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Blockchain-Based Energy Applications: The DSO Perspective

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ABSTRACT This paper discusses blockchain-based energy applications from the distribution system operator (DSO) perspective. Blockchain has a potential impact on newly emergent actors, such as electric vehicles (EVs) and the charging facility units (CFUs) of the electricity grid. Although Blockchain offers magnificent decentralized solutions, the central management of DSOs still plays a significant, non-negligible role, owing to the reality of the existing grid structure. Numerous related studies of proposed blockchain-based EV systems have investigated the energy costs of EVs, fast and efficient charging, privacy and security, P2P energy trading, sharing economy, the selection of appropriate CFUs location, and scheduling. However, cooperation with DSO organizations has not been adequately addressed. Blockchain-based solutions mainly suggest an entirely distributed and decentralized approach for energy trading; however, converting the entire power system infrastructure is considerably expensive. Building a thoroughly decentralized electricity network in a short time is nearly impossible, particularly at the national grid level. In this regard, the applicability of the solutions is as significant as their appropriateness, especially from the DSO perspective, and must be examined closely. We searched and analyzed the blockchain literature related to EVs, CFUs, DERs, microgrids, marketing, and DSOs to define the DSO-based requirements for potential blockchain applications in the energy sector, specifically EV evolution.

INDEX TERMS AMI, blockchain in energy, DERs, DSO blockchain, EVs, market, microgrid, SCADA.

I. INTRODUCTION

The smart grid (SG) in the context of an electricity grid is one in which all the parties aim to reach the general aim of a sustainable, economical, and secure electricity supply environment [1], [2]. Increments in the usage of EVs, global orientation to low carbon energy solutions (renewable energy sources (RESs)), and the tendency of sustainable distributed energy resources (DERs) have made SG control and management methods more difficult and complicated. Energy in various areas necessitates common agreement on solutions for similar problems. However, the use of electricity in numerous sectors has joint tenancy features. Moreover, every part of the system affects other parts positively or negatively. Nevertheless, the value of the traded energy and the number of grid participants have increased rapidly; all these changes have necessitated cyber security and greater grid stability. Additionally, the natural development and transformation process of grid technologies have resulted in a more decentralized grid system yearly. Blockchain (BC) is one of the most promising solutions for these issues; in terms of realizing SG requirements, it will most likely subdue the entire power grid and make itself a significant part of our daily electric usage routine. The literature comprehensively discusses the distributed structure of BC and energy [3]–[5], particularly DERs, electric vehicles (EVs), smart meters, supervisory control and data acquisition (SCADA), marketing operations, and microgrids, as well as possible BC

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solutions [6]. BC technology seems relatively mature in the cryptocurrency area but is immature in the energy sector [7]. Security, privacy concerns, and a wide range of potential aspects of energy BC applications on grids, the existence of distributed energy users, and possible local markets in the future seem appropriate for the BC era. However, an essential part of the SG—the distribution system operator (DSO)—is missing [8]. The natural electrical connection of the grid parties and their inevitable relation with DSOs makes a relatively central authority, the DSOs, indispensable in the future. Additionally, the existence of DSOs may fuel privacy and security concerns. Despite the considerable expectation of independent SG from third-party interventions with the help of decentralized BC technology, the role of central grid operators and their compulsory existence should be clarified. Meanwhile, the number of customers, prosumers, and sources of distributed generation (DG) have increased rapidly [9]. Hence, managing the activity of numerous parties and additional marketing operations with only a few sources is challenging. In recent years, the modern world has embarked on a new promising solution, BC [10], [11].

Alonso *et al.* highlighted some of the problems of DSOs, such as a lack of unity of regulations worldwide, multiple DERs at different voltage levels, the deployment of millions of e-mobility solutions, voltage/reactive power management, congestion management problems of SGs, and the need to improve SCADA abilities [12]. These problems have invoked new concerns and threaten reliability, stability, and network-maintaining quality. In this situation, the DSO suffers two main problems: the exponential increment of DERs and their intermittent pattern caused by instant weather changes as well as the dramatic increase in EVs and the effect of their user patterns on the grid. These uncertainties and quantitative rapid changes are more likely to affect the operations of DSOs significantly. Some of the areas, which are slightly harder to implement in SGs, are well suited to the application of BC technologies. For instance, marketing staff, P2P trading, EVs (V2G, V2V, G2V), and billing workload seem appropriate, and their problems are soluble with BC. Conversely, regarding adapting equipment, such as smart meters and SCADA, in many countries, the DSOs in charge of maintaining these Smart Meters/SCADA-related devices find them harder to customize. Xie *et al.* comprehensively surveyed smart cities under smart citizens, smart healthcare, SGs, smart transportation, and supply chain management [9]. Although studies suggest an entirely distributed and decentralized approach to energy trading, the power system infrastructure still needs to be managed by DSOs [13]. Many environments lack a direct connection between consumers and producers [14]. Therefore, there is no choice other than to facilitate existing DSO components in the network. The greatest limitation on rapid changes in the current SG is that the energy flow must still go through the centralized electricity utility network. In this context, despite the centralized structure of DSOs, decentralized solutions are required [15].

More importantly, to the best of our knowledge, one important point is missing or not adequately discussed in this study. If we consider the near future, the BC affordance of the existing structure of the electricity grid is directly related to the DSOs. Many DSO occupations and problems are soluble by incorporating them into the BC. However, future challenges, such as the cost of transformation, appropriateness, and privacy issues, limits DSO in the face of rapid development. At first glance, at the national grid level, a thoroughly decentralized electricity network is nearly impossible, owing to the centralized nature of the DSO and existing grid structure, at least soon. However, apart from optimizing these solutions, the transaction cost of the new technology, possible needs for new devices, suitability of existing structure, the resilience of communication substructure, and adequate employee needs are main concerns for the near future [16]. In this regard, the applicability level of the solution is as significant as its appropriateness. Despite these requirements, there are no studies on DSO interactions and their impact on the near future of BC [17]. This study investigates the literature on DSOs and BC and discusses its convenience or inappropriateness in the following respects: (i) the responsibilities that DSOs burden; (ii) possible costs of the transition from conventional to more decentralized BC-based modern electricity networks; (iii) the applicability of BC to the existing power systems and possible solutions; (iv) the suitability of the existing structures of DSOs [18].

In the modern world, the fulfillment of the responsibilities of DSOs is significantly involved in maintaining resilience, stability, and fault detection/elimination systems [19]. However, all transaction details and the user's private data must be secured even from DSOs owing to the possible malicious manipulations. All these duties can only be conducted with the help of distributed BC technology. Teufel *et al.* found that social and technical transformation and political decisions, and digitalization, have resulted in major challenges that significantly affect the development of the energy market from conventional to contemporary [20]. The method and speed of the transformation of current power grids are not exactly clear but are relatively foreseeable [21]. According to the predetermined rules of the smart contract, all parties can be combined to realize trusted trading between peers, ensure grid flexibility and reliability, and equalize the rights of all the parties [22]. Reference [5] offers a smart contract implementation under different BC technologies to take advantage of its features in an energy-trading area.

Until recent decades, electricity markets were technically designed to deduce real-time demand-supply balance and manage the bottlenecks, constraints, and congestion in transmission systems [23]. Conversely, from the beginning of the development of DERs, EVs, and local markets, the issues and solutions became the responsibilities of DSOs and TSOs. Soon, DSOs will probably manage the network's optimum power flow and maintain the security of the grid. Authors have conducted a comprehensive survey of future SG under the sub-headings AMI, SCADA, energy trading and marketing, EVs and charging unit management, and microgrids; however, the role of the DSO and applicability of BC are lacking [24]. Owing to security and privacy concerns, Alladi *et al.* investigated the applicability of BC in SGs [25]. BC in SGs face challenges regarding scalability, centralization, development and infrastructure costs, and legal and regulatory support. BC and distributed energy were examined and categorized under technological, economic, social, environmental, and industrial dimensions. Moreover, related studies have investigated technical and institutional readiness-related issues thoroughly [26]. However, while some studies have addressed the applicability of BC and SG, none have investigated the existing situation of DSOs and BC to the applicability of DSO thoroughly [24]–[27]. In their study, Wu and Tran organized the features of the energy internet as accurate measurement, wide-area multisource cooperation, smart control, and open trading [28]. Although most parts of SG are inseparable and profoundly relevant to each other, they need to be clustered to be understood clearly.

Wide energy trading and bilateral power flow may create feasibility and stability issues. Therefore, in the thriving energy sector, the security of supply and grid sustainability must be considered significant as the cyber-security of the system. To avoid possible detrimental consequences, the DSO and its grid parties (SCADA, AMI) are discussed, and their existence in BC in energy is emphasized. Whensoever all these facts are considered, it seems that the electricity grid's physical manager, the DSO, will most likely retain its substantial and more active role in terms of maximizing the benefits of the majority, overcoming grid congestion, and fulfilling other grid requirements.

This study discusses this situation, particularly from the perspective of DSOs and the practicability of BC solutions in the not-too-distant future under SCADA, AMI, EVs, DERs, microgrids, marketing, DR, DSO/TSO interaction, environmentalism, and grid investment topics. Within the context of this study, we investigate and discuss the literature related to the interaction between DSOs, EVOs/CFUs, DERs/RESs, microgrids, and electricity markets with the aid of BC technology. Subsequently, we examine the applicability of BC in the existing DSOs scheme. This paper proceeds as follows. Section 2 sketches the background of BC technology, including consensus algorithms (CAs) and their outstanding features. Section 3 discusses the DSO services required to participate in the BC system. Section 4 further investigates the DSO-related grid parties and their interactions comprehensively. Section 5 discusses problems and possible solutions. Section 6 further concludes the study.

II. OVERVIEW OF BLOCKCHAIN

BC technology is an immutable transaction ledger that allows for a secure and distributed system without the need for a central authority [29]. In BC, each transaction is maintained in a block on the network. A block, like a chain structure, stores the hash value of the previous block. This structure further creates immutability. Each transaction on the BC can be stated using cryptographically signed blocks, transactions are then verified by network users [30]. Different consensus algorithms are used by BC to verify transactions. Consensus algorithms are agreements made among a group of people to validate transactions. The decision is made by majority voting at the end of the verification procedure [31]. Smart contracts are also an important component of many BCs and distributed ledger platforms. A smart contract is a set of rules executed on a BC. As the software representative of users, it automatically accomplishes specific obligations and tasks in the face of conducive conditions. Smart contracts are used to handle data, contracts, and relationships, and provide functionalities to other contracts and complicated authentication [32], [33].

There are two types of BC ledgers: public and private [34]. While the ledger of a public BC is transparent and permissionless and can be viewed by anybody, the ledger of a private BC is only accessible to users who have been granted permission. Consequently, it is possible to construct many channels and link a given number of users to them; non-registered users cannot view the data. Moreover, confidential information will remain private. Further, instead of utilizing their real identities, all users in BC systems have public and private keys. While everyone has access to public keys, private keys are unique to each user and are used to sign transactions. Hence, the first iteration of BC, the Bitcoin network, is considered pseudo-anonymous. In addition to the fact that the BC network comprises multiple components, the importance of the users involved in the network cannot be overlooked. The system needs an incentive design to ensure the participation of system users in the network and maintain their continuity. An incentive is a component of a platform's value proposition that helps organize the system for which the platform's token will be designed. Pay-for-performance reward systems that award individuals with money, are examples of incentives, as are systems that do not involve any financial rewards [35].

A. CONSENSUS ALGORITHM

Consensus algorithms (CAs) enable a consensus on specific requests in distributed systems. To compromise systems, these systems do not need to be reliable in these CAs. Consequently, CAs are used to build a BC framework that does not require mutual trust. They play a critical role in ensuring the security and efficiency of the BC. Choosing the best consensus algorithm for a given problem is critical to enhancing the system performance, which could increase the number of BC-based applications. There are many different types of CAs. All existing CAs are grouped under two main categories: lottery-based and voting-based (Fig. 1). Voting-based consensus techniques are democratic because they achieve consensus on critical network decisions, by calculating the number of votes cast by nodes on the network. Random-selection-based CA methods are more scalable. Further, these lottery-based CA methods require the consolidation of multiple chains. The validator, or the node that selects the next block to be appended to the ledger,

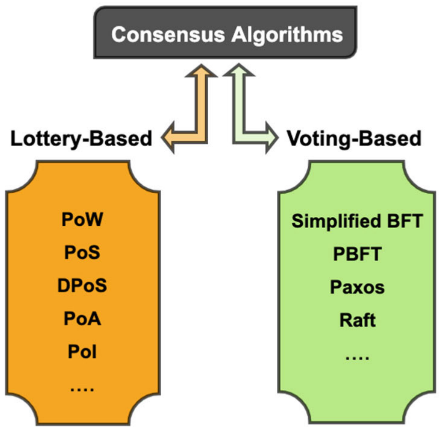

FIGURE 1. Two main types of consensus algorithms.

is elected by the lottery-based consensus algorithms. These elections are like a lottery. The winner is the validator, after which a new draw is required for each new block. Voting-based methods are quicker to achieve finality but slower to reach a distributed consensus owing to message exchanges between nodes. In summary, each algorithm has its set of benefits and drawbacks based on the system's purpose and requirements [31].

In the context of EV energy interactions, there is no need for a high volume of energy or money transfers owing to the lack of consumed/produced energy by EVs compared to other energy-related transactions, such as the energy trade volume of high power producing energy units. In most cases, the traded energy of EVs is extremely low. Therefore, the selected CAs for EV projects need to be secure. However, the energy consumption feature of the CAs for EV projects should be prioritized. In summary, the CA should be sufficiently secure to ensure all the transactions but more energy efficient not to waste energy. High electricity consumption may exceed the requirements of low-value low-cost transactions for EV charging. From the perspective of DERs, security would be much more significant in mitigating possible cyber-attacks as the potential high-value money transfers would increase hacker appetite. From the electricity market perspective, the security, scalability, and transaction period of the system are much more significant than the energy consumption.

Additionally, the duration of the transaction settlement is a considerably important qualification for CAs. The transaction period represents the speed of the system, and all the parties, especially the DSOs and EVs, which require higher transaction speeds. From the EV's perspective, grid connection/disconnection can occur at any time. However, DSOs would be relatively at the center of the system. It is a fast event owing to the EVOs' usage habits and reduction of the charging period with the help of new quick charge technologies, even for a few minutes. Therefore, transactions must be sufficiently fast to reach the flow of life [36]. Privacy is an indispensable characteristic of CAs. Data privacy is related to anonymity [21]. Nevertheless, data security concerns protecting data from unauthorized access. For EV users, a trip, either personal or business, is always considered sensitive personal data. Therefore, all personal data need to be preserved in a top-level secure manner. To prevent any possible exploitation, the selected CA must provide data privacy and security assurance.

B. SEVERAL CONSENSUS ALGORITHMS IN THE ENERGY SECTOR

While designing or selecting a proper CA, electric energy, computational CPU power, or the amount of money should be considered. Validation or incentives determine system vulnerability to malicious attacks or potential cyber-attacks and result in an equilibrium between system security and costs. High-cost distributed consensus solutions are worthwhile to endure to create a more secure BC environment. However, in addition to that necessity, private BCs can be redundant. Moreover, in most cases limited expenditure is sufficient. From the perspective of the DERs, the security of the system is a more important feature, whereas EVs require high incentives, maximized privacy, and a lower level of energy consumption. In summary, the selection criteria change from one project to another, depending on the requirements of the users. From the EV perspective, the selected CA should highly incentivize users to participate and share their CFUs publicly, for everyone's benefit. In addition, high-level privacy is a significant requirement in the sector. Nevertheless, from the DERs perspective, the security of the system is more significant owing to possible high-volume energy transactions.

The literature has investigated several CAs. However, CAs in energy-related studies are extremely limited. Andoni *et al.* investigated a wide view of distributed consensus algorithms and the system architecture of BC technologies in the energy sector [37], providing reviews of 140 BC research projects, and classifying them according to their activity field, the platform of implementation, and strategy of consensus. P2P (peer-to-peer), M2M (machine-to-machine), B2B (business-to-business), and trading schemes are mentioned as related use cases. According to the activity field, only 7% of the studies were related to e-mobility. From the platform perspective, which was used to adopt the system, 50% of the studies used Ethereum; the most used consensus algorithm was PoW (55%) and PBFT (15%), respectively, in all energy-related BC studies. Proof-of-Work (PoW) is the most mature CA ever used. Despite its high security and scalability, the main problem with PoW is the significant amount of energy wastage and speed. PoW based on reputation (PoWR) is used to minimize transaction confirmation latency and new block creation time. The efficiency of energy trading, load balancing level increased, and computational complexity was minimized by leveraging contract theory in EV energy trading; however, storage and scalability issues remain [38]. A credit-based PoW consensus algorithm is proposed to ensure a secure and reliable smart city environment [39].

The other mature and proven CA is Proof-of-Stake (PoS), while one of the promising application fields is the Internet of Vehicles [40]. However, it is argued that its energy efficiency and fast structure make the rich most probably richer. Another CA, the PoB, has a similar idea of proving transactions like POS and similar issues. A Proof-of-Benefit (PoB) mechanism with an online benefit-generating (ONPoB) algorithm has been proposed and argued to likely substantially reduce power fluctuations in future SGs [41]. Delegated Proof-of-Stake (DPoS) is a more energy-efficient and scalable but semi-centralized version of the PoS. DPoS consensus-algorithm-based energy sharing was introduced into the internet of vehicle models to design a more efficient trading environment [42]. Practical Byzantine Fault Tolerance (PBFT) is a faster and more economical solution than PoW. Unlike PoS, there is no required asset for the consensus process; this is to increase transaction throughout and reduce transaction delays [43]. Another study proposed a game-theory-based PBFT consortium BC and considered the profit of the energy seller in the P2P trading scheme [35]. Contrary to the advantages of PBFT, its disadvantage is there may be delays as the network waits for all nodes to vote. However, Delegated Byzantine Fault Tolerance (DBFT) uses PBFT's mathematical solution with one difference—there is no need to wait for all the nodes to vote. This less delay-offering solution may threaten network decentralization. A DBFT application is proposed as a secure charging scheme for EVs [45]. A utility-based DBFT consensus algorithm is used. An optimized smart contract ensures fast and reliable mining and validation processes for EV location preservation [46].

The directed acyclic graph (DAG) verification process is faster than PoW/PoS; additionally, power consumption is extremely low, and no mining process is needed [47]. Liu *et al.* used proof-of-eligibility based on BFCV (Byzantine-fault-tolerance-connected vehicles) to ensure a group of vehicles within the vicinity of the information source provide a correct consensus, to further ensure the safety of vehicles in traffic [48]. Proof-of-authority (PoAu) is a type of modified PoS algorithm that is seemingly more appropriate for utility companies to govern and regulate in a centralized manner [49]. V2G has some concerns, such as relatively transparent information, excessive transaction quantity, unrevealed rules, and the randomness of trading hours. To overcome these issues, the PoAu consensus algorithm may be chosen. It is preferred to reduce the need for computing resources, enhance the efficiency of transactions, and eliminate mining requirements. The identified aggregator nodes are privileged, and charging piles are ordinary nodes—there is no need for ordinary nodes to store all other transactions; only the storage of the privileged node's record of all transactions is sufficient [50]. Byzantine fault tolerance (BFT)-based BC is used and compared with PoW under finality and scalability performance; the results support the BFT [51]. A pricing-based incentive mechanism was proposed with the help of a proof-of-reputation algorithm, to efficiently reach consensus in vehicle energy delivery networks [52].

Table 1 highlights some features of the CAs used in the energy sector.

III. USE OF ESSENTIAL DSO SERVICES AND BLOCKCHAIN

A. SCADA

SCADA is one of the key instruments for the grid management of DSOs to monitor and orient grid events and power flow, manage active/reactive power, and detect electrical fault points. The reality of the presence of cyberattacks creates a considerable need for intensive attention to the SCADA system for security, privacy, reliability, sustainability, and the continuity of electricity procurement. SCADA systems typically comprise elements, such as sensors, relay devices, circuit breakers, voltage regulators, power measurement units, and communication network components [53]. It collects all distributed information of sources and data in a central database. All these system parts lack computational abilities owing to low computational power. The absence of computational power on controlling units, such as sensors, circuit breakers, actuators, delays, or rarity of computational power on other SCADA units causes failure to directly participate in BC as a node. Additionally, the impulse response of the current SCADA and grid management systems must be within seconds in BC systems. Conversely, BC technologies consume more time than the existing structures. Kong *et al.* examined the necessary countermeasures for improving this time efficiency by facilitating a multi-chain approach and using the PBFT consensus algorithm [37]. Related studies have proposed a novel consensus algorithm—PoRCH (Proof of Random Count in Hashes)—which does not require any incentive or penalty mechanism for validator/miner nodes [54]. The security and robustness of the entire power grid mainly depend on the security of the SCADA system as the grid's centralized nature and structure are vulnerable to cyber-attacks [11]–[55]. The high-level decentralized SCADA system architecture is highlighted to protect the grid from data poisoning, and identity spoofing [56]. Except for the difficulty of managing centralized systems like SCADA as decentralized systems like BC, the grid devices are indispensable, owing to their physical connection structure, the natural structure of electricity, and lack of an alternative to these devices. However, the SCADA system pieces are under the control of DSOs, and the weak points of all the systems are not tamperproof against physical interventions too. Future studies should investigate this point comprehensively.

B. AMI

Generally, advanced metering infrastructures (AMI) are high-level measurement, metering, and monitoring devices that allow widespread communication among all grid users. Particularly, smart meters and telemetry devices are assumed

TABLE 1. Comparison of consensus algorithms.

Consensus Algorithm	Main Goal	Drawbacks	Decentralization Level	Determining Verifiers Based on	Energy Consumption Level	Hardware Dependency	Scalability Level	Vulnerable to Attacks	Transaction Speed	Mining
PoW [38,39]	Sybil-proof	Energy consumption, hardware dependency	High	Work	High	Yes	High	51% attack, double-spend	Slow	Yes
PoS [40]	Energy efficiency	Domination of large stakeholders	Medium	Stake	Low	No	High	51% attack, double-spend	Fast	No
DPoS [42]	More energy efficiency, organizing PoS, fair reward distribution	Centralization possibility	Medium	Vote	Low	No	High	51% attack, double-spend	Fast	No
PBFT [43-44]	Improving security level in an economical way	Low scalability, possible Sybil attack in large scale networks	High	Vote	Low	No	Low	Sybil attack	Slow	No
DAG [47]	Speed, scalability, reducing hardware dependency	Centralization possibility	High	N/A	Low	No	Low	-	Fast	No
DBFT [45,46]	Improving speed and scalability of PBFT	Centralization possibility	Medium	Vote	Low	No	Medium	51% attack, double-spend	Slow	No
PoB [41]	Alternative Agreement of PoW	Energy consumption, hardware dependency, domination of large stakeholders	High	Burnt Coins	High	No	Medium	51% attack, double-spend	Fast	Yes
PoAu [49-57]	Speed, low transaction fee, Suitable for DApps	High centralization possibility	Low	Random among trusted nodes	Low	No	High	-	Fair	No

to be sealed tamper-proof devices, to confirm the amount and flow direction of energy [57], [58]. According to their adoption of the SG by the current TSO/DSO, the environment requires digitalization and advanced capability to monitor the grid's power flow, voltage, frequency, and stability. Teufel *et al.* discussed the current and prospective applicability of BC technologies in the energy sector [20], from old to new energy transformation processes characterized by structural coupling with multiple sectors and technological developments. In this context, as well as the current importance of smart meters, most will probably play a key role in this transition. The smart meters and BC of DSOs ensure the trust and security of the system and that DSOs bill and trace energy exchanges [59], [60]. These trusted parties, considered BC nodes, provide connections between users and the outside world. One of the main components of the SG is smart meters. Therefore, this type of current technology must be used to adapt BC to the new energy trading era [61], [62]. Despite the immutability, transparency, resilience, and automation advantages of BC, the knowledge on the influence of current hardware and communication limitations is little [63], [64]. The authors demonstrate a real case study of BC-managed microgrids that offer a higher bandwidth to maximize the throughput per second in an AMI environment. Additionally, the number of validators, the maximum data rate of the communication infrastructure, and the available network infrastructure affect the throughput and latency directly. Additionally, the hardware capacity of smart meters is adequate nearly nowhere and requires additional improvements. Therefore, governments or utility companies should further push smart meter producers to reach the level of novel, sophisticated, and customizable devices. Enabling highly efficient collaboration between local prosumers, consumers, and DSOs is viable if and only if there are computationally capable smart meters.

However, smart meters can send and receive data about consumed or produced energy and additional information, such as price and cut-off data for managing and billing [61], [65]. Smart meters have many security vulnerabilities, such as the interference of unauthorized users through manipulations at a physical metering box and of metering data, and interventions of eavesdroppers in wireless/wired communication channels to capture customer data for malicious purposes [66], [67]. Automatic billing services for all electricity users may reduce the overall administrative costs of DSOs, which may secondarily reduce the electricity prices for customers [6]. BC has a remarkable cyber security ability to protect all users and promises considerable benefit to society. However, DSOs must prevent physical interventions and manipulations. Instant physical attacks and retroactive past attacks and measures to prevent such situations should be considered, considering the immutability of BC technology. Another important point is how the DSOs should interpret past attacks and how to penetrate BC to correct all the wrongdoings. Under these conditions, the responsibility of DSOs is as significant as the general security of the entire energy environment. This DSO role, its limits, and its scope on the system are regrettably mentioned nearly nowhere in the BC and energy-related studies. Although the adaptation of current metering, measuring, controlling, and communication systems are requirements, BC systems require high throughput and speed. However, the current abilities and hardware backgrounds of smart meters are limited.

IV. GRID STAKEHOLDERS AND BLOCKCHAIN

DSOs have new roles and responsibilities in the decentralized energy era. From voltage control and management of power flow to the contribution of nationwide frequency control, the new crucial operation and working areas of the DSO need considerable precision and sensitivity. The increase in the number of DERs, EVs, and the need for a new energy market have led to new requirements for systems like BC, to create a decentralized, reliable, and secure energy environment. BCs with EVs, ESSs, DERs, and energy markets were investigated from the DSO perspective.

A. EVS/ESSS (ENERGY STORAGE SYSTEMS)

The growing popularity of EVs has resulted in new challenges and opportunities in the modern world. From the electric car customer's perspective, they offer a lower carbon footprint and environmentally friendly choices to individuals, cheaper journey opportunities, and perhaps more car engine power for low-income customers, who are eager for higher power. From a car maker's perspective, they provide opportunities to make electric cars more suitable, efficient, and sufficient, and hence gain market share. However, the main reason for forcing electric car makers to move toward this area and EV users to refer to this choice is the government's compulsory laws to reach lower CO_2 emission levels. The CO_2 emission standards of the European Union will gradually force car manufacturers to reach an average EV sales share of 5% in 2020, 10% in 2021, and 20% in 2025 [68], [69]. From the DSO viewpoint, EVs provide new opportunities for creating more sustainable energy systems and smoothing consumption patterns and hence entail less distribution grid investment and fewer technical losses. Contrary to these positive effects, there are certain adverse effects of EVs.

The more decentralized electricity grid participants, such as DERs (solar, wind, hydro), and EVs there are attached to the grid, the more the likelihood of a powerful, reliable, and robust distribution grid. In contrast, the instant production and consumption patterns can cause electricity disasters, as well as nationwide power outages. The proposed BC and EV design should ensure grid robustness by attending DSOs, perhaps by including the DSO as part of the incentive mechanism. In the system framework, DSOs can determine the congestion points with deficient or surplus energy data beforehand, to canalize EVOs to those specific locations. If the grid needs more energy, then fully charged vehicles are directed to energy shortage points through an incentive mechanism and vice versa. Therefore, EV and BC interactions ensure the sustainability of the national grid. However, the cost of producing and delivering electricity is not entirely dependent on the amount of energy used but mostly on that of short-term demand. Grid investment is directly related to the peak load of the network. Therefore, intelligent, self-sufficient grid management schemes are required. Particularly, EVs can result in more distribution grid investment owing to the possible instant load increases if they cannot be managed effectively. To mitigate the investment amount of DSOs, many countries have created different political demand-side management (DSM) aspects. In addition to these grid enhancement offerings, EVs/CFUs can ensure grid capacity improvement; if the EVs are canalized to the energy shortage points, then the short-term grid investment expenses would decrease. In conclusion, centralized and unidirectional power flow can cause more power loss owing to the extremely long transmission and distribution networks. A decentralized grid with an increasing number of EVs makes for a more energy-efficient system owing to the proximity of the consumer and producer to each other.

From the viewpoint of EV makers, modern electric cars have attracted eco-sensitive customers by using environmentally friendly solutions, such as suggesting emission-free EVs. Despite its benefits in creating new trading opportunities by utilizing EV technology, EV producers will put up with the need for more research and development investment expenses. However, it is considered compensable, owing to the ever-growing number of EVs sold. Additionally, the multi-dimensional problems of EVs are expected to be solved in many ways in the future. However, expanding the usage of EVs worldwide with the help of BC makes them beneficial for all customers and most probably encourages EV producers to make vehicles better, cheaper, and beneficial to users. In sum, an increase in new EV sales and more customers choosing EVs would likely boost the car production sector, which would benefit car producers, potential customers, DSOs, and the environment.

In addition to these impacts on all parties and EVOs, one specific issue can be stated as the main problem, the range of the cars from the single charge and, consequently, the availability of charging utilities/stations. Despite EVs being cheaper, more environmentally friendly, and relatively comfortable, their battery performance significantly limits their range. Although car producers are working on more durable vehicle power supply solutions, it is a challenging problem to solve soon. However, alternative solutions can be created by third parties. The problems of EV ranges and the locations of charging facility units can be solved by using the distributed, private, and secure structures of BC networks. Imagine traveling from one location to another by EV, where, most often, the EVO is obligated to navigate to reach the target area in an optimum manner. In this journey, the fastest and cheapest route will certainly be chosen. However, finding possible locations of service areas and alternative charging opportunities is another major obligation for travelers not to be stranded on the road. Thus, convenient charging facility units that belong to other EVOs become a part of the solution to the already diminishing battery power of the EV. If all included CFU owners make their devices available for strangers when they are not used, EVOs can spend less energy and time while finding charging locations. Therefore, concerns regarding reaching CFUs before depleting the battery will be reduced. Finding appropriate CFUs for BC-user EVOs will be considerably easy in city centers and rural areas, owing to the available distributed CFUs. The main obstacles to the spread and proliferation of CFUs and a charging system are privacy, security, and lack of encouragement processes. Hence, in the BC-centered EV era, EVOs will be free to travel far distances, feel secure and safe, and have their privacy preserved. Nevertheless, CFU owners will be free to trade (sell/buy) energy with other participants without third-party intermediaries. Additionally, through the automatic payment mechanism, the grid and off-grid electricity stakeholders can participate in the EV charging system without having to worry about billing staff and payment details.

Apart from these positive and negative effects of EVs with BC, the owner of the grid assets, the DSO, is mentioned almost nowhere. The electricity grid is compared to a living being that requires regular maintenance and repair. Several grid situations, such as overloading grid equipment, may affect EV/ESS users adversely. To keep the electricity grid alive, the DSO must manage the load and power flow directly. Rapid increases in the number of EVs/ESSs will most probably create congestion at the weak points of the grid. Therefore, the overloaded charging scheme may be interrupted by the DSO using the BC structure to keep the grid alive. However, it is necessary to determine how the DSO act in that situation. Additionally, interruptions must be fair and sustainable for all users. This poses an obstacle to the operation of liberal and self-sufficient BC in energy studies.

B. EV-BLOCKCHAIN-RELATED WORKS

EVs and the e-mobility area have attracted attention among companies and researchers, owing to their inevitable decentralization process. Most EV owners have a car charging facility/unit for their use, which can be either connected to the grid (on-grid) or not (off-grid). Regardless of whether they are on- or off-grid electricity users, property owners or EV charging facility owners are free to rent their charging capacity and share their facilities publicly when they are not using them. Thus, both parties eliminate intermediaries and allow individual trading opportunities, and are also freed from the monopolies of commercial charging station companies. Although this projection gives freedom to the charging station owners, it has some drawbacks, such as how to pay for the consumed energy. Might the cash system violate the privacy rights of car owners? By constructing BC-based networks, EV owners can gain greater privacy when traveling between different locations, including foreign countries. In this regard, Teufel *et al.* take a holistic approach to BC technology in the energy sector based on a literature review and expert interviews [20]. It considers that the greatest impact of BC will occur in the short term on EV integration, while in the long term, BC will affect P2P energy trading on microgrids. It has been argued that the most challenging part of BC development in the electricity sector is inflexible regulations. Additionally, researchers have emphasized the need for a consensus between past and future decentralized energy systems, where BC is perfectly suited to this requirement. However, this study investigates all the energy sectors and EVs, apart from the interaction of DSOs with others and the short-term necessities of BC. Conversely, another study classified 140 BC research projects according to the activity field, and only 7% of the studies related to e-mobility [70].

The adoption of EVs to improve transportation opportunities requires further research. Particularly, the optimum charging station location, battery limitation, management of charging scheme, and impact of the EV on the power grid require more studies [71]–[73]. On the one hand, EV owners expect their cars to be charged in the fastest and cheapest way. On the other hand, DSOs struggle to manage peak load and system robustness issues. In addition to these problems, one of the major problems is the privacy of EV owners and the security of the entire system. Lazaroiu *et al.* proposed a method based on fuzzy logic for faster and efficient charging by connecting publicly available private charging points and the PoS consensus algorithm used owing to its energy-saving fast structure [74]. They mainly focused on grid congestion management and peak load hour compensation. Fuzzy logic is used to generate the weight of each member of the system to generate a new block. This study focuses on the excessive power production of PV panels and stores surplus energy to reach common fairness between individuals. However, the author's major consideration is the lack of efforts to promote the involvement of EVOs/CFU owners and DSOs. EVs and energy storage units act as charging points for filling energy valleys and feeding back into the power network to reduce the peak demand that is a major DSO burden [75]. A secure and credit-based BC payment mechanism enabled V2G energy delivery in microgrids and overcame confirmation delays. The auction mechanism and a smart-contract-based trading platform on a private Ethereum network were proposed and simulated. Further, an existing metering staff of utilities remained unchanged to avoid major infrastructure changes [76]. DSOs are considered incentivized by the energy transaction corresponding fee payment of the BC users. However, the stimulation is superficial owing to the reality that DSOs prepare billing for all energy transactions, except for limited off-grid connections in some cases. Therefore, the incentivizing ability of the proposed system was meaningless. Charging location selection is presented based on a protocol for dynamic tariff decisions, different pricing of energy providers, and distance to the EV. The bidding mechanism, offered as an EV, signals the demand; the charging station sends bids like an auction using BC [77]. The price will be the lowest for EVs and the highest for charging stations. The main motivation is finding the cheapest and most appropriate CFU. However, it is not clear why EVOs participate in this system. Although DSOs should be significant and natural users of BC/energy studies, they were not mentioned.

Despite all these studies, reasons to encourage all EVOs, CFU owners, and DSOs to participate in the BC have been neglected. Fu *et al.* offer a cooperation system that connects companies and their customers via smart contracts [78]. For the benefit of EV users and new energy companies, a novel convenient charging system is proposed to maintain the fairness of user allocation and balance the profit of the company alliance based on a consortium BC. The Limited Neighborhood Search with Memory (LNSM) algorithm is used to make a faster smart contract with better performance. However, despite all these allocation schemes for the appropriate EV charging pile, the situation of the DSOs and the responsibility due to possible grid congestion resultant status were not mentioned.

Sharma *et al.* and Pustišek *et al.* focused on selecting the most convenient EV charging station autonomously, booking charging slots from remote locations to schedule charging time and cost values by implementing a BC-enabled EV charging infrastructure approach [79], [80]. Information regarding when and where users charge their vehicles is ensured by the BC network. However, charging costs are detailed as the time of use, type of charging power source, and waiting time of users among others, while the DSO rights and reasons for forcing it to involve its entire system are not mentioned. In SG systems, P2P energy trading (ET) schemes based on Ethereum smart contracts to procure more secure, private, and adequate latency and real-time settlement have been proposed [81]. The aforementioned system design of energy trading between EV owners and prosumers, who are interested in selling surplus energy, is facilitated. The performance was evaluated by comparing the data storage cost and latency. However, scalability was not verified. Nevertheless, the DSOs and measures intended to softly force the EV/CFU owners to enter the system are not touched on.

When all such BC and EV-based studies are examined, they investigate the energy costs of EVs, fast and efficient charging, selection of appropriate CFUs location, scheduling, and booking charging slots automatically. Although they attempt to solve the main problems of the state-of-the-art confusions of EVs, there is a lack of linkage between DSOs' interaction with EVs and a shortage of encouragement of EVs/CFU owners to participate. Although BC offers decentralized networks, owing to the reality of the existing grid structure, the central management of DSOs plays a significant, non-negligible role. In summary, there is a considerable requirement for a scheme that offers less grid capacity enhancement investments, fewer grid losses, and a sustainable power system but strengthens DSO operations through the BC's decentralized structure. However, struggling to find appropriate CFUs should be facilitated by a reward mechanism for EVOs and CFU owners so that the traveling area of the EVOs can be significantly expanded. It is necessary to determine how to enroll DSOs and secure the rights/responsibilities of DSO while maximizing the benefit to EVs/ESSs owners.

1) FUTURE EV USAGE AND ITS PROBLEMS

It is not too far-fetched to expect EVs throughout the world in every city or rural area. Nevertheless, it is difficult to create available charging units for cars to prevent them from running out of energy. In this context, most EVOs would have their EV charging units. However, establishing a new CFU may be expensive. Further, the time to amortize this new device would be long. Additionally, energy storage units will soon be common. These types of extra loads create an intensive need for demand-side management solutions and difficult situations from a grid management perspective. Moreover, in a charging scheme, the relation between EVOs, CFOs, and charging stations requires clearer explanations. Payment details, the privacy of EVOs, and the security of the offered solutions are commonly discussed. Gabay *et al.* mainly focus on the privacy issue of the charging period scheduling of EVs [82]. The main issues are that the daily or hourly locations of car users must be protected as private data. In summary, the main problems caused by commonly used EVs soon can be described as follows:

- Finding an available charging facility during a trip will be difficult or impossible, in rural areas.
- Shorter and less comfortable journeys are less preferable for EV usage. Therefore, the global CO_2 emissions goal may be unattainable.
- Overloaded grid problem may make congestion management extremely difficult, or unmanageable.
- Increments in short-term energy demand would increase grid investments owing to the relationship between instant electricity demand and grid capacity.
- Increments in energy demand and the number of unbalanced loads are more likely to increase grid losses and energy wastage.
- The applicability of BC technologies to the existing DSO structure is a complicated task owing to the need for the central authority as the main actor.
- Constructing an EV charging facility for the EVOs' use would be expensive.
- Privacy concerns of the EVOs' trip data are emerging.
- Security concerns and vulnerability against cyberattacks are also vital and up-to-date topics.

- Mature incentives or reward mechanisms to promote EVOs and CFUOs to participate as actors in the system are lacking.

2) BENEFITS OF EV WITH THE HELP OF BLOCKCHAIN

The negative sides of EVs can be made into positives. The benefits of the wide usage of EVs with the help of BC technology are as follows.

- Every EV owner can be a charging station owner; therefore, a more decentralized EV network system can be created, where finding the CFUs will be easier
- Increments in using EVs result in less global CO_2 emissions and lower carbon footprint (decarbonization) for individuals and companies
- A reliable and robust energy system can be obtained by promoting EV usage by BC
- Decentralized bi-directional V2G and V2V low-cost energy transaction
- Sustainable and renewable energy usage will be encouraged by providing trading opportunities
- Decreasing technical losses of the electricity distribution grid and enhancing grid efficiency
- Supporting EVs as ancillary services (real-time energy management) and as grid inertia sources
- V2G and more smooth consumption pattern, and therefore, less distribution grid investment
- There will be no need for extra billing staff or individuals to trade face to face.
- More secure and private transactions and freedom of traveling ensured

The benefits of the BC mechanism contemplated in the study of Liu *et al.* are obvious: the contribution of EV charging on the SG improves resilience and minimizes the power fluctuation level [83]. This study aims to reduce the overall charging cost for EV users using the proposed novel adaptive BC-based electric vehicle participation (AdBEV) scheme. Crasta *et al.* proposed a BC-based solution to DSO, to be freed from the extra burdens of the EV charging schedule and facility constraint problems while ensuring fairness between EVs [84]. Matsuda and Taraka showed that EV agent systems within BC platforms are adequate to maximize the value of local renewable energy sources [85]. Some benefits of the study are that the load variance of the power grid is mitigated by the effect of peak load shifting, reducing the stability and safety issues of the power grid [86]. As per the above, all general negative effects of EVs may be converted into positive effects by leveraging BC technology. However, all beneficial features of the BC seem utilizable. However, it is not clear how DSOs will act as BC users. Instant overloaded grid equipment and its management using a BC should be investigated. How the power flow can be oriented while saving the fairness of users is notable.

The issues and potential problems demonstrate possible adverse even devastating effects of the proliferation of EVs on the grid. All these possible detrimental impacts and other issues (privacy, security) are solvable by adapting BC technology into that area. In sum, the existence of DSO may keep EV users in suspense owing to its central nature, despite BC's improved data security feature. In contrast, EVs' inattentive consumption patterns may keep DSOs in suspense owing to the relatively unexpected rise and new extra grid load of EVs. DSOs' essential responsibilities and EVs' expectations should be managed within common grounds by utilizing a wide range of BC features. Interaction between EVs and DSOs most likely gain importance; that mutual effect will provide direction to the development ultimately.

C. USE OF BLOCKCHAIN IN DERs AND MICROGRIDS

The cost of renewables, energy storage, and other technological developments are rapidly decreasing; therefore, this situation will prompt the users to become more actively involved in the grid. The cost of the transition from conventional grid systems to SG systems, with the help of AI and BC technologies, is relatively high. Nevertheless, the benefits are abundant, particularly for DER [87]. Some benefits of information technologies are considered the lively collection of energy consumption/production statistics, enhanced grid efficiency, peak demand adjustment, and sustainable energy trading that can ensure the possibility of choosing low carbon energy sources. This provides extended support for other plug-in energy infrastructures (e.g., city surveillance systems, public lighting), advances the support of EVs, and reduces the suspicions of reliability and stability concerns. Additionally, effective monitoring of the grid could help address the issues of grid congestion and massive energy transfers. The resilience of the grid can be ensured against extreme weather, acute accidents, asset failures, and even operational human errors by distributed smart devices and BC. All system components are cordially related to each other. In the modern world, uncertainties in RESs owing to instant changes in weather conditions and changes in human consumption behavior may adversely affect the performance of planned P2P trading [88]. Therefore, utilities have no choice other than fight-and-innovate strategies, while acknowledging customers as potential generators through such devices as rooftop PV units [70]. However, within the grid modernization concept, the cost of system-wide participation of DERs is as important as integrating them effectively, as an inseparable part of the network [89]. There is a considerable need for a novel BC structure, as DSOs influence the power grid the most and will plan the BC framework in the presence of DERs [8]. Nevertheless, most often, microgrids comprise DERs and consumption units and are expressed as interconnected electricity devices, local balancing of electricity consumption and production, and small-scale, self-controlled grid systems [90]. However, as a highly scalable and flexible solution, microgrids are also a potential source of inefficiencies and vulnerabilities, especially owing to the transmission of energy over long distances through transmission lines. The DSO is responsible for monitoring and controlling the utility network to guarantee quality and sustainability, even in a highly decentralized microgrid-based environment. Although widespread microgrid implementation collectively provides new opportunities, it also mandates that the power distribution network adapts to a new feasibility paradigm [91]. Most grid-connected microgrids belong to facility owners [92]; recognizing the contribution of microgrids to existing distribution infrastructure is a special topic. P2P energy trading projects mainly focus on microgrid-level investigations owing to the existence of adaptable local markets and available information and communication technology) [93], [94]. In the P2P, prosumer to the grid, prosumer to community scheme, P2P trading is probably the structure that is furthest from today's central grid model. Different consensus algorithms have been proposed to achieve fairness and the optimum profit of microgrids and miners in the IoT [27]. This decentralized structure requires a decentralized solution, such as BC. Nevertheless, the main obstacle to P2P energy trading in microgrids is regulatory challenges [95].

The existence of DERs and prosumers creates a bidirectional power flow reality. Therefore, DSOs must behave like traditional TSOs and be more active in redirecting energy. Reduction in the investment costs of DERs and widespread BC applications may accelerate the transformation process. In the future, BC technology will most likely play a significant role in the DER-connected grid with the help of its secure, distributed, and adequate structure for energy trading. However, in the short term, DSOs will remain the main actors of the grid and significant energy providers in the trading system. Production instability owing to sudden weather changes may cause extreme surplus energy. DSOs are responsible for managing local and broad energy disturbances with canalizing power from more to fewer points with the help of BC under these conditions. Additionally, legislation in favor of grid users will likely foster BC usage in microgrids. However, inner energy trading operations are relatively independent of DSOs; moreover, the interconnection of multiple MMG schemes would only be possible with the existence of a physical connection of DSOs.

D. BLOCKCHAIN IN A DECENTRALIZED ENERGY MARKET

Most studies on energy trading and BC have focused on the electricity market, P2P energy trading, and V2G and V2V approaches [96]–[98]. However, today's widespread market structure is centralized in day-ahead and intraday markets. In this energy trading scheme, transactions must be timely owing to the timely usage of electricity. Contrary to classic cryptocurrency algorithms, especially in the electricity market, the transactions have time constraints on aggregation and processing. Therefore, in sufficiently large environments, communication problems and possible solutions must be strictly considered. The energy internet requires real-time settlement, intelligent interaction and decision-making, and extensive interconnection among all parties [99]. Moreover, electricity trading is distinguished from other commodities by its physical laws and technical constraints [90]. DSOs must be considered third-party validators for energy exchange to not violate technical network constraints, a methodology based on sensitivity analysis, and economic benefits [100]. Apart from maintaining the existing retail market, allowing DSOs to manage local flexibility markets and negotiate in them is an alternative solution to manage grid constraints [101]. A possible limitation of the DSO-managed local market design is that it may fail to exceed the minimum voltage and power flow limits of the transformer [102]. To manage these issues, the requirement for coordination efforts between users and DSOs has increased. owing to the intermittency and bidirectional energy flow [63].

Guerrero *et al.* presented P2P energy trading in a low-voltage network with a low requirement for the DSO scenario [103]. Trading in the market occurs between closest agents. Therefore, it is argued that the mechanism reduces technical power losses and network congestion with the lowest level of DSO involvement. The main goal of the DSO is to match the electrical distance between peers. In Lee *et al.*'s study, messaging was authenticated for prosumers and consumers to notify and verify the injection of surplus energy to the grid [14]. DSOs' responsibilities are described as handling financial operations, monthly billing of customers and prosumers, and maintaining the physical part of the grid, such as registering new smart meters to the system [104]. Token-based smart contracts were further utilized and the total amount of energy compared with DSO in trading [105]. Despite the DSOs' responsibility to institute reliable measures to prevent customers from stealing electric power, this study does not examine the need for new devices or new approaches. Additionally, the DSO should be a guarantor for the rights and duties of each party. This study does not discuss the transaction rate within a market time step. Owing to the distributed nature of marketing operations and its direct relevance to money, it is highly applicable to BC, despite some drawbacks, such as lack of regulatory legislation, deficiency of distributed hardware capacity, and the significant lack of practical experiments.

The primitive version of the market contained only a few market participants (TSO, DSO, and big power plants). Power flow was unidirectional, and trading was somewhat limited and mainly dependent on TSO operations. The TSO was the central authority responsible for electrical and commercial affairs. The main structure of the present national market comprises several users (DERs, prosumers, big consumers, and microgrids). Consequently, power flow has started becoming bilateral. Moreover, the market is freer than before. Although the DSO has new roles (DSM) on the grid, with the TSO overwhelmingly managing the main tasks (frequency control, ancillary services), the DSO supports the TSO. However, the inclusiveness of the market is satisfying, and the smallest consumers are still out of the market. Additionally, the BC-based national market is far from true. Contrary to that slower development, the inclusiveness of the national market soon is expected to be wider, where most users will be market participants. More importantly, an increase in the requirements of DSM, the number of

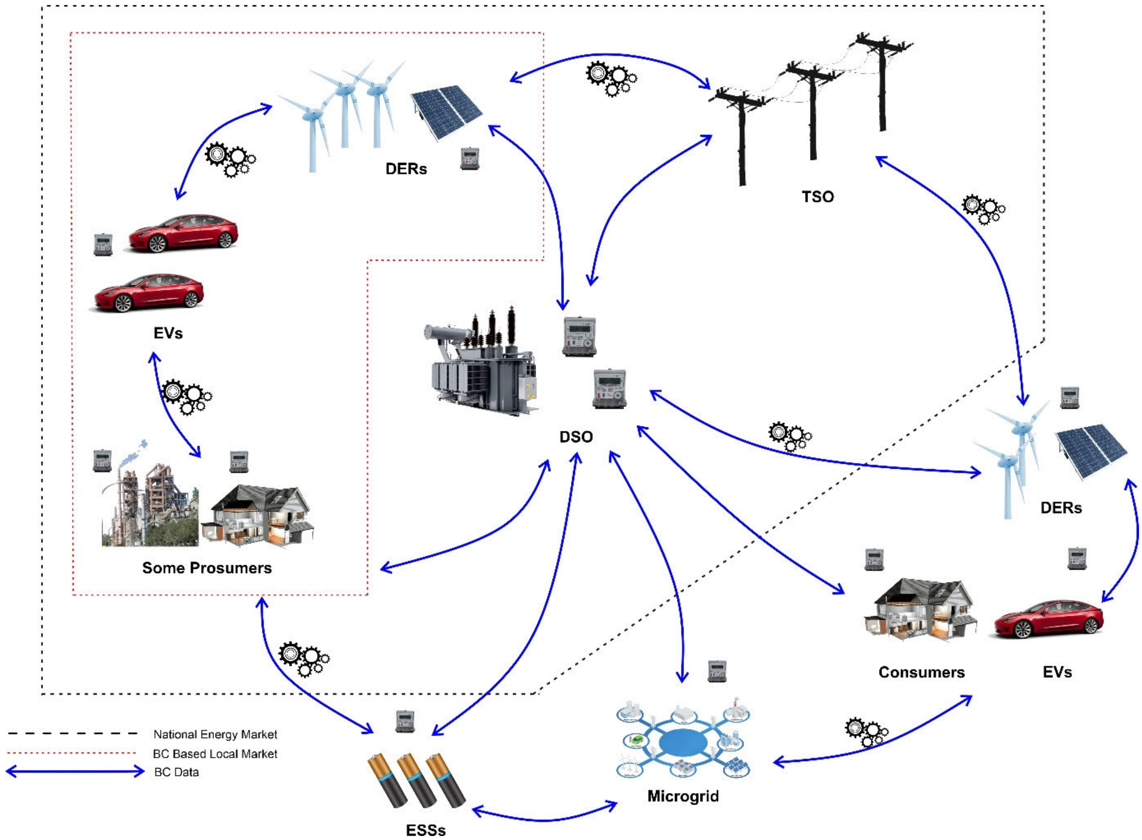

FIGURE 2. Near future energy market structure towards a decentralized BC-based general market.

rooftop PVs, new distributed electricity generation methods, and EVs may advance DSO. Additionally, the development of BC and brand-new EVs will most likely stimulate the transformation process the most. The proliferation of BC and new pilot projects based on BC may create new interconnected local markets also connected to the national market (Fig. 2). These local markets will most probably comprise EVs, DERs, and DSO. However, in the new era of BC, the market may not embrace all small electricity users. Further, the DSO will continue to perform its critical duties. The DSO's electrical and commercial active role may affect new issues, such as centralization, manipulation, and intervention possibilities in the new market model. To arrive at the ultimate decentralized BC-based energy market target, the limits of the DSO, technical responsibilities, and commercial duties must be strictly determined.

E. BLOCKCHAIN CONTRIBUTION IN DEMAND RESPONSE

BC's incentive mechanism and smart contract's transparency and reliability features will have a positive effect on the smart grid. Power grid quality criteria can be ensured by the DSO with the aid of regulating the voltage/frequency fluctuations. The goal of DR is to incentivize the desired behaviors of customers, producers, and prosumers while disincentivizing undesired usage behaviors. In the study of Alonso *et al.*, the open automated demand response (OpenADR) mechanism is argued to successfully apply the PoC peak shaving scenario [12]. In the study of Nuur *et al.*, continuously growing demand and the high penetration of intermittent resources have become challenging issues. The study proposes a game-theoretic approach for DSM to reduce peak-to-average and smooth the dips [106]. Further, in the study of Pop *et al.*, the Ethereum platform is used to self-enforce the smart contract that defines the energy flexibility of each prosumer and related reward/penalty mechanism [107]. Moreover, Stephent *et al.* analyze collective self-consumption, address measures to encourage consumers to participate in the DR, and propose the consumption management of prosumers and consumers through BC [108]. Thomas *et al.* use a smart-contract-based DC control element to satisfy control instructions. Zhou *et al.* propose an encouragement method for EVs to enhance participation and maximize social welfare, and further necessitate the comprehensive investigation of central authorities like the DSO [84]–[92], [92]–[109]. Ali *et al.* suggested that renewables and the energy storage integration of DSO-level aggregators be directed for DR purposes [110], [111]. In Di Silvestre *et al.*'s study, load increment and reduction requests were notified by DSOs to make the system flexible. The DSO communicates with each customer to reduce use proportionally by facilitating smart contract abilities [112]. In Edmonds *et al.*'s study, homeowners are required to send forecasted consumption patterns to the responsible DSO to reach a balanced power grid goal [113]. After aggregating the forecasted data, the utility solves the convex optimization problem of power balancing. Therefore, DSO and BC secure user privacy to encourage users to participate and balance the power grid. However, timely forecasting and aggregation unleash scalability concerns. Cost-related DR was investigated in Canada. Brown argued that the existence of DR drives electricity customers to consume more energy than the existing DR option [114]. Khajeh *et al.* addressed the DR problem at three points in the electricity network [22]. TSO-DSO-Customer level flexible resources are considered each level's system operator's deployment responsibility. The power of each branch and voltage of each node used is integrated; after price customization calculations, the optimum power flow scheme is reached [115].

F. BLOCKCHAIN FOR TSO/DSO INTERACTIONS

The requirements for determining the roles, needs, and guiding principles of the TSO/DSO interaction are highlighted in one study [116]. The hierarchical relationship between the TSO and DSO would be more horizontal in the future. In the old version of the grid, the DSOs have limited duties and responsibilities compared to TSOs. BC and rising distributed technologies will most probably influence bilateral interactions, such as power flow direction, grid responsibilities, and technical requirements. Additionally, DSOs have been considered responsible for voltage regulations, consumption billing, and customer operations, particularly household customers. Contrary to the customary structure, DSOs will significantly burden other works through issues, such as frequency control, managing DG (solar, wind, etc.) participation, local markets, ancillary services, optimum power flow, and creating more democratizing grid structures henceforward [117]–[122]. However, TSOs would have interpenetrating and mutual duties and responsibilities against DSOs. TSOs may act as partners of future grid operations and transfer some liabilities, such as facilitating the power of DSOs and related DERs in possible blackouts. All these situations were already inevitable, but heretofore with the emerging BC technology, these changes will speed up and be driven toward an ambitious ideal grid. Like all other grid shareholders, the TSO/DSO relation requires BC technology and its practical solutions [22].

1) GRID CAPACITY INVESTMENT LINKAGE WITH BLOCKCHAIN

Electricity grid vulnerabilities against extreme weather conditions and federal funding opportunities that support grid resilience are highlighted in [123]. Additionally, grid investments and BC collaboration are discussed under two topics. The first, as mentioned in the DR and EV subtitles, is mitigating the peak demand by encouraging users to participate in grid management by facilitating BC and smart contracts. Leveraging BC technology can reduce peak demand, hence reducing the DSOs' grid capacity increment investments. For detailed clarification, the abovementioned subsections can be referred to accordingly. The other important subject of BC and grid investment is related to tracing grid investment and making it more transparent. In most of the world, the grid infrastructure is public property, representing an investment of billions of dollars. In underdeveloped low-income countries, the corruption level is significantly higher than in the rest of the world. In Ahmad *et al.*'s study, a BC-based custody evidence recording framework is highlighted to ensure data reliability and prevent possible misconduct interventions. Shwetha *et al.* use a BC-based verification system to ensure commodity/food security through accountability in the public distribution system [124], [125]. Alketbi *et al.* take advantage of BC technology to manage the data integrity of government services more securely [126]. Hence, as a similar application, to prevent undesirable corruption, a smart contract structure would be extremely beneficial for pursuing and recording the investment details in an immutable and transparent way. All the grid investment auction details, payment details, competence of electricity contractor details, and useful economic life of the grid components can be traceable, owing to the unalterable BC technology. Despite the impossibility of preventing corruption entirely, tracking the relevant money and clearing the debate about public wastage by smart contracts would be a remarkable solution.

2) BLOCKCHAIN FOR ENVIRONMENTALISM

Renewables are highlighted in tandem with carbon trading by Hua and Sun [127] and Keypour and Bazyari [128]. BC usage in SGs affects the environment in two ways: First, by encouraging participants to produce and consume low carbon energy, the CO2 emission level decreases [129], [130]. Second, a possible mining procedure for BC may increase energy wastage. Carbon trading projects are environmentally friendly [6]. First, the carbon emission level may be evaluated. Moreover, all the produced environmentally hazardous CO_2-equivalent green energy may be bought from the specific market using a smart contract. However, the carbon trading markets are considerably similar and appropriate to the distributed nature of BC; the application is in the initial stages owing to the computational constraints and response speed issues [131]. However, although the BC offers significant benefits, the amount of energy consumed in the mining process will amount to 45.8 TWh, according to Vranken [132] and Stoll *et al.* [133]. While the energy production methods mainly originate from fossil fuel sources, this is a vast figure for environmental concerns. In summary, despite computational constraints and the response speed issues of BC in carbon trading, DSOs would play a crucial role owing to their existing infrastructure.

V. DISCUSSION

Erturk *et al.* investigated the positive and negative impacts of the application of BC in smart energy [134].

TABLE 2. The short-term applicability of blockchain from the DSO perspective.

DSO & Blockchain Aspects	Shortcomings in Terms of		Applicability in the Short Term	Main Obstacle of Blockchain
	Computational Power	Incentive Mechanism		
SCADA	High	N/A	Medium	- Low computational power at end points (sensors, relay devices, circuit breakers) - Highly centralized structure
AMI	High	N/A	Medium	- Low computational power - Low communication power - Lack of widespread communication network substructure - Scalability
EVs	Low	High	High	- Lack of incentive mechanism - Privacy concerns - Scalability - Negative effects on the grid (e.g., grid congestion)
DERs	Medium	Medium	High	- Security concerns
Microgrids	Medium	Medium	Medium	- Lack of legal regulation
Marketing	N/A	Low	High	- Lack of legal regulation - Scalability - Speed - Security - Privacy
Demand Response	N/A	High	High	- Lack of legal regulation
DSO/TSO Interaction	N/A	No	Medium	- Lack of legal regulation

Beneficial impacts are classified as improved system security, increased data privacy, removal of intermediaries, and immutability, whereas adverse effects are sorted as scalability, cost of establishment/maintenance, and the need for further studies [135]. In conclusion, it is recommended that economic feasibility and other costs should be examined. However, the BC in the energy sector, especially the EV and prosumer sides, did not prove to be an entirely secure and privacy-preserving solution. Significant challenges to the application are the cost of integrating the new BC-based technology with existing devices and the convenience level of the grid framework [37]. To this end, the hardware cost of the BC-enabled counterpart of the grid management, monitoring, and measuring devices is still extremely expensive, and further research is required to achieve the complete adoption of BC in the power grid [6]. The demand for communication and data processing will increase steeply owing to the steepest increase in the quantity of transaction data, simultaneous energy trading of participants every second, and an increase in the number of network users. Additionally, instant changes in the network will require researchers to investigate less-data-costly options, such as side chains [9]–[24]. BC technologies in SGs are categorized as DR, EVs, IoT, decentralized energy management, environmentalism, energy trading, finance, and cybersecurity [8]. Kulkarni *et al.* viewed BC technology as a solution to the problem of a lack of electrification in rural areas owing to its low cost and accurate transaction opportunity [136]. The issues and challenges that SG faces are as follows: mistrust in the industry, vulnerability to security threats, functionality and low penetration of EVs, frequency and voltage problems owing to grid imbalance, and lack of standardization [137]. The concept, structure, architecture, and trading mechanism of "Energy Internet" have been discussed. However, the transaction costs are claimed to remain an obstacle, but utilities can promote such transformation [28].

All DSO-related energy parties are listed, and the short-term applicability levels in a general BC are interpreted in [Table 2]. Apart from local projects and those containing only one type of grid user, a condition referred to as general BC expresses the environment that contains all electricity users in one place or nested BC environment as well. SCADA and AMI are the main grid management and monitoring technologies for DSOs. The central operation part of the SCADA system has high computational power, but the distributed parts of the SCADA and AMI lack computational power. Additionally, neither DSO unit requires intensive mechanisms to participate in the BC system. While communication is not an issue for SCADA, the communicational power of smart meters should be enhanced, after which new expensive hardware investments are required [138]. This investment should be undertaken by the DSO, for which the motivation must be specified. Meanwhile, SCADA has a centralization issue; however, AMI systems are highly decentralized. Therefore, as all aspects of both grid components are considered, SCADA and AMI nodes are noted as having medium-level

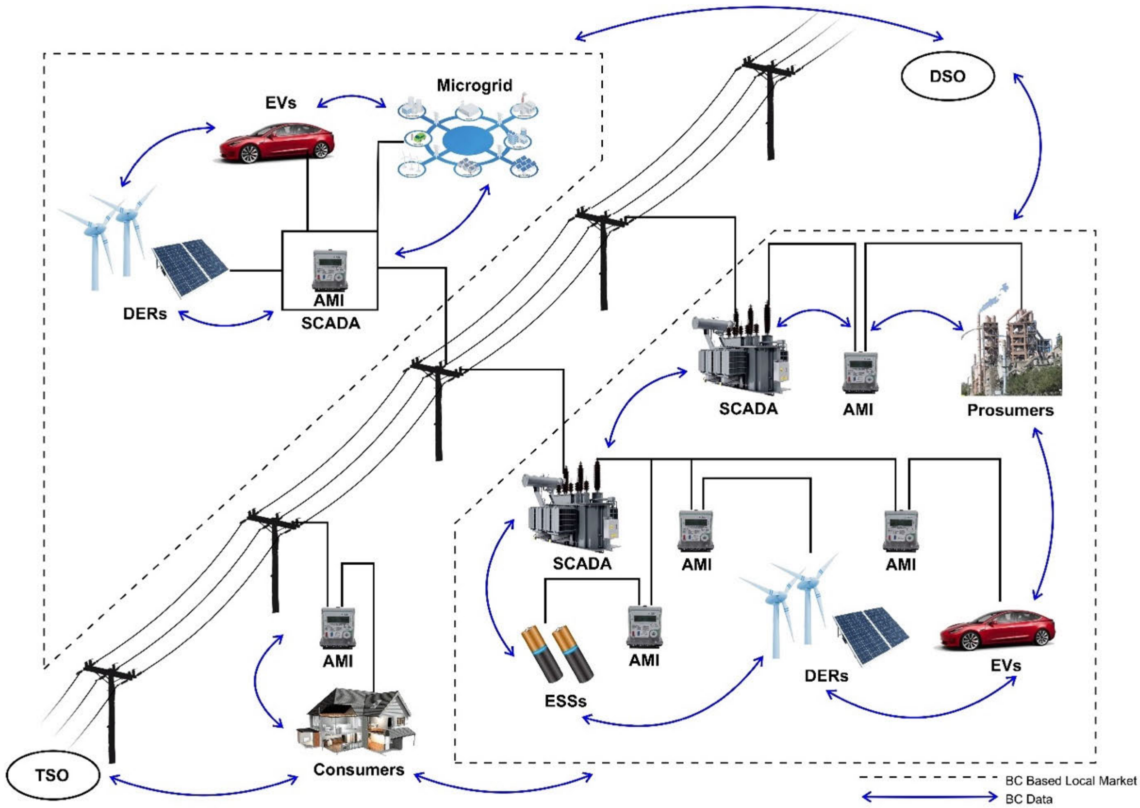

FIGURE 3. DSO Grid Control Unit (Scada, AMI) Connection Diagram.

applicability in the short term. EVs most likely have substantial computational power arising from smart cars and CFUs. The EV environment is most likely the pioneer unit, as well as a forcing point for the encouragement of the implementation of new BC soon. Owing to the worldwide EV circulation, the desire for BC will increase. However, with the dilemma that while an incentive mechanism can be implemented to compel all the EV users to participate in the system, this may have harmful negative effects on the grid. Therefore, these unintended conditions may be self-destructive. Moreover, it is difficult to enhance EV usage. Nevertheless, the need for a privacy-preserving environment for EVs and the demonstration of existing EV projects indicate its applicability level as high in the short term. Conversely, the up-to-date requirements for the computational power of microgrids ''and DERs'' are generalized and categorized as medium level. Given the established place and exact situation for all DERs and microgrids, it is relatively harder to determine the exact situation for all DERs and microgrids. Although self-sufficient microgrids are highly appropriate for BC frameworks owing to their local and minimal conformation, the self-contained nature, and limited need for an on-grid system, the participation of microgrids in a widely established BC environment is challenging. Therefore, its applicability is considered medium level. Marketing and demand response do not require additional computational power owing to the inclusiveness of other BC users. Demand response may require a highly stimulated structure in the BC. The inadequacy of legal regulation is one of the notable obstacles to the BC transformation.

a) From the SCADA and AMI perspectives, the main obstacle that emerging BC technologies face is the deficiency of the computational power of existing devices. The SCADA network is a centralized system. Moreover, decentralized BC is highly contradictory. AMI has insufficient communication hardware to manage BC necessities. Further, the number of participants can cause scalability issues. Although SCADA is fast in the current situation, it is weaker in terms of cyber security, compared with BC. In AMI, however, more attention should be paid to privacy issues as it caters more to individual use. In summary, if BC performs better in terms of speed, only then can it be more successful in terms of AMI and SCADA, secure and private in existing systems.
b) From a BC-related EV perspective, the existing structure is insufficient to encourage most EVOs to participate in the BC environment owing to the lack of an intensive/reward mechanism.
c) Both DERs and microgrids have a lack of regulatory unity and raise potential security concerns.
d) From the market perspective, transaction time/speed is a significant and non-negligible matter. Regardless of the amount of energy, energy trading occurs every

second, and future BC structures must manage these scalability and speed issues.

e) Apart from cyber-attacks, it is a matter of debate regarding who should be responsible for the physical manipulation or intervention of measurement or control devices. In the event of such physical attacks owing to the decentralized nature of the BC, it is almost impossible to detect the amount and party of the commercial relation. The difficulty of determining possible fraud also poses new challenges to DSOs. One of the partial solutions can be the use of AI technology to detect possible physical fraudulent attacks from the previous consumption or production patterns of users. However, this seems inadequate for the current infrastructure.

f) Unlike cryptocurrencies, transactions in the electricity sector are continuous. In other words, the validation of transactions takes time. Moreover, with cryptocurrencies, users must wait until confirmation. However, in the energy sector, energy flow is perpetual. Moreover, even if a transaction is not confirmed, real trading will be almost complete and energy will be delivered to the other party.
Therefore, it is unclear what will happen if communication or validation problems occur in the system.

Along with the increase in DERs (connected to the DSO level), bilateral power flow has been increasing gradually in recent years, a situation that forces DSOs to act more like TSOs. In this context, future research should investigate the DSO-level ancillary service–BC interaction and its areas of application, particularly regarding the sustainability of the grid in a secure and private manner.

Grid management, grid control, grid monitoring, and customer management are vital responsibilities of the DSO; therefore, the positions of SCADA and AMI are extremely specific (Fig. 3). SCADA and AMI, particularly AMI, are directly or indirectly and electrically connected to all customers/stakeholders. Any load change in the grid, even infinitesimal changes, must be evaluated and controlled by the DSO and responded to as soon as possible. The DSO's technical centrality makes its existence crucial in BC networks, especially in the consumption/production billing of grid usage, registration of new customers in the system, and other grid management procedures. However, the security, privacy, immutability, and accountability attributes of the energy system procured by BC technology, its physical security, security of supply, the technical and commercial quality of the system, improved the efficiency of grid operations, reductions in technical losses, and sustainability of the entire energy system must remain under the control of the DSO. These inseparable features of the energy network make the DSO crucial and more important.

VI. FUTURE RESEARCH DIRECTIONS

Considering the implications presented in this article, several new questions remain to be resolved. A few of the most prominent are summarized in this section. Despite the transition to a decentralized structure because of BC, the self-managed smart BC promises a stronger infrastructure. This BC structure, which is as flexible and as strict as possible within the framework of its rules, can be turned into a great advantage and can be used in every area in the network. For example, a mechanism, such as ancillary service, which has an important role in energy supply security and electricity technical quality, can be used more efficiently and safely because of BC. Ancillary service and similarly VPP should include all energy users in the system and be examined in detail, especially for EVs.

Although BC-based systems (especially in the financial sector) have proven themselves in terms of security, it is not certain what other problems may arise in an area, such as the energy sector where there is a multifaceted and physical instant trade. Considering that the system will run on millions of nodes, this will result in serious security problems, and hence, should be examined comprehensively. Additionally, the increase in the number of nodes will result in scalability and validation speed problems.

The limited adoption of BC technology and the fact that it has not been able to create satisfactory trust in terms of social perception is one of the most important problems in BC. Therefore, it would be beneficial to test different scenarios by investigating all kinds of incentive mechanisms so that everyone can adapt to this system. Additionally, with the regulation arrangements, citizens can act more freely.

Today, there are BC-based projects that work locally, which this study has attempted to summarize. There are multiple players in the energy sector. However, current projects have not been able to propose a system that includes all energy users. Regulatory arrangements are needed to ensure coordination among all energy users. BC applications in energy should be evaluated as a libertarian field with legislation and its way should be paved. Especially in some countries, the overwhelming power of governments in the energy sector necessitates regulation.

VII. CONCLUSION

Many studies have discussed the benefits of BC applications and the possible negative aspects of the energy sector. In summary, it seems that DERs, microgrids, and particularly EVs and CFUs will be emergent actors of the electricity grid, and from the DSOs' perspective, there will be challenges on the grid, such as the short-term peak load management problem and grid capacity concerns owing to the quick charging technology and instant energy production changes. However, the security, privacy, scalability, and transaction speed of BC technologies in the energy sector are other concerns. Despite BC's magnificent, decentralized solutions, the role of DSOs is undeniable owing to the existing grid structure. Numerous BC-based studies have highlighted EVs, energy markets, DERs, microgrids, and DR from the perspective of appropriateness. Nevertheless, the applicability of BC in the energy system and the considerable need for the current operation of DSOs have not been extensively addressed. Although BC has an excellent problem-solving capacity, the transition from conventional to modern BC-based power grids is significantly expensive and difficult to realize in a short time. In the short term, building a completely distributed power system will be nearly impossible. Moreover, the transition must be examined comprehensively. We searched and analyzed the BC-based energy sector literature and defined DSO-based requirements for potential BC applications in the energy sector.

ABBREVIATIONS

DSO: Distribution System Operator
TSO: Transmission System Operator
BC: Blockchain
SCADA: Supervisory Control and Data Acquisition
AMI: Advanced Measurement Infrastructure
EVs: Electric Vehicles
EVOs: Electric Vehicle Owners
CFUs: Charging Facility Units
CFUOs: Charging Facility Unit Owners
DERs: Distributed Energy Resources
DG: Distributed Generation
RESs: Renewable Energy Sources
PV: Photovoltaic
SG: Smartgrid
P2P: Peer-to-Peer
V2V: Vehicle-to-Vehicle
V2G: Vehicle-to-Grid
M2M: Machine-to-Machine
B2B: Business-to-Business
DR: Demand Response
DSM: Demand Side Management
ESSs: Energy Storage Systems
CAs: Consensus Algorithms
PoW: Proof-of-Work
PoS: Proof-of-Stake
PoWR: Proof-of-Work based on Reputation
PoB: Proof-of-Benefit
ONPoB: Online Benefit Generating PoB
BFT: Byzantine Fault Tolerance
PBFT: Practical Byzantine Fault Tolerance
DBFT: Delegated Byzantine Fault Tolerance
DAG: Directed Acyclic Graph
PoAu: Proof-of-Authority
PoR: Proof-of-Reputation
PoRCH: Proof-of-Random Count in Hashes
LNSM: Neighborhood Search with Memory
ET: Energy Trading
AdBEV: Adaptive Blockchain-based Electric Vehicle Participation
ICT: Information and Communication Technology
OpenADR: Open Automated Demand Response
IoT: Internet-of-Things

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