IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received June 20, 2020, accepted July 1, 2020, date of publication July 8, 2020, date of current version July 21, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.3007935

Demystifying Distributed Ledger Technologies: Limits, Challenges, and Potentials in the Energy Sector

ALEN HRGA, (Member, IEEE), TOMISLAV CAPUDER, (Member, IEEE), AND IVANA PODNAR ŽARKO, (Member, IEEE)
Faculty of Electrical Engineering and Computing, University of Zagreb, 10000 Zagreb, Croatia

Corresponding author: Alen Hrga (alen.hrga@fer.hr)

This work was supported in part by the European Structural and Investment Funds under Project *bigEVdata* (IT solutions for analytics of large datasets in electro mobility, project identifier: KK.01.2.1.01.0077) and in part by the Croatian Science Foundation under Project IP-2019-04-1986.

ABSTRACT

The success of the sustainable transformation of the energy sector, both in terms of planning and operation, relies on new entities, business models, and technologies. The shift from a relatively small number of centralized bulk producers and single direction energy flow to a decentralized multi-actor renewable system with a two-way flow of energy and multi-way flow of information needs to be accompanied by new technological solutions. Blockchain and other Distributed Ledger Technologies (DLT) represent a new technology for the energy sector, creating both opportunities and challenges for different aspects of energy systems, such as energy production, peer-to-peer (P2P) energy markets, green certificate registries, etc. Due to its decentralized nature and no need for intermediaries, DLT can facilitate energy democratization processes and decentralized energy production. In this paper, we present a systematic review of DLT principles, its theoretical background, and the most notable implementations, as well as an in-depth analysis of representative research projects and companies researching DLT use cases in the energy sector, taking into consideration technical aspects of DLT. We provide an insight into the benefits and limitations of DLT and identify technical challenges that need to be solved to enable widespread usage of DLT in energy systems. Additionally, we provide suggestions and guidelines for implementing DLT in different categories of use cases in the energy sector.

INDEX TERMS Distributed ledger technology (DLT), energy systems, cryptocurrencies, tokenization, energy transition.

I. INTRODUCTION AND LITERATURE REVIEW

Due to an increasing number of new entities and processes becoming part of transmission and distribution power networks, such as electric vehicles and renewable energy sources (wind and photovoltaics), new ideas and technologies are considered for their better integration into existing business and operation models of energy systems. One of the technologies gaining momentum in the field of energy and power systems is the Distributed Ledger Technology (DLT), in particular, blockchain and distributed application platforms such as Ethereum [1] or Hyperledger [2]. An inherent characteristic of DLT is its decentralized design and implementation based on peer-to-peer (P2P) networks. P2P network is a self-organizing decentralized network of equal and independent participants, i.e., peers, with a dynamic network topology, where each peer enters and exits the network at its own will. This decentralized design makes DLT a suitable candidate for integrating distributed energy resources (DER) into existing energy systems in terms of payment, proof of electricity generation and its origin as well as an enabler of P2P energy markets [3]–[5]. DLT offers the maintenance of an immutable, transparent, and fully replicated ledger of transactions without a centralized intermediary to validate

The associate editor coordinating the review of this manuscript and approving it for publication was Eklas Hossain.

This work is licensed under a Creative Commons Attribution 4.0 License. For more information, see https://creativecommons.org/licenses/by/4.0/

inserted transactions and to orchestrate the network. In the energy world, this implies that each household could actively participate in buying and selling of its energy, independently of the mediators such as suppliers or power exchanges; a goal defined by the [6] as a key in the low carbon energy transition. However, the available DLT implementations exhibit limitations in terms of scalability due to low transaction throughput. Nonetheless, they are considered as one of the emerging technologies for the next generation of applications in many fields [7], e.g., finances, healthcare, gambling, real estate, governance, energy systems [8], etc. Regarding the energy sector, DLT and cryptocurrencies offer some interesting features, but due to their technical limitations and existing regulations in the sector, widespread usage of DLT is currently limited. The purpose of this paper is to analyze the technical aspects of DLT and to provide an insight into the benefits and limitations of DLT usage in various categories of energy applications. Additionally, we provide guidelines for selecting an appropriate type of DLT platform to maximize the benefits for each energy application category.

Existing work in the field of energy system applications relying on DLT includes surveys and reviews [9]–[12], power exchange markets [13]–[15], DERs (including photovoltaics, energy storage, and demand response) and payment systems [16], [17], as well as electric vehicle (EV) charging and energy systems management [18]–[21]. One of the first reports on DLT applications in power systems was published by The German Energy Agency and European School of Management and Technology (ESMT). ESMT has conducted a survey among German energy executives and created a report on current and future actions regarding the blockchain applications in power systems, as well as their opinion about the future role of blockchain in the energy sector [22]. The report identifies e-mobility as one of the most promising areas for the application of DLT and concludes that blockchain networks can be used to facilitate the mechanisms of access control and data privacy. The European Commission's Joint Research Centre published a detailed report that identifies the potential of DLT for a range of sectors with an emphasis on EU policies and consumer and data protection [23]. Most notably, the report emphasizes the need to review existing policies and laws to facilitate the integration and usage of DLT in various sectors.

There are several other reviews of DLT use cases in the energy sector, including an overview blockchain activity in the European energy sector written by the SolarPlaza team [24]. The team has created a guide and interactive map of all European DLT projects and platforms as well as energy initiatives driven by DLT. Andoni *et al.* published an overview of blockchain technology in the energy sector [25] which is based on the SolarPlaza catalog. Their study reviews more than 140 research projects mostly based on the blockchain technology, and identifies the potential and relevance of blockchain technology for energy applications, but does not take into consideration the technical aspects and limitations of DLT platforms. In [26], the authors discuss transactive energy concepts and propose several layered architectures for designing transactive energy systems (TES). They provide a DLT overview and comparison in the context of TES, as blockchains are the fundamental part in their proposal of a distributed TES. However, the paper does not take into consideration DLT suitability for different types of energy applications. Di Silvestre *et al.* published the paper about current trends and future applications of blockchains in power systems [27]. The authors clarify some of the technical aspects regarding blockchain technology but focus on future trends and applications in the energy sector. In [28], the authors identify and summarize the challenges and provide a comprehensive review and evaluation of trading schemes in blockchain-based energy trading. They investigate possible issues related to blockchain which are relevant to energy trading (e.g. transition towards decentralization, data privacy, etc.). In [29], the authors present ideas to tackle the challenges of using blockchain-based cryptocurrencies in modern power grids, such as utilizing cryptocurrency mining as a demand response mechanism. They focus on technical and economical aspects of power grids, and the integration and management of cryptocurrencies. However, the paper is focused only on *blockchain-based* DLT, and cryptocurrencies as a blockchain application.

The paper provides a comprehensive technical review of DLT and corresponding applications in the energy sector. Unlike previously published work, it explains the key technical aspects of DLT and, in addition to advantages, identifies also obstacles for DLT usage in specific energy applications. Since low transaction throughput is the major obstacle for practical adoption of DLT solutions in the energy sector, we further elaborate specific solutions dealing with scalability issues (sharding, payment and state channels, and sidechains [30], [31]). We also analyze direct acyclic graphs and corresponding implementations IOTA [32] and Nano [33], which offer improved scalability and performance compared to blockchain-based DLT solutions, and are thus more suitable for certain use cases in energy and power systems. We highlight the following novel contributions:

1) Comprehensive overview of DLT principles, including an analysis of the key concepts of DLTs, components, and architecture, with an emphasis on technical features and limitations.
2) Review of representative energy projects using DLT in their products and platforms, including a discussion assessing the feasibility of solutions and benefits gained from using DLT in terms of technical aspects of the technology.
3) Suggestions and guidelines for identifying adequate DLT solutions to integrate them into different categories of use cases in the energy sector with a final goal of maximizing the benefits and reducing implementation costs.

The rest of this paper is organized as follows: Section II presents the concepts of DLT and includes a comprehensive technical review of various DLT solutions with an overview of existing platforms that use advanced mechanisms, e.g., smart contracts and code execution. Section III reviews the role of DLT in energy and power systems and existing concepts and applications. Section IV discusses various types of DLT solutions appropriate for different use cases in energy systems. Section V concludes the paper and comments on the possible future evolution of DLT usage in energy and power systems.

II. DISTRIBUTED LEDGER TECHNOLOGIES

Distributed ledgers are immutable and replicated synchronized databases (or data structures) shared and maintained by the mutually untrusted network of nodes, i.e., peers. Generally, DLT platforms consist of three components:

1) *P2P network* for peer interaction and network maintenance with a goal of sharing distributed ledger transactions among all peers in the network;
2) *Distributed data ledger* for storing all transaction and application data; and
3) *Consensus mechanism* for orchestrating transaction insertion into the ledger in a distributed way.

In the context of data structures, there are several specializations of DLT: the most notable are blockchain and directed acyclic graph (DAG), which are explained in the following subsections. DLT specializations are different in terms of ledger data structures, consensus mechanisms, transaction inclusion confidence,[1] size and scalability. A detailed review of blockchain compared to DAG can be found in [34], [35].

A. BLOCKCHAINS

1) OVERVIEW

A blockchain is a simple, append-only data structure, similar to a linked list, which in addition to data in the form of transactions, also holds a digital signature of the previous block, as depicted in Figure 1. Every block has a metadata section with several attributes, such as the cryptographic hash of all transactions in the block, cryptographic hash of the previous block to ensure data immutability, and a *nonce* field which is used for the consensus mechanism [36]. It was conceptualized in 2008, implemented in 2009 in the Bitcoin network [37], and has experienced a wider adoption after the creation of the first blockchain application platform-Ethereum.

Bitcoin was the only cryptocurrency network for six years, until the release of Ethereum in 2014. Creators of the Ethereum platform proposed a Turing-complete[2] scripting language to be added to Bitcoin for implementing more complex financial mechanisms on top of the existing Bitcoin network, but they failed to reach an agreement with the Bitcoin community and a novel DLT platform with a more general scripting language was proposed. In the first whitepaper [38], Ethereum is described as a decentralized mining network and software development platform integrated into a decentralized solution that facilitates the creation of new cryptocurrencies and programs sharing a single immutable blockchain (a ledger of cryptographic transactions). Ethereum is currently the most popular blockchain platform because it was the first to enable the creation of custom cryptocurrencies in the form of digital tokens and new types of digital assets. Today, several blockchain application platforms enable the creation of digital assets, such as EOS [39], NEO [40], Aeternity [41], etc. Such programmable blockchains have resulted in the emergence of new DLT-based applications that go beyond cryptocurrencies to be applied in different sectors which require a decentralized immutable ledger and transaction execution platform within an environment of untrusted stakeholders. One of the best-known use cases of blockchain so far is asset ownership management, while programmable blockchains are used most frequently for the implementation of decentralized crowdfunding campaign platforms, the so-called crowdsale platforms, for a public sale of digital assets on the blockchain.

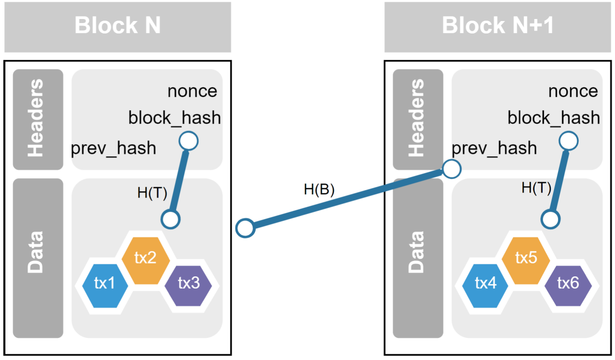

FIGURE 1. Blockchain ledger data structure. Cryptographic hashes are the basis for immutability: the hash of all transactions inside a block is stored in block_hash, and the hash of the previous block is stored in prev_hash parameter of the next block.

2) CONSENSUS MECHANISMS

Consensus mechanisms are used in blockchains for orchestrating transaction insertion in a distributed way: for every new block to be added into the ledger, a peer proposing a new block must be elected by a consensus algorithm. When elected, the peer proposes a new block to be added into the ledger, while all other peers validate block transactions, and will accept the block only when all transactions are valid. In other words, a peer fights for the right to write transactions into the ledger by means of the offered consensus mechanism. There are several consensus mechanisms used in DLT networks: the most popular are Proof-of-Work, Proof-of-Stake (and delegated Proof-of-Stake variation), and Proof-of-Authority.

Proof-of-Work is a simple distributed consensus mechanism that relies on a cryptographic hash. Cryptographic hash functions are one-way functions where it is almost

---

[1] A transaction is considered final and immutable only when N new transactions or blocks are added to the shared data structure, e.g., after six new blocks in Bitcoin, twelve new blocks in Ethereum, or after 7 transactions in IOTA ledger data structure.

[2] A language is considered to be Turing-complete if it implements all Turing machine operations and can solve any computational problem in a deterministic way.

impossible to calculate input data from the result of a function call and they are usually used to ensure data integrity and immutability. In the first step of Proof-of-Work (1), a network validator (miner) collects published transactions (denoted as $t_{B,i}$) to form a new block of transactions B for which it calculates a cryptographic hash named *block hash* (denoted as H_B).

$$H_B = H(t_{B,1}, t_{B,2}, \ldots, t_{B,N}) \tag{1}$$

To ensure that a fixed interval of time passes between creating two blocks, a mining difficulty variable is introduced and denoted as w. The value of w consists of binary ones and zeros which change dynamically over time following an increase or decrease of processing power in the network-if the computational power of the network increases, then the mining difficulty increases, and vice versa. After H_B is calculated, a miner must find the value of parameter *nonce* (denoted as μ) such that hash of the combination of H_B and μ results with a new hash starting with the predetermined number of binary zeros (2). This is a computationally difficult process because millions of iterations are required to find an exact value of μ which conforms to the equation.

$$H(H_B, \mu) \wedge w = 0 \tag{2}$$

After finding the *proof of work* (the exact value of μ), the μ is written to the block header and then the block is transmitted to the network. It is trivial for other nodes to verify block validity using equation (2) because they now know the value of H_B and μ- validation has a priori complexity of $O(1)$. Thus, for a malicious user who wants to change or insert a transaction in a block B_i, he/she must find the proof of work for the selected block and all blocks up to the last block B_N and rewrite blockchain ledger on all nodes in the network, which is practically impossible to perform.

Although the Proof-of-Work mechanism of consensus is still dominant, it consumes a lot of electricity and will be replaced in future and existing DLT platforms by alternative consensus mechanisms that are energy efficient. The most practical alternative is Proof-of-Stake where a network validator stakes cryptocurrency units and thus ensures that a new block will be formed following the network rules, otherwise it will lose its stake. More and more networks, such as Ethereum and EOS, have implemented (or are in the process of implementing) a Proof-of-Stake consensus mechanism.

Another consensus mechanism that is gaining popularity is *Tendermint*. It is similar to delegated proof-of-stake (dPoS) consensus: a node can stake funds to be nominated as a validator for creating the next block, but it can also delegate its stake to another node. The main difference between Tendermint and dPoS is that in dPoS, a validator is chosen randomly in the set of nominated nodes, and in Tendermint, nominated nodes use classical Byzantine Fault Tolerant (BFT) consensus to create new blocks. A detailed comparison of Tendermint and EOS dPoS can be found in [42].

One of the consensus mechanisms used in combination with private networks is *Proof-of-Authority* (PoA). It is a reputation-based consensus that relies on a limited and well-known set of validators. Validators are uncompromised nodes in charge of validating transactions and adding new blocks to a transaction ledger. PoA systems are highly scalable and have a high transaction throughput, but in such systems, it is more difficult to guarantee data and transaction immutability.

3) KEY FEATURES AND LIMITATIONS

One of the key features of DLT is traceability-by using DLT, we can guarantee time traceability of transactions because they are grouped in immutable blocks. When considering the usage of DLTs in energy domains such as energy markets, it is important to emphasize that DLTs do not guarantee traceability inside a block, but just between blocks. For example, a DLT network guarantees that transaction $t_{B,i}$ in block B happened before transaction $t_{B-1,j}$ in block $B - 1$, but it cannot guarantee that the $t_{B,i}$ happened before $t_{B,i-1}$. This is a feature of distributed environments where every peer generates events (transactions), but also a consequence of the fact that miners have the freedom to choose transaction processing order when creating a new block.

Due to their global scale, public blockchain networks come with two important limitations: *transaction prioritization* and *block confirmation time*. If there is network congestion because of a high number of pending transactions, miners can choose which transactions they will validate, and the general rule is that they pick transactions that offer high transaction fees. In a scenario of network congestion, if a user does not offer a high transaction fee to miners, his/her transaction will require a lot of time to be included in a block, or it will get rejected after some time. When a transaction is added in a block, it can be considered accepted and immutable only when a block confirmation time passes. Confirmation time is a consequence of a consensus protocol and network latency. If two blocks are created at the same time, they are appended to the same parent block and then miners do not know from which block to continue the chain. This phenomenon is called a *fork* and is depicted in Figure 2. In the case of a fork, every node decides for itself from where will it continue creating blocks. After some time, one side of a fork will be longer (have more blocks than the other side), and the rest of the miners will reject all blocks which are not a part of the longest chain. The probability of a fork from a certain block decreases with every newly created block, and if a person wants to be sure that his/her transaction will not be eventually rejected, he/she must wait for N new blocks to be created after the block containing his/her transaction ($N_{Bitcoin} = 6$, $N_{Ethereum} = 12$). Considering an average block creation time, we can conclude that a transaction is effectively confirmed and considered immutable only after approximately 90 minutes in the case of the Bitcoin and 3 minutes in the case of Ethereum.

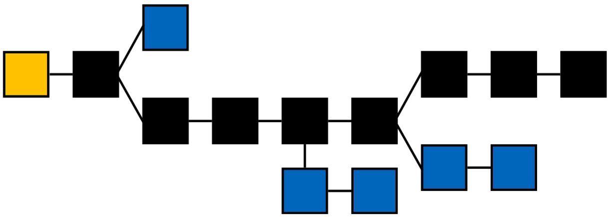

FIGURE 2. **Blockchain ledger fork: blue blocks will get rejected after some time because they are not part of the longest chain.**

4) TECHNOLOGY CHALLENGES AND FUTURE DEVELOPMENT

Ideally, blockchains should be decentralized, secure, and scalable, but existing blockchain platforms offer today only decentralization and security at the expense of scalability. Blockchains cannot support an increasing number of transactions because of the requirement that every node stores the entire transaction ledger locally. Because of the increasing popularity and number of users of the well-known blockchain platforms, a lot of effort is invested to find solutions for blockchain scalability. Since it is difficult to implement all three main properties (security, decentralization, and scalability) on the base layer (1st layer) of blockchain platforms, a lot of scaling solutions focus on building protocols and infrastructure on top of the base layer (2nd layer).

Sharding [43] is one of the 1st-layer scaling solutions. The main idea behind sharding is to divide state and transaction history of a blockchain ledger into $K = O(\frac{n}{c})$ partitions (shards) and to delegate maintenance of the ledger to a subset of nodes. For example, shards could be formed by putting transactions whose identifier (transaction hash) starts at 0×00 into the first shard, identifiers which start with 0×01 into the second shard, etc. Sharding is at the moment one of the most promising blockchain scaling solutions and it is scheduled for implementation in the Ethereum 2.0, but there are still challenges that need to be addressed, such as *single-shard takeover attacks* [44], cross-shard communication [45], etc.

Second layer solutions are also referred to as *off-chain* solutions because they are created on top of the base layer. *State channels* and *sidechains* are considered as two main representatives of this group. The idea behind them is to process all transactions off-chain and periodically synchronize the aggregated state with the main chain (base layer). The main difference between state channels and sidechains is in the data structure representing transactions: nodes in state channels form a fully connected graph where every node is responsible for maintaining transactions data by themselves, whereas in sidechains, another blockchain (sidechain) with its internal consensus mechanism and data structures is formed and shared between nodes. State channels perform well in an environment with a small and predefined set of members, whereas sidechains in an environment with a larger group of members. Another difference between them is in the definition of *finality*-state channels have instant finality (a transaction is accepted when all parties involved sign it), and finality in sidechains depends on the mining power of a sidechain. The major downside of second layer solutions is that they require that a node must always be online to maintain a channel/sidechain to be able to close it properly and write an aggregated state to the main chain. Representatives of second layer solutions are Ethereum's Raiden Network [46] and Plasma [31], Bitcoin's Lightning Network [30], and NEO's Trinity [47] protocol.

B. DIRECTED ACYCLIC GRAPHS

1) OVERVIEW

DAGs are special data structures that resemble flowcharts where all nodes are headed in the same direction and no node in the graph can be referenced back since the graph is directed and without cycles. DAG-based ledger data structures, such as IOTA and Nano, use different DAG structure implementations. IOTA uses the *Tangle* [48] structure to link transactions.[3] Nodes in Tangle represent transactions, and to have transactions verified by IOTA, one must approve (validate) two previous transactions. There is no mining included, except minor *Proof-of-Work* to prevent spam. An example Tangle ledger data structure is depicted in Figure 3.

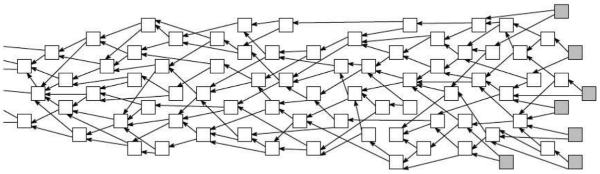

FIGURE 3. **IOTA Tangle ledger data structure [48].**

In Nano, two transactions must be generated to transfer cryptocurrency from one account to another-*send* transaction and *receive* transaction, which means that every transfer must be confirmed by the receiver's node. Nano uses the *Block-Lattice* [49] structure to link transactions. A node must be available online to receive cryptocurrency transactions. An example block-lattice ledger data structure is depicted in Figure 4.

In DAGs, every transaction must validate previous transactions, so there is no need for dedicated validators, miners, or consensus protocols mandatory in blockchains. Thus, users pay minor or no transaction fees for their transactions. DAGs are well suited for high volumes of transactions (macro and micro) and value transfer, so they can be used for exchanging data between devices and sensors. Depending on the implementation, there may be a minor Proof-of-Work triggered when submitting a transaction, but only to prevent spamming in a DAG network.

---

[3] `http://tangle.glumb.de/`

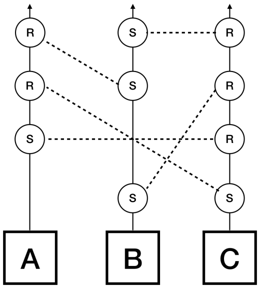

FIGURE 4. **Visualization of a block-lattice. Every transfer requires a send (S) and receive (R) point, each signed by the account owners [49].**

2) KEY FEATURES AND LIMITATIONS

In DAG, transactions are represented as vertices, and links as edges. Publishing a transaction in IOTA requires linking a new transaction to any two previous transactions[4] and validating their transaction data. The number of incoming edges, i.e., links, to a transaction is called *transaction weight*. When a transaction weight reaches a predefined threshold, it is considered valid. In Nano, graph edges are formed by send (S) and receive (R) points in the graph. Depending on a DAG data structure, time traceability can be guaranteed only for directly or transitively linked transactions, as depicted in Figure 5.

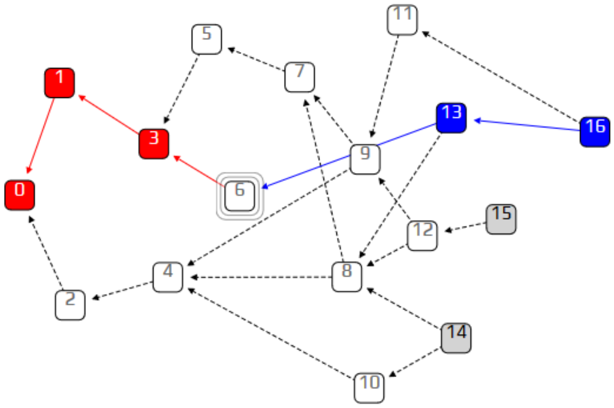

FIGURE 5. **Time traceability example with IOTA Tangle [50]. For t_6, the following applies: t_0 (genesis), t_1, and t_3 happened before, and t_{13} and t_{16} happened after t_6. For t_6 and t_8 it is not possible to determine their ordering.**

3) TECHNOLOGICAL CHALLENGES AND FUTURE DEVELOPMENT

DAGs offer low or no transaction fees and high transaction processing speeds. Transactions in DAGs can be simultaneously validated, so DAGs are more scalable and efficient. DAGs become more secure as they grow, but they can be vulnerable to attacks potentially causing a significant reduction of transaction processing volume. To reduce the risk of exploiting a DAG network until the volume of transactions becomes stable, a lot of DAG solutions use a centralized transaction coordinator or pre-selected validator nodes whose role is to orchestrate the validation process of incoming transactions. These validators represent centralization points in DAG networks. Only when there is no longer a need for central coordinators, DAG networks will become fully decentralized.

C. OVERVIEW OF DLT PLATFORMS

The Bitcoin network was the first platform that used a distributed ledger to store transactions and account data. It uses an embedded programming language called *Script* which is used to implement more advanced (but still simple) transaction mechanisms, multi-signature wallets, etc. Script is not a Turing-complete language, which means that implementing complex functionalities is not possible. The Bitcoin network is a digital electronic-cash payment system and the only task of its underlying blockchain ledger is to maintain data integrity and prevent the double-spending problem. To support more complex transactions in DLT networks, it was necessary to introduce a Turing-complete language and adapt the underlying distributed ledger to new features. Ethereum and similar platforms are decentralized application platforms that have introduced such new features in the form of *smart contracts*: applications that run exactly as programmed without any possibility of downtime, censorship, fraud or third-party interference. According to [51], there are three types of smart contract applications:

- Financial applications: custom currencies, insurance, and other financial derivatives;
- Semi-financial applications: money transactions including a non-financial side, such as bounty programs;
- Non-financial applications: examples are online voting, decentralized governance, reputation systems, etc.

Bitcoin is often labeled as a decentralized calculator, while Ethereum is compared to a decentralized computer, since Ethereum and similar blockchain-based application platforms extend the following features of Bitcoin: they provide faster block mining, smart contracts, support for uncle blocks, simpler transaction structure, etc. To improve network scalability and transaction processing speed, new data structures for building distributed ledgers were conceptualized and implemented. DAG data structures are designed to increase scalability, to mitigate computation overhead produced by mining, and to enable faster transaction processing. Except for spam prevention, mining is not required by DAG platforms which makes them suitable for value transfer and microtransactions. DAG platforms are more stable as they grow-more transactions mean greater transaction processing speed and lower confirmation time.

DLT platforms described above are used in the public setting, but many can also be used in a closed private environment where each user/node is authenticated. Private DLTs use different consensus mechanism compared to public solutions

---

[4] an algorithm ensures a random selection of transactions for verification, to prevent users from only validating their own transactions.

TABLE 1. Overview of DLT platforms.

Platform	Features	Scope	Ledger structure	Confirmation time	State of the network
Bitcoin [37]	value transfer	public	blockchain	up to 2 hours	advanced
Ethereum [38]	programmability, value transfer	public	blockchain	minutes	advanced
EOS [52]	programmability, value transfer	public	blockchain	minutes	early
Hyperledger [2]	Programmability	private	blockchain / distributed database	seconds	medium
Corda [53]	Programmability	private	blockchain	seconds	medium
IOTA [48]	microtransactions, IoT	public	Tangle (DAG)	up to 60 seconds	early
Nano [49]	microtransactions	public	Block-Lattice (DAG)	up to 10 seconds	early
ByteBall [54]	anonymity, spending conditions, messaging	public	DAG	minutes	early
Quorum [55]	programmability	private	blockchain / distributed database	seconds	early
Stellar [56]	value transfer for fiat and cryptocurrencies	public	blockchain / distributed database	seconds	early
Monero [57]	value transfer, anonymity	public	blockchain	minutes	medium
Radix [58]	value transfer	public	Tempo	seconds	early

and run DLT software nodes within a private network of a company, university, consortium, etc. With such changes, an improved transaction processing speed can be achieved, but ledger data still remains visible to all members of a private network. To enable data privacy inside a network, further enhancements are needed to produce a custom private consortium DLT. A well-known representative of a private consortium DLT is Hyperledger, a project created and maintained by Linux Foundation. The project includes several distributed ledger frameworks and tools, including smart contract engines, graphical interfaces, client libraries, and monitoring tools. The most popular Hyperledger solutions are Fabric, Sawtooth, and Burrow, and they all provide distributed ledger support for different use cases in an enterprise environment. Frameworks are modular to provide plug-and-play support for different network types and consensus mechanisms. Hyperledger products are a good fit for use cases and environments in which users must be authenticated, and a network must implement access control, data privacy, and confidentiality. Depending on the applied consensus mechanism and number of users, such solutions can offer high transaction throughput and low network latency. A brief comparison of DLT platforms can be found in Table 1.

It is a common belief that DLTs can be applied in many domains and applications. However, DLTs are adequate for quite a narrow scope of applications which include potentially many mutually untrusted stakeholders. Today, there are over 5000 active cryptocurrencies [59] and their main function is keeping a record of transactions and account balances of all participating users. Other specific systems-of-record use cases of DLT technology are the following:

- Digital identity: cryptographic keys for user identification on a blockchain platform are in the hands of individuals, so the owner of a digital asset representing user identity is the user himself, as long as he/she controls his/her private keys.
- Tokenization: tokens represent digital assets bound to existing physical items for purposes of origin provenance, supply chain management [60], intellectual property, anti-counterfeiting, and fraud detection. Another way to think about tokens is as digital bearer bonds or ownership of access rights on a software platform.
- Inter-organizational data management: sharing records between corporations in a decentralized way.
- Governance: managing network permissions, authorizing transactions and changing network parameters in a decentralized way.
- Smart contracting: providing mechanisms for locking/unlocking funds and setting up digital relationships.

There are also other less popular use cases, but all of them are allowing people to form and secure digital relationships in a decentralized way by using means and technologies that were not available before the advent of DLT.

To summarize, DLT offers different features, performance, and consensus mechanisms. On a general level, we distinguish DLTs designed for public and private environments. Both types can be used for applications in the energy sector, depending on a particular use case and its need for network access control, data privacy, and anonymity. For example, public DLT environments are not suitable for modeling a day-ahead energy market because of the lack of data privacy in public DLTs which is a prerequisite for implementing market clearing protocols. If an application is deployed on a public DLT platform such as Ethereum or NEO, application data in a ledger is visible to everyone while users are pseudo-anonymous (they are represented with their public keys). In private DLT environments, access control and user management can be implemented in a centralized way, while transaction processing is decentralized using an immutable ledger. Comparison of DLT network characteristics is shown in Table 2.

III. DISTRIBUTED LEDGER TECHNOLOGIES IN ENERGY AND POWER SYSTEMS

When a decentralized application is submitted to a public blockchain platform (e.g., Ethereum), its transactions and wallet addresses are publicly visible to block explorers[5] and sites that provide DLT decentralized application (DApp) statistics, e.g., *State of the DApps* [61]. State of the DApps currently keeps track of more than a dozen DLT platforms, including Ethereum, EOS, POA [62], Go Chain [63], Steem [64], etc. According to their survey, there are

---

[5] A block explorer is a *browser* for the blockchain, similar to web browsers for internet web pages.

TABLE 2. Comparison of DLT characteristics.

	Public blockchains	Private / Consortium blockchains	Directed acyclic graphs
Access control	**Permissionless**, everyone can access the network	**Permissioned**, only authenticated users can access the network	**Permissionless**, everyone can access the network
Security	All application and transaction validation data is public	A user must be authenticated and have the right to access a transaction	More secure as a network grows
Consensus	Proof-of-Work, Proof-of-Stake, delegated Proof-of-Stake	Proof-of-Authority, BFT	No consensus mechanism
Speed	Low transaction throughput due to consensus on a global level	Medium transaction throughput which degrades with an increasing number of network nodes	High transaction throughput, well suited for microtransactions
Open challenges	Block confirmation time (5 minutes to 6 hours), block finality (6-12 confirmations)	Loose decentralization (network is decentralized on a localized level), scalability is reduced with a large number of block validators	Centralized validators coordinate the network until it becomes stable in terms of volume of transactions

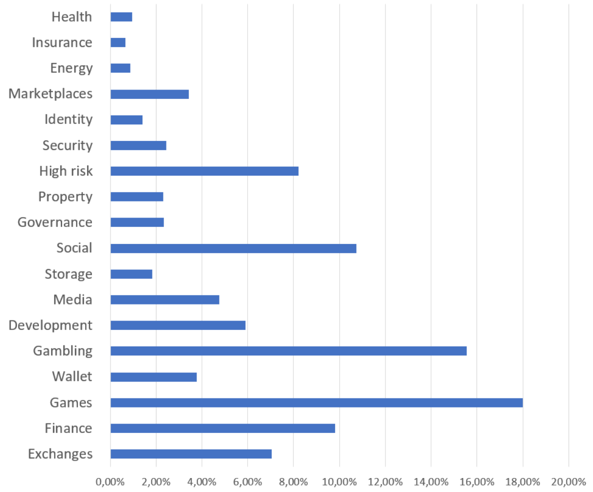

FIGURE 6. Percentage of decentralized applications by industry sector.

over 3400 decentralized applications currently deployed on DLT application platforms, but only 1% of decentralized applications are categorized as energy sector applications, as depicted in Figure 6.

The energy sector could be one of the leading industries in DLT applications [65], but a lot of problems remain unsolved, e.g., DLT governance, transaction throughput, etc. For example, the governance of decentralized applications is difficult in a public P2P setting because public DLTs are permissionless-everyone can join the network because of the absence of access control mechanisms. Some key insights provided by SolarPlaza in their guide [24] include the fact that, despite Ethereum's decentralized permissionless nature, over 50% of DLT projects use public Ethereum blockchain platform for their application layer, and the most common use case is P2P energy trading. Applicability of DLT in the energy trading context is somewhat questionable as there are still many technological challenges unresolved which hinder its full and adequate implementation. In the case of energy trading, it is desirable to have access control since false trading block orders could give incorrect signals and eventually result in power system imbalances. This would imply selecting a private network with high throughput capabilities not to delay or cancel a transaction due to technology limits.

Another aspect where DLT could create a significant impact is data management. If there is sensitive data that must be shared with other businesses or regulating institutions, e.g., energy transaction data, blockchain is a good technology to use. In terms of data storage and security, a private blockchain is similar to a distributed database with shared access. The main difference is that blockchain is append-only and immutable because it is backed by cryptographic mechanisms (records cannot be updated like in conventional databases). In terms of data access rights, private or consortium blockchain can be modeled as any relational database with administrative and read/write access rights. Regarding public blockchains and data storage, they are used in combination with decentralized storage solutions, such as *Interplanetary File System* (IPFS) [66]. Actual data is stored on IPFS nodes, and data signatures are stored in blockchain transactions. As in the blockchains, data on IPFS nodes is public, replicated (but not fully), and cannot be deleted. With these features, blockchain could reduce the risk of fraud, error, and invalid transactions, as well as improve reliability and security of financial or state-changing transactions.

Many companies and startups offer a solution to some specific areas of the energy sector. In this paper, representatives of each area will be listed and analyzed. In the following sections, the proposed solutions are categorized as follows:

- Energy tokenization and investments,
- P2P trading,
- EV charging and e-mobility and
- Cryptocurrencies and platforms

Apart from the mentioned areas of applications, many authors are researching new models and concepts related to P2P trading in a decentralized setting [67], [68], energy generation transparency and case studies involving electricity billing and cryptocurrencies [69]. Researchers are trying to design a blockchain platform and consensus mechanism that would fit the energy sector. In [70], researchers define the design of P2P exchange which would be acceptable to distribution system operators (DSO), and for this purpose, they design a new consensus mechanism based on *Proof-of-Stake* consensus model where a stake is defined using kilowatt-hours generated by an energy source. Smart meter, enhanced with a module for signing transactions, would be a network validator which leads to the assumption that a smart meter would have a responsibility to store all account and transaction data and would quickly rise to dozens or even hundreds of gigabytes. Since the authors are basing their consensus model on Proof-of-Stake which is used only in public networks, it can be concluded that such a network would be a public blockchain network. In that case, there is no way to prevent unauthorized access and publishing of transactions containing malicious data.

A. ENERGY TOKENIZATION AND INVESTMENTS

The idea behind tokenizing energy is twofold:

- fixate produced kilowatt-hours to cryptocurrency units or other digital assets, to link produced energy to financial mechanisms on a blockchain, and
- provide transparency for produced energy, for monitoring purposes on the market layer

It is common to use these tokens fixated to produced energy in crowdfunding campaigns called *initial coin offerings*. Initial coin offering (ICO) is a process, similar to crowdfunding, where companies and startups raise funds from investors, who in return get a token or some other kind of digital asset [71]. ICOs promise quick liquidity, immutable contract guarantees, and democratic access to investment capital. They are often used for raising funds because the rigorous and regulated capital-raising process can be simplified and bypassed. Over 28% of DLT energy companies have conducted an ICO or similar kind of token sale [24], e.g., Irene Energy [72], Treon [73] or Etain Power [74].

One of the approaches in energy tokenization and project funding with an ICO is to use energy token as a *utility token*. In this approach, a company uses funds collected in an ICO to invest in product development and embedding utility tokens to a product or a platform. Investors can use tokens to get special products or discounts only available through token payments or to sell their tokens in a market. With this approach, all limitations of DLTs are inherited, including low transaction throughput and transaction fees. Another problem when modeling tokens on a DLT cryptocurrency application platform is a dependency on the cryptocurrency unit embedded with a platform. For example, if a token is created on the Ethereum platform, a user must own ethers, as well as energy tokens to make a transaction. For example, if person A transfers to person B 50 units of *energy tokens*, a sender must pay a transaction fee to miners in the form of *ethers* for transaction processing. This implies, in some way, that a person must hold two currencies instead of one to make a transaction. This can be solved with the concept of *meta-transactions* [75], but they are still in an early stage of adoption.

Another approach in energy tokenization is to use an energy token only in the investment phase as a decentralized proof that an investor really owns a portion of tokens. Thus, the project is utilizing the best feature of DLT-immutable records of ownership proofs. This approach is used by energy companies like PowerLedger [76] and Pylon Network [77]. They use blockchain's immutability for safely recording people's investments in the form of energy tokens and their custom solutions for product development which are completely separated from public blockchain platforms.

There are many examples of tokenizing assets related to energy and power systems. Solarcoin [78] is a reward program launched for solar energy generation and they fixated one coin (token) to one MWh of energy production. Sun Exchange [79] has launched a crowdfunding platform for investing in solar panels located mostly in Africa. They had an ICO campaign with SUNEX utility energy token which can be used to stake in their insurance fund or to get discounts and priority when investing in solar cells. According to Etherscan,[6] there are currently around 400 accounts which hold SUNEX tokens and around 1100 SUNEX token transfers have been made so far. WePower [80] network released a crowdfunding platform for funding renewable energy sources. They also created energy token WPR and fixated it to 1 kW. New green energy projects can register to the platform and try to sell their future production to collect funds for building plants and required facilities. If their campaigns are successful, they are obligated to donate 0.9% of produced energy to WPR token holders, who can either use it or sell it through the WePower platform.

These projects exploit one of the best use cases of DLT: they hold immutable records of investment proofs in the form of tokens or some other custom digital assets. If there are no complex financial instruments implemented, both blockchains and DAGs are a good fit for energy tokenization and investment platforms.

B. P2P TRADING AND MICROGRIDS

A lot of effort and money is invested in finding the best ways for the integration of DERs powered by wind and photovoltaics (PV) in a transmission or distribution network. Research results provided by SolarPlaza have shown that P2P trading is one of the most common use cases of DLTs in energy and power systems with over 50% being implemented on the Ethereum platform.

Australian start-up Powerledger [76] is developing a series of products, along with a P2P trading platform powered by their custom blockchain. They conducted a successful ICO campaign which resulted in 17 million AUD. Their platform is a combination of the public Ethereum blockchain which holds proofs of investments in the form of ERC-20[7] tokens and custom private blockchain for their products. They separated the application layer from the investment/financial layer from the and solved transaction throughput problems for their applications. Similarly, the Pylon network has conducted a successful ICO campaign and developed custom

---

[6] `https://etherscan.io/token/0x173c856478a6fa1e64ff27be57cdac01d5e7f4ba`

[7] *Ethereum Request for Comment* (ERC) is a set of technical standards used for all smart contracts on the Ethereum blockchain, ERC-20 describes a set of rules for token implementation.

smart meters that enable communication with blockchain. Source code for their custom blockchain is open-sourced and available online.[8] Since their custom smart meters (metrons) are blockchain-aware, it means that they must have access to blocks and transactions, which requires potentially hundreds of gigabytes of data space, and it is highly unlikely that they store it on a metron device. If that is the case, it is implied that metrons communicate with trusted endpoints for sending and receiving blockchain transactions. That is the approach that introduces a certain degree of system centralization and trust. In this use case, centralization is not a problem, but it introduces a new spectrum of potential security issues.

SunContract [81] is a Slovenia-based startup that uses blockchain technology to create a decentralized energy market where the users can trade electricity in a P2P manner. They have created the SNC token and collected 2 million USD and 8700 ETH in an ICO campaign. They are registered as an entity of the Slovenian energy systems and market, and have their own Energy Identification Coding (EIC) code. SunContract is connecting power producers and consumers under a new balance group [82] with the goal of fulfilling electricity needs on the local level through a public blockchain-based platform before entering the wholesale market. Their trading algorithm is responsible for price matching, and blockchain and smart contracts for the settlement between users (with SNC tokens). The platform is not fully decentralized because trading and price-matching algorithms are run from a centralized point. Volt Markets [83] is using Ethereum blockchain to track energy origin and enable energy trading in a P2P manner. Information about energy origin is stored in a decentralized way, but the data inputs are centralized. Their other use case is to use blockchain for issuing renewable energy certificates (RECs). In this case, they are using blockchain ledger as a decentralized registry of certificates and certificate owners. LO3 Energy [84] developed *Brooklyn Microgrid* project which uses a P2P platform to trade energy in a microgrid [85]. The custom private blockchain with the Tendermint consensus mechanism is used for trading and settlement, where Tendermint provides instant finality of transactions (there is no need for waiting for N new blocks to consider a transaction immutable). The distributed systems operator has access to microgrid data and it manages energy use, load balancing, and demand response at negotiated rates.

Due to the decentralized P2P nature of DLT networks, it is often thought that DLTs are applicable for the integration of new entities in distribution network level in the areas of energy markets, payment and settlement, but there are a lot of challenges to solve before mainstream adoption of DLTs. For example, if the need arises for the energy regulation entities to intervene and stop or revert DLT transactions (e.g. for some legal complaint), it is impossible to do it in decentralized, fully replicated P2P system. Another thing to consider is data privacy-when using public blockchains and DAGs it is impossible to achieve complete transaction data privacy or any kind of permissions/authentication management. Transaction data can be viewed by downloading a DLT ledger structure or through any web block explorer. DLTs are envisioned as global computers with data coming from the decentralized single point of truth in the form of blockchain or DAG ledger structures. Blockchains are inherently *not scalable* because every node in the network must validate incoming transactions from every deployed smart contract application. For example, if application A has 10 transactions per day, and application B has 10 thousand transactions per day, transaction A would be slower than usual (and more expensive because of greater transaction fee) even though it has only 10 transactions to process. A similar situation happened to Ethereum in 2017 when the first collectible crypto game called CryptoKitties [86] was deployed to the network. 1,5 million users who played the game generated over 25% of transactions on the Ethereum, slowed transaction processing speed and driven up transaction fees dramatically. This incident has led to delays in ICOs, token distributions, P2P trading platforms, and other non-game related transactions.

Blockchain optimizes transaction processing speeds with blocks containing more than one transaction, but time traceability is not implemented inside a block. If transaction t_i is submitted after transaction t_j, there is no guarantee that t_i will be processed before t_j, as described in section II-A3. A node can decide to process t_j immediately in the current block, and t_i in the next block. For example, when modeling a P2P energy market (e.g. *intra-day* market with 15-minute trading timeslots) on a public blockchain, several scenarios may occur that violate intra-day market rules.

Assume that we define two types of transactions in a trading platform: $BUY(n, p)$ and $SELL(n, p)$, where n is energy (in MWh), and p is a selling price (in EUR). Assume that transactions are defined in a chronological order:

1) $SELL(100, 3000)$
2) $BUY_1(100, 3000)$
3) $BUY_2(100, 3000)$

Under normal circumstances, bids $SELL$ and BUY_1 would be matched, but because of the issue of time traceability inside the block, transactions may not be processed in chronological order.

For example, it may occur that a miner chooses to process transactions in the following order:

1) $SELL(100, 3000)$
2) $BUY_2(100, 3000)$
3) $BUY_1(100, 3000)$

Bids $SELL$ and BUY_2 would be matched, even though BUY_1 arrived for processing before BUY_2. It is also possible for a miner to delay transaction processing until the next block because of the network congestion or a low transaction fee. In this scenario, it may occur that only the bids BUY_1 and BUY_2 would be processed, and the $SELL$ bid would need to wait for a new block to be created. If such a situation occurs

---

[8] https://github.com/klenergy/pyloncoin

at the end of a trading timeslot, BUY_1 and BUY_2 would not be matched. Users can try to resend their bids, but there is no guarantee that a similar situation will not happen again.

There are several propositions and research projects that offer solutions to time traceability inside a block problem [87], but consensus protocols and mining algorithms on big blockchain platforms remain unchanged. In the context of P2P energy markets, this problem could be avoided with the usage of private DLT solutions.

C. EV CHARGING AND E-MOBILITY

E-mobility is one of the areas where DLT could bring benefits in the areas of payment, settlement, and roaming.

Share&Charge [88] is a German company founded in 2016 which allows people to share their private home charging stations and parking lots. The payment and settlement are based on the public Ethereum network. In the first phase of the project, there were 1224 registered charging stations in Germany and more than 1500 registered users. In 2018 the company became an affiliate of the Energy Web Foundation which runs its own energy blockchain based on Ethereum. One of the first company's products was released in 2019 and it enabled machine-to-machine payments via car electronic wallet, in combination with ISO 15118 standard. Even though application business logic was modeled in a decentralized way (smart contracts on the Ethereum platform), the solution uses a centralized service that holds private keys of all registered users. Eventually, the service was migrated from a public DLT network to a semi-private (consortium) network because of the scalability issues that come with a public DLT solution [89].

Car eWallet [90] is using the Hyperledger Fabric blockchain to model a car as an autonomous entity. A car data structure is stored on Hyperledger and contains car and billing information, as well as car pass, ownership ledger, mileage, maintenance, etc. By using a private solution, all transactions on the blockchain network are related to the Car eWallet's applications and all customer data is private. On the other hand, with a private blockchain, a certain degree of decentralization is introduced because private blockchains often work using *Proof-of-Authority* or a similar consensus mode.

Chubu Electric Power [91] is one of the largest electricity providers in Japan and is currently testing cryptocurrency payments for their EV customers. They are facilitating the Bitcoin's Lightning network [30] payment channels for increasing transaction speed, but the downside of such channel solutions is that nodes must always be online to maintain a channel.

InnoEnergy [92] is a European company researching smart communities and e-mobility. They are exploring the value of directed acyclic graphs solutions such as IOTA to tackle the challenges in the area of e-mobility [93].

A consortium DLT solution (without platform-embedded cryptocurrency) could serve as an integrating component for public EV charging providers and enable roaming services where every participating EV provider company would be one of the nodes in a blockchain network. If a customer belonging to the provider A charges on a charging station belonging to provider B, the transaction would be visible to both providers. The result of this system is enabling charging to customers between roaming areas, with both providers being able to settle roaming transactions between them because all transactions are visible to all participating nodes. Censorship and fraud would be impossible because this system would use blockchain for storing EV charging transactions. Adding new providers to the network would be as simple as adding a new software node to the network.

D. CRYPTOCURRENCIES AND PLATFORMS

Cryptocurrencies can be introduced in energy markets or electricity billing as one of the possible payment methods.

Grid+ [94] is a retail electricity provider that uses intelligent software and hardware to offer low prices for electricity for its users. One of the offered products is a platform based on the Ethereum to allow users access to their local energy market and pay for electricity with cryptocurrencies and hardware device called Grid+ Agent. It also provides safe offline storage for users' private keys in the form of smart cards. The company has conducted a successful ICO and collected 57.5 million USD.

Energi [95] created a custom blockchain solution with embedded smart contracts that runs on Tendermint consensus which is suitable for specialized application blockchains. Their NRG coin serves as an incentive for using renewable energy at the local level.

Veridium [96] is using Ethereum to store carbon credits as TRG energy/carbon tokens which can be acquired with cryptocurrencies.

ImpactPPA [97] is trying to create a new cryptocurrency and use the raised ICO money to install renewable energy solutions in communities that lack access to electricity. They have built a custom smart meter which is blockchain-aware and periodically sends data to the blockchain. Since a smart meter does not store all blockchain transactions in a device itself, this solution also introduces a certain degree of centralization.

EnergyCoin [98] is a cryptocurrency based on the bitcoin protocol, but it runs on the *Proof-of-Stake* consensus because it is more environment-friendly than Proof-of-Work which requires mining. It is built by a non-profit EnergyCoin foundation sponsored by community donations and provides an infrastructure and application layer on top of the EnergyCoin cryptocurrency to enable more complex financial instruments, tokens, and decentralized applications.

Almost every cryptocurrency platform is an open-source project, and its code can be reused and extended to create new cryptocurrencies. Depending on a use case in the energy domain, having many specialized DLTs may be one of the solutions to problems with scalability and transaction throughput because users will be dispersed to many specialized platforms that are not connected at all. This would not

TABLE 3. Suitable DLT types for energy application categories considering technical aspects and open challenges of DLT.

Category	DLT type (data privacy)	DLT type (data structure)	Description
Energy trading	Private / no DLT	Blockchain	DLT is not suitable for centralized markets. Private DLT solutions should be used for local markets or energy communities because of transparency, data integrity, and fast settlement. If a public DLT is used for energy trading, it could increase costs because of the block time traceability issue described in III-B.
Energy payment and settlement	Public / Private	Blockchain / DAG	Public DLT platforms generally can be used for payment: DAG is fast and scalable, and blockchain is secure and robust. A private blockchain can be used for storing and providing immutable records of energy transactions.
New DLT application platforms	Public / Private	Blockchain	Depending on the globality and requirements of applications, blockchains can be used in public or a private environment. DAG platforms are not suitable for building application platforms because they often lack smart contract support.
EV charging payment and settlement	Public	Blockchain / DAG	Both public blockchains and DAGs are fit for payment and settlement in the EV charging field. Private blockchains can be used for storing transaction records.
Data / asset registry	Public	Blockchain	Public blockchains with smart contract support are a perfect fit for building asset registries. Asset registries can be modeled with a private blockchain but would be loosely decentralized and less secure.
Investments and tokenization	Public	Blockchain	Smart contracts and public blockchains can be used to implement investments and fund management mechanisms in a fully decentralized way.
Renewable energy certification	Public	Blockchain	Special kind of asset registry, where assets are energy certificates. Energy certificates can be modeled with smart contracts and public blockchains in a fully decentralized manner.
Energy origin tracking	Private	Blockchain	Private DLT is required due to high transaction throughput and data access control; the blockchain data structure has to secure energy transaction immutability. Energy origin tracking can also be modeled with public blockchains, but adding new records would be slower and more expensive.
Grid management	no DLT	no DLT	Grid management often implies automatization, and since smart contracts are not self-executable and cannot perform automatic tasks in a decentralized way, DLT is inappropriate.

apply to some energy market use cases. For example, when placed in the context of going towards a single European electricity market that should allow greater choice, lower prices, greater flexibility, and stability, having many independent platforms might not be an optimal solution.

One of the major drawbacks of all DLT platforms is the lack of interoperability. DLT platforms cannot easily communicate to external platforms and services-it is impossible to send requests from a DLT network to an external service. One of the solutions to this problem for certain use cases is to introduce one or multiple trusted centralized or decentralized services, such as Oraclize [99] or ChainLink [100], which will periodically send data to the DLT platform.

IV. DISCUSSION

An ideal DLT is decentralized, secure, and scalable, but currently, existing DLT solutions do not offer all of the listed properties simultaneously. For example, Ethereum is decentralized and secure, but not scalable, while Hyperledger offers security and improved scalability and the expanse of decentralization. Sharding and similar scaling solutions are scheduled for implementation in Ethereum, but currently, it is not possible to determine whether these extensions will compromise security.

Based on the analysis of technical aspects of various DLT solutions in the context of the energy sector, we provide suggestions and guidelines for integrating DLT in different categories of use cases in the energy sector in Table 3.

Currently, public blockchains are typically used as registries and asset ownership management tools. Digital asset data stored on a blockchain in a decentralized way is globally available, immutable, and resistant to failures. By using smart contracts, complex ownership and financial mechanisms can be implemented on top of those digital assets, so public blockchains fit well to be used for energy crowdfunding campaigns, energy certificate registries, electric vehicle information registries, etc.

Private and consortium blockchains can be used to ensure data privacy, security, and immutability, as well as data transfer among trusted network participants. For example, they can be used to transfer roaming data for EV charging between operators, or for exchanging electricity consumption data and power flows between transmission system operators (TSO). Private blockchains can ensure data access control and security, so they can be used to implement P2P markets on all levels, from microgrids to wholesale markets. If a requirement for a blockchain-based P2P market is to integrate it with external systems (such as DSOs or other markets), it could increase costs for integration because private blockchains are not globally available, so extra modules would need to be implemented for communication with external entities.

Regarding DAG solutions, they fit well to use cases requiring value and data transfer and can be deployed in large systems with many sensors and actuators. In theory, they provide an unlimited speed of transaction processing (limited only by hardware), but because of a large spectrum of attack vectors, DAGs still use centralized coordinators and preselected validator nodes to maintain the network and validate incoming transactions.

V. CONCLUSION

Distributed ledger technologies are facilitating new concepts and business models in the energy sector. A lot of resources are being invested in the development of decentralized solutions in the areas of energy trading, investments, and e-mobility. Despite initial skepticism and controversy, initial coin offerings (ICOs) and energy tokens enabled the funding of many innovative products and inspired many people to research DLT applications outside of financial applications. A lot of research is focused on private and public blockchains to integrate blockchain cryptocurrencies in existing systems, while system requirements are opening new horizons and ideas such as DAG-based solutions due to their ability to improve scalability and transaction throughput compared to blockchain. The paper explains and elaborates on how a specific decision on using DAG over blockchain for a particular solution depends on a particular use case since they are both decentralized and require no intermediaries. On one side blockchains can enable complex mechanisms through smart contract capabilities, and on the other side, DAGs offer processing speed and scalability of financial transactions.

In this line, the paper contributes to this emerging field by clearly explaining the key differences and features of representative distributed ledger technologies, blockchains, and directed acyclic graphs. By reviewing and explaining technological aspects, we establish that DLT offers a narrow niche for applications in the energy sector, but they fit very well into that niche. DAG solutions are best suited for payment systems, while the most promising application of blockchains is the storage of asset ownership records in energy applications. Most importantly, the paper categorizes energy applications and platforms and presents several solutions for each category, as well as discusses the benefits and limitations of their approaches. As a result of this research, we provide summarized recommendations and guidelines based on the analysis of technical aspects of various DLT solutions in Table 3.

Although many researched projects are still in an early stage of development, they are already showing promising results and demonstrating DLT usage viability in the energy sector.

REFERENCES

[1] *Ethereum—Blockchain App Platform*. Accessed: Sep. 5, 2019. [Online]. Available: https://www.ethereum.org/

[2] Linux Foundation. *Hyperledger*. Accessed: Sep. 5, 2019. [Online]. Available: https://www.hyperledger.org/

[3] E. S. Kang, S. J. Pee, J. G. Song, and J. W. Jang, "A blockchain-based energy trading platform for smart homes in a microgrid," in *Proc. 3rd Int. Conf. Comput. Commun. Syst. (ICCCS)*, Apr. 2018, pp. 472–476.

[4] S. J. Pee, E. S. Kang, J. G. Song, and J. W. Jang, "Blockchain based smart energy trading platform using smart contract," in *Proc. Int. Conf. Artif. Intell. Inf. Commun. (ICAIIC)*, Feb. 2019, pp. 322–325.

[5] J. A. F. Castellanos, D. Coll-Mayor, and J. A. Notholt, "Cryptocurrency as guarantees of origin: Simulating a green certificate market with the ethereum blockchain," in *Proc. IEEE Int. Conf. Smart Energy Grid Eng. (SEGE)*, Aug. 2017, pp. 367–372.

[6] European Commission, Clean energy for all Europeans. (Aug. 2019). *Publications Office of the European Union*. [Online]. Available: http://dx.doi.org/10.2833/9937

[7] IEEE Future Directions Blockchain Initiative, "Reinforcing the links of the blockchain," IEEE, Tech. Rep., 2017. [Online]. Available: https://blockchain.ieee.org/publications#white-papers

[8] ENTSO-E Monitoring Report 2018—Research, Development and Innovation Projects, "State-of-play of the implementation of the RD&I roadmap 2017–2026," ENTSO-E, Brussels, Belgium, Tech. Rep., 2019. [Online]. Available: https://rdmonitoring.entsoe.eu/

[9] A. Goranovic, M. Meisel, L. Fotiadis, S. Wilker, A. Treytl, and T. Sauter, "Blockchain applications in microgrids: An overview of current projects and concepts," in *Proc. 43rd Annu. Conf. IEEE Ind. Electron. Soc. (IECON)*, Jan. 2017, pp. 6153–6158.

[10] A. S. Musleh, G. Yao, and S. M. Muyeen, "Blockchain applications in smart grid–review and frameworks," *IEEE Access*, vol. 7, pp. 86746–86757, 2019.

[11] P. Siano, G. De Marco, A. Rolálan, and V. Loia, "A survey and evaluation of the potentials of distributed ledger technology for Peer-to-Peer transactive energy exchanges in local energy markets," *IEEE Syst. J.*, vol. 13, no. 3, pp. 3454–3466, Sep. 2019.

[12] A. Ahl, M. Yarime, K. Tanaka, and D. Sagawa, "Review of blockchain-based distributed energy: Implications for institutional development," *Renew. Sustain. Energy Rev.*, vol. 107, pp. 200–211, Jun. 2019. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S1364032119301352

[13] K. Shuaib, J. A. Abdella, F. Sallabi, and M. Abdel-Hafez, "Using blockchains to secure distributed energy exchange," in *Proc. 5th Int. Conf. Control, Decis. Inf. Technol. (CoDIT)*, Apr. 2018, pp. 622–627.

[14] P. Xie, W. Yan, P. Xuan, J. Zhu, Y. Wu, X. Li, and J. Zou, "Conceptual framework of blockchain-based electricity trading for neighborhood renewable energy," in *Proc. 2nd IEEE Conf. Energy Internet Energy Syst. Integr. (EI2)*, Oct. 2018, pp. 1–5.

[15] I. Kounelis, G. Steri, R. Giuliani, D. Geneiatakis, R. Neisse, and I. Nai-Fovino, "Fostering consumers' energy market through smart contracts," in *Proc. Int. Conf. Energy Sustainability Small Developing Economies (ES2DE)*, Jul. 2017, pp. 1–6.

[16] T. Cioara, I. Anghel, C. Pop, M. Bertoncini, V. Croce, D. Ioannidis, K. Votis, D. Tzovaras, and L. D'Oriano, "Enabling new technologies for demand response decentralized validation using blockchain," in *Proc. IEEE Int. Conf. Environ. Electr. Eng. IEEE Ind. Commercial Power Syst. Eur. (EEEIC/I&CPS Europe)*, Jun. 2018, pp. 1–4.

[17] A. C. Tsolakis, I. Moschos, K. Votis, D. Ioannidis, T. Dimitrios, P. Pandey, S. Katsikas, E. Kotsakis, and R. García-Castro, "A secured and trusted demand response system based on blockchain technologies," in *Proc. Innov. Intell. Syst. Appl. (INISTA)*, Jul. 2018, pp. 1–6.

[18] S. Jeong, N.-N. Dao, Y. Lee, C. Lee, and S. Cho, "Blockchain based billing system for electric vehicle and charging station," in *Proc. 10th Int. Conf. Ubiquitous Future Netw. (ICUFN)*, Jul. 2018, pp. 308–310.

[19] C. Liu, K. K. Chai, X. Zhang, E. T. Lau, and Y. Chen, "Adaptive blockchain-based electric vehicle participation scheme in smart grid platform," *IEEE Access*, vol. 6, pp. 25657–25665, 2018.

[20] A. Sheikh, V. Kamuni, A. Urooj, S. Wagh, N. Singh, and D. Patel, "Secured energy trading using Byzantine-based blockchain consensus," *IEEE Access*, vol. 8, pp. 8554–8571, 2020.

[21] L. Thomas, Y. Zhou, C. Long, J. Wu, and N. Jenkins, "A general form of smart contract for decentralized energy systems management," *Nature Energy*, vol. 4, no. 2, pp. 140–149, Feb. 2019, doi: 10.1038/s41560-018-0317-7.

[22] C. Burger, A. Kuhlmann, P. Richard, and J. Weinmann, "Blockchain in the energy transition. A survey among decision-makers in the German energy industry," in *Proc. German Energy Angency*, 2016, p. 41. Accessed: Aug. 22, 2018. [Online]. Available: https://www.dena.de/fileadmin/dena/Dokumente/Meldungen/dena_ESMT_Studie_blockchain_englisch.pdf

[23] L. Calès, S. Nascimento, A. Polvora, A. Anderberg, E. Andonova, M. Bellia, A. Santos, I. Kounelis, I. N. Fovino, M. P. Giudici, E. Papanagiotou, M. Sobolewski, F. Rossetti, and L. Spirito, "Blockchain now and tomorrow," Publications Office Eur. Union, Brussels, Belgium, Tech. Rep. JRC117255, Sep. 2019, doi: 10.2760/901029.

[24] SolarPlaza. *Blockchain & Energy in Europe*. Accessed: Sep. 5, 2019. [Online]. Available: https://www.solarplaza.com/channels/future-grid/11969/blockchain-energy-europe/

[25] M. Andoni, V. Robu, D. Flynn, S. Abram, D. Geach, D. Jenkins, P. McCallum, and A. Peacock, "Blockchain technology in the energy sector: A systematic review of challenges and opportunities," *Renew. Sustain. Energy Rev.*, vol. 100, pp. 143–174, Feb. 2019, doi: 10.1016/j.rser.2018.10.014.

[26] M. F. Zia, M. Benbouzid, E. Elbouchikhi, S. M. Muyeen, K. Techato, and J. M. Guerrero, "Microgrid transactive energy: Review, architectures, distributed ledger technologies, and market analysis," *IEEE Access*, vol. 8, pp. 19410–19432, 2020.

[27] M. L. Di Silvestre, P. Gallo, J. M. Guerrero, R. Musca, E. R. Sanseverino, G. Sciumè, J. C. Vásquez, and G. Zizzo, "Blockchain for power systems: Current trends and future applications," *Renew. Sustain. Energy Rev.*, vol. 119, Mar. 2020, Art. no. 109585.

[28] N. Wang, X. Zhou, X. Lu, Z. Guan, L. Wu, X. Du, and M. Guizani, "When energy trading meets blockchain in electrical power system: The state of the art," *Appl. Sci.*, vol. 9, no. 8, p. 1561, Apr. 2019.

[29] M. Ghorbanian, S. H. Dolatabadi, P. Siano, I. Kouveliotis-Lysikatos, and N. D. Hatziargyriou, "Methods for flexible management of blockchain-based cryptocurrencies in electricity markets and smart grids," *IEEE Trans. Smart Grid*, early access, Apr. 28, 2020, doi: 10.1109/TSG.2020.2990624.

[30] J. Poon and T. Dryja. (2016). *The Bitcoin Lightning Network: Scalable Off-Chain Instant Payments*. [Online]. Available: https://lightning.network/lightning-network-paper.pdf

[31] J. Poon and V. Buterin, "Plasma: Scalable autonomous smart contracts scalable multi-party computation," Plasma, White Paper, 2017, pp. 1–47. [Online]. Available: https://plasma.io/plasma.pdf

[32] Iota Website. *IOTA—Redefining Trust, Value, and Ownership*. Accessed: Sep. 5, 2019. [Online]. Available: https://www.iota.org/

[33] Nano Website. *Nano—Making Money Efficient for a More Equal World*. Accessed: Sep. 5, 2019. [Online]. Available: https://nano.org/

[34] F. M. Benčić and I. P. Žarko, "Distributed ledger technology: Blockchain compared to directed acyclic graph," in *Proc. IEEE 38th Int. Conf. Distrib. Comput. Syst. (ICDCS)*, Jul. 2018, pp. 1569–1570.

[35] M. J. M. Chowdhury, M. S. Ferdous, K. Biswas, N. Chowdhury, A. S. M. Kayes, M. Alazab, and P. Watters, "A comparative analysis of distributed ledger technology platforms," *IEEE Access*, vol. 7, pp. 167930–167943, 2019.

[36] Z. Zheng, S. Xie, H. Dai, X. Chen, and H. Wang, "An overview of blockchain technology: Architecture, consensus, and future trends," in *Proc. IEEE Int. Congr. Big Data (BigData Congress)*, Jun. 2017, pp. 557–564.

[37] S. Nakamoto. (Sep. 2008). *Bitcoin: A Peer-to-Peer Electronic Cash System*. [Online]. Available: https://bitcoin.org/bitcoin.pdf

[38] G. Wood, "Ethereum: A secure decentralised generalised transaction ledger," Ethereum Found., Bern, Switzerland, Ethereum Project Yellow Paper, 2014, pp. 1–32.

[39] EOS. *EOS Website*. Accessed: Sep. 5, 2019.[Online]. Available: https://eos.io/

[40] Neo. *Neo Smart Economy*. Accessed: Sep. 5, 2019. [Online]. Available: https://neo.org/

[41] Aeternity. *Aeternity Blockchain: Scalable Smart Contracts Interfacing With Real-World Data*. Accessed: Sep. 10, 2019. [Online]. Available: https://aeternity.com/

[42] Interchain Foundation. (2017). *Consensus Compare: Tendermint BFT vs. EOS dPoS*. Accessed: Sep. 10, 2019. [Online]. Available: https://blog.cosmos.network/consensus-compare-tendermint-bft-vs-eos-dpos-46c5bca7204b

[43] Ethereum Wiki. (2018). *Sharding FAQ*. Accessed: Sep. 10, 2019. [Online]. Available: https://github.com/ethereum/wiki/wiki/Sharding-FAQ

[44] A. Chauhan, O. P. Malviya, M. Verma, and T. S. Mor, "Blockchain and scalability," in *Proc. IEEE Int. Conf. Softw. Qual., Rel. Secur. Companion (QRS-C)*, Jul. 2018, pp. 122–128.

[45] Ethereum. *Crossing Shards—Intro to Sharding and Cross-Shard Trust*. Accessed: Feb. 12, 2020. [Online]. Available: https://medium.com/scalar-capital/crossing-shards-e03aed0c39d1

[46] Raiden Network Whitepaper. *Raiden Network—Fast, Cheap, Scalable Token Transfers for Ethereum*. Accessed: Feb. 12, 2020. [Online]. Available: https://raiden.network/101.html

[47] Trinity Whitepaper. (2018). *Trinity—Universal Off-Chain Scaling Solution*. Accessed: Sep. 10, 2019. [Online]. Available: https://trinity.tech/#/writepaper

[48] S. Popov. (2017). *The Tangle*. [Online]. Available: https://iota.org/IOTA_Whitepaper.pdf

[49] C. Lemahieu, "Nano: A feeless distributed cryptocurrency network," Nano Found., London, U.K., White Paper, 2014, pp. 1–8. [Online]. Available: https://nano.org/en/whitepaper

[50] V. Saini. (2018). *IOTA Tangle Visualisation*. Accessed: Sep. 10, 2019. [Online]. Available: https://public-rdsdavdrpd.now.sh/

[51] Ethereum. *Ethereum Whitepaper*. Accessed: Jul. 24, 2019. [Online]. Available: https://github.com/ethereum/wiki/wiki/White-Paper

[52] EOSIO. (2017). *EOS.IO Technical White Paper*. [Online]. Available: https://github.com/EOSIO/Documentation/blob/master/TechnicalWhitePaper.md

[53] R. G. Brown, "The corda platform: An introduction," R3 Consortium, New York, NY, USA, White Paper, 2018, pp. 1–21. [Online]. Available: https://www.corda.net/content/corda-platform-whitepaper.pdf

[54] A. Churyumov, "Byteball: A decentralized system for storage and transfer of value," Obyte, Moscow, Russia, Tech. Rep., 2018, pp. 1–49. [Online]. Available: https://obyte.org/Byteball.pdf

[55] Quorum. (2018). *Quorum Whitepaper*. [Online]. Available: https://github.com/jpmorganchase/quorum/blob/master/docs/QuorumWhitepaperv0.2.pdf

[56] D. Mazieres, "The stellar consensus protocol: A federated model for Internet-level consensus," Stellar Develop. Found., San Francisco, CA, USA, White Paper, 2016, pp. 1–32. [Online]. Available: https://www.stellar.org/papers/stellar-consensus-protocol.pdf

[57] N. V. Saberhagen, "Crypto note v2.0," Monero, Sydney, NSW, Australia, White Paper, 2013, pp. 1–20. [Online]. Available: https://whitepaperdatabase.com/monero-xmr-whitepaper/

[58] D. Hughes, "Radix—Tempo," Radix DLT, London, U.K., White Paper, 2017, pp. 1–15. [Online]. Available: https://docs.radixdlt.com/kb/learn/whitepapers/tempo

[59] CoinMarketCap. (2019). *Cryptocurrency Market Capitalizations*. Accessed: Sep. 12, 2019. [Online]. Available: https://coinmarketcap.com/

[60] F. M. Benčić, P. Skočir, and I. P. Žarko, "DL-tags: DLT and smart tags for decentralized, privacy-preserving, and verifiable supply chain management," *IEEE Access*, vol. 7, pp. 46198–46209, 2019.

[61] State of the Dapps. *Dapp Statistics*. Accessed: Sep. 5, 2019. [Online]. Available: https://www.stateofthedapps.com/stats/

[62] Poa Network. *Poa Network Website*. Accessed: Sep. 10, 2019. [Online]. Available: https://poa.network/

[63] G. Chain. *Go Chain—The Blockchain Company*. Accessed: Sep. 10, 2019. [Online]. Available: https://gochain.io/

[64] Steem. *Steem—Powering Communities and Opportunities*. Accessed: Sep. 10, 2019. [Online]. Available: https://steem.com/

[65] Statista. *PWC. N.D. Industries Seen as Leaders in Blockchain Technology Development Worldwide as of 2018*. Accessed: Sep. 5, 2019. [Online]. Available: https://www.statista.com/statistics/920747/worldwide-blockchain-technology-development-leading-industries/

[66] IPFS. (2019). *IPFS Website*. Accessed: Sep. 12, 2019. [Online]. Available: https://ipfs.io/

[67] C. Zhang, J. Wu, Y. Zhou, M. Cheng, and C. Long, "Peer-to-peer energy trading in a microgrid," *Appl. Energy*, vol. 220, pp. 1–12, Jun. 2018. [Online]. Available: http://linkinghub.elsevier.com/retrieve/pii/S0306261918303398

[68] A. Pouttu, J. Haapola, P. Ahokangas, Y. Xu, M. Kopsakangas-Savolainen, E. Porras, J. Matamoros, C. Kalalas, J. Alonso-Zarate, F. D. Gallego, J. M. Martin, G. Deconinck, H. Almasalma, S. Clayes, J. Wu, M. Cheng, F. Li, Z. Zhang, D. Rivas, and S. Casado, "P2P model for distributed energy trading, grid control and ICT for local smart grids," in *Proc. Eur. Conf. Netw. Commun. (EuCNC)*, Jun. 2017, pp. 1–6.

[69] Z. Li, J. Kang, R. Yu, D. Ye, Q. Deng, and Y. Zhang, "Consortium Blockchain for Secure Energy Trading in Industrial Internet of Things," *IEEE Trans. Ind. Informat.*, vol. 14, no. 8, pp. 3690–3700, Aug. 2018.

[70] D. Vangulick, B. Cornélusse, and D. Ernst, "Blockchain for peer-to-peer energy exchanges: Design and recommendations," in *Proc. Power Syst. Comput. Conf. (PSCC)*, Jun. 2018, pp. 1–7.

[71] A. Hrga, F. M. Benčić, and I. P. Žarko, "Technical analysis of an initial coin offering," in *Proc. 15th Int. Conf. Telecommun. (ConTEL)*, Jul. 2019, pp. 1–8.

[72] Irene Energy. (2018). *Irene Energy Website*. Accessed: Sep. 10, 2019. [Online]. Available: https://irene.energy/

[73] Treon. (2018). *Treon Whitepaper*. Accessed: Aug. 29, 2018. [Online]. Available: https://www.treon.io/data/Treon-WhitePaper-v4-17-Jul-18.pdf

[74] E. Power, "Etain power—A blockchain-based energy ecosystem powered by AI," Power Infinity Ltd., Singapore, pp. 1–64, 2019. Accessed: Sep. 10, 2019. [Online]. Available: https://www.etainpower.io/resource/EtainPowerWhitePaper.pdf

[75] A. T. Griffith. (2018). *Ethereum Meta Transactions—Lowering Barriers to Drive Mass Ethereum Adoption*. Accessed: Sep. 10, 2019. [Online]. Available: https://medium.com/@austin_48503/ethereum-meta-transactions-90ccf0859e84

[76] PowerLedger. *PowerLedger—Energy, Reimagined*. Accessed: Sep. 10, 2019. [Online]. Available: https://www.powerledger.io/

[77] Pylon Network. *Pylon Network—The Green Energy Economy is Here*. Accessed: Sep. 10, 2019. [Online]. Available: https://pylon-network.org/

[78] Solarcoin. *Solarcoin Website*. Accessed: Sep. 10, 2019. [Online]. Available: https://solarcoin.org/

[79] Sun Exchange. *Sun Exchange—Connecting the World to the Sun*. Accessed: Sep. 10, 2019. [Online]. Available: https://thesunexchange.com/

[80] WePower Network. *WePower Network Whitepaper*. Accessed: Sep. 10, 2019. [Online]. Available: https://wepower.network/media/WhitePaper-WePower_v_2.pdf

[81] Sun Contract. *Sun Contract Website*. Accessed: Sep. 10, 2019. [Online]. Available: https://suncontract.org/

[82] *SONCE*. Accessed: Apr. 5, 2020. [Online]. Available: https://www.sonce.com/

[83] Volt Markets. *Volt Markets Website*. Accessed: Sep. 10, 2019. [Online]. Available: https://voltmarkets.com/

[84] LO3 Energy. *LO3 Energy Website*. Accessed: Feb. 22, 2019. [Online]. Available: https://lo3energy.com/

[85] E. Mengelkamp, J. Gärttner, K. Rock, S. Kessler, L. Orsini, and C. Weinhardt, "Designing microgrid energy markets: A case study: The Brooklyn Microgrid," *Appl. Energy*, vol. 210, pp. 870–880, Jan. 2018. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S030626191730805X

[86] CryptoKitties. *CryptoKitties Website*. Accessed: Sep. 10, 2019. [Online]. Available: https://www.cryptokitties.co/

[87] P. M. da Silva, M. Matos, and J. Barreto. *Fixed Transaction Ordering and Admission in Blockchains*. Accessed: Sep. 10, 2019. [Online]. Available: http://conferences.inf.ed.ac.uk/EuroDW2018/papers/eurodw18-Silva.pdf

[88] Share & Charge. *Share & Charge Website*. Accessed: Sep. 10, 2019. [Online]. Available: https://shareandcharge.com/

[89] H. Garcia. *The Next Share & Charge*. Accessed: Feb. 15, 2020. [Online]. Available: https://medium.com/share-charge/the-next-share-charge-bc5f6807ddd6

[90] Car e-Wallet. *Car e-Wallet Website*. Accessed: Sep. 10, 2019. [Online]. Available: https://car-ewallet.de/

[91] Chubu Electric Power. *Chubu Electric Power Website*. Accessed: Sep. 10, 2019. [Online]. Available: http://www.chuden.co.jp/english/

[92] InnoEnergy. *InnoEnergy Website*. Accessed: Sep. 10, 2019. [Online]. Available: http://www.innoenergy.com/

[93] W. Pimenta. *Iota Partners With Innoenergy on Smart Energy Community*. Accessed: Feb. 15, 2020. [Online]. Available: https://blog.iota.org/iota-partners-with-innoenergy-on-smart-energy-community-5dc483b42aa0

[94] Grid+. *Grid+ Website*. Accessed: Sep. 10, 2019. [Online]. Available: https://gridplus.io/

[95] Energi. *Energi Website*. Accessed: Sep. 10, 2019. [Online]. Available: https://www.energi.world/

[96] Veridium. *Veridium Website*. Accessed: Sep. 10, 2019. [Online]. Available: https://www.veridium.io/

[97] ImpactPPA. *ImpactPPA—A Decentralized Utility Company*. Accessed: Sep. 10, 2019. [Online]. Available: https://www.impactppa.com/

[98] EnergyCoin. *EnergyCoin Website*. Accessed: Sep. 10, 2019. [Online]. Available: https://energycoin.eu/

[99] Oraclize. *Oraclize Website*. Accessed: Aug. 22, 2019. [Online]. Available: http://www.oraclize.it/

[100] S. Ellis, A. Juels, and S. Nazarov, "ChainLink—A decentralized oracle network," Chainlink, George Town, Cayman Islands, White Paper, 2017, pp. 1–38. [Online]. Available: https://link.smartcontract.com/whitepaper

ALEN HRGA (Member, IEEE) received the M.Sc. degree in software engineering and information systems from the Faculty of Electrical Engineering and Computing, University of Zagreb, in 2018, where he is currently pursuing the Ph.D. degree in computing. Since 2018, he has been a Research Associate with the Department of Energy and Power Systems. His professional interests include software engineering, augmented and mixed reality, and distributed ledger technology. He was the Organizer of the first blockchain development meetup in Zagreb and several other workshops on blockchain technology.

TOMISLAV CAPUDER (Member, IEEE) received the Ph.D. degree. He is currently an Assistant Professor with the Faculty of Electrical Engineering and Computing, University of Zagreb. His research interests include energy systems planning and modeling, integrated infrastructures, distributed energy systems, energy markets, and environmental issues in power systems.

IVANA PODNAR ŽARKO (Member, IEEE) received the B.Sc., M.Sc., and Ph.D. degrees in electrical engineering from the Faculty of Electrical Engineering and Computing, University of Zagreb, Croatia, in 1996, 1999, and 2004, respectively. She was a Guest Researcher and a Research Associate with the Technical University of Vienna, Austria, and a Postdoctoral Researcher with the Swiss Federal Institute of Technology, Lausanne (EPFL), Switzerland. She is currently a Full Professor with the University of Zagreb, where she is leading the Internet of Things Laboratory. She has participated in a number of research projects supported by national sources and EU funds. She was the Technical Manager of the H2020 Project Symbiote: Symbiosis of Smart Objects Across IoT Environments and is currently leading two national research projects. She has coauthored more than 70 scientific journal articles and conference papers in the area of large-scale distributed systems, the IoT, and big data processing. She serves as a Program Committee Member of a number of international conferences and was the Chapter Chair for the IEEE Communications Society, Croatia Chapter, from 2011 to 2014.

• • •