical perspective, DLT could start to be used for all three aspects of investment planning. The awareness of power utilities (if DLT is for internal information sharing) and the public (if DLT involves sharing of the data about customers or fundraising from the public) needs to be further enhanced, and the relevant laws and regulations need to be made to regulate the information sharing and fundraising. In the long term, DLT may still be useful for data management and information sharing, but whether it would be used for fundraising is not clear, considering the many issues of ICOs [90] and the features of DSOs and their projects, which are regulated natural monopolies and are for the social welfare of all customers.

V. CONCLUSION

As a radical decentralized data management technology, DLT has the potential to support a trustworthy digital infrastructure for future electricity distribution networks in the context of DNO–DSO transition during the net-zero transition.

DLT can be applied to support all the five categories of DSO functions, that is, "planning," "operation," "market," "asset," and "connection." The key functions identified with high potential and priority include P2P energy trading, flexibility market facilitation, EV charging, network pricing, distributed generation register, data access, and investment planning. Other highly potential functions include DER planning, black start and system restoration, supervisory control and data acquisition (SCADA), carbon footprint, and renewable energy certificate.

Tapping the potential of DLT for DSO applications needs coordinate development in technology, law, and regulation, as well as engagement of customers and other stakeholders.

From the technical perspective, at a high level, the features of DLT in decentralization, verifiability, transparency, tamper proof, redundancy, open source, and customizability are well-matched with the needs of DSO in trustworthiness, security, reliability, scalability, "no vendor lock-in," and flexibility. However, there are also concerns about whether DLT will compromise customer privacy and whether DLT can satisfy the speediness requirement of some DSO functions. It is also important to recognize that DLT actually refers to a large family of technologies and has many variants with distinctive performance and, thus, pros and cons in different technical dimensions. Satisfying certain needs of DSO will, therefore, require adopting proper types and variants of DLT.

Having proper law and regulation schemes in place is the prerequisite for rolling out DLT across future distribution networks on a large scale. Generally, there is still a lack of mature laws and regulations in using DLT for information sharing, data access, fundraising, or protecting data security and customer privacy. The roles and legal responsibilities of the parties involved in smart contracts, as well as the legal status and implications of smart contracts themselves, also remain to be clarified. Each detailed application, such as P2P energy trading and flexibility market facilitation, requires dedicated regulations for DLT application as well.

With regard to the engagement of customers and other stakeholders, customers have an interest and willingness in participating in DLT-based applications, such as the situation in P2P energy trading. There have been examples of practical engagement of customers, utilities, and other stakeholders in several projects in some key DSO functions, such as P2P energy trading, flexibility market facilitation, EV charging, and distributed generation registers. Nevertheless, the existing deployment still lies on a limited scale and fields, and there has been great room for enhancing the awareness and knowledge of customers and other stakeholders in the application of DLT in future distribution networks. ■

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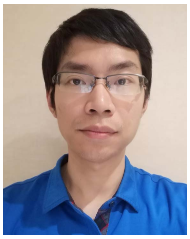

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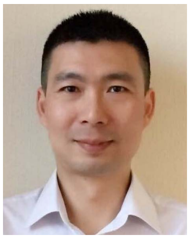

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