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# Blockchain for Distributed Energy Resources Management and Integration

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**ABSTRACT** Power grids all over the world are transitioning towards a decentralized structure. Under such a transition, blockchain technology is emerging as a potential solution for technical, deployment and decentralization issues, given its security, integrity, decentralized nature and required infrastructure. Moreover, blockchain technology offers excellent features like non-repudiation and immutability which makes it a promising application for DER integration and management on reliability factors. In this paper, a comprehensive review of blockchain applications for DER management and integration is presented. First, a blockchain-based literature review of research activities in the DER integration area and related tasks including entrepreneurial efforts is carried out. Next, the different opportunities and challenges of DER integration and management in power grids, i.e., centralization, regulatory support, development costs are discussed. Finally, some key research challenges and opportunities of including blockchain technology to DER integration and management issues are presented.

**INDEX TERMS** Blockchain, distributed energy resources (DER), distributed ledger technologies, consensus algorithms.

## NOTATION

This section presents the main notations used in the document.

AI	Artificial Intelligence.
AMI	Advanced Metering Interfaces.
DER	Distributed Energy Resources.
DERMS	Distributed Energy Resources Management System.
DG	Distributed Generation.
DLT	Distributed Ledger Technologies.
DPoS	Delegated Proof-of-Stake.
DR	Demand Response.
DSO	Distribution System Operator.

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ESS	Energy Storage Systems.
EV	Electric Vehicles.
HEMS	Home Energy Management System.
IoT	Internet of Things.
IoE	Internet of Energy.
ICT	Information and Communication Technology.
LCOE	Levelized Cost of Energy.
OPF	Optimal Power Flow.
PoA	Proof-of-Authority.
PoC	Proof-of-Capacity.
PBFT	Practical Byzantine Fault Tolerance.
PoS	Proof-of-Stake.
PoW	Proof-of-Work.
PV	Photovoltaics.
P2P	Peer-to-Peer.
SGs	Smart grids.

RES	Renewable Energy Sources.
VPPs	Virtual Power Plants.
V2V	Vehicle-to-Vehicle.
V2G	Vehicle-to-Grid.

## I. INTRODUCTION

The transition to sustainable energy is encouraging the integration of increasing amounts of renewable energy (i.e., wind and solar PV) into the electrical grids around the world [1], [2]. The development of renewable energy sources (RES) has been enabled by the deregulation of the energy sector and driven by the promise of financial rewards and energy policy initiatives in several countries. These situations have led to an energy transition trend towards decarbonization, decentralization, digitalization and democratization. Thus, the traditional way of generating, transmitting and distributing electricity has changed significantly as generation units are now more distributed, more efficient and closer to the end-users [3]–[6] offering them opportunities for individual participation and empowerment [7], [8].

This process is bringing meaningful changes as traditional large-scale synchronous generators are being replaced by emerging small-scale distribution-level low-carbon technologies (i.e., local distributed generation (DG) in cities, energy storage systems (ESS), electric vehicles (EVs), and demand response (DR)) [9], [10]. All of these resources are lumped together under the label of *distributed energy resources* (DER). Many investments have been made worldwide to develop more affordable, flexible and efficient solutions that allow a wider adoption of these resources at the end-user level for improving the efficiency, reliability and flexibility of electric grids [3], [11].

The intended benefits of efficient and progressive DER integration and management are considerable [12]–[17]. End-users such as residences or industrial users are empowered by the inherent DER flexibility, since they are now able to manage their energy production and consumption. Now, owners can participate actively in the energy acquisition and cost reduction by doing energy management. Moreover, DER flexibility is valuable for power systems, as they offer opportunities to alleviate grid infrastructure investment costs, and provide ancillary services such as frequency control, voltage control and storage reserves, amongst others.

It is important to mention that decentralization in power systems using DER can occur in several dimensions: physical decentralization, which refers to the disaggregation of power generation through the installation of small or medium size energy resources directly to low or medium voltage distribution grids [18], [19]; market decentralization, meaning new trading and clearing mechanisms that allow financial and data integration to DERs in a secure, local and straightforward way with end-users (e.g., P2P energy trading); and decentralization of the operation, where more than one *manager* (e.g., DERMS, VPP, Local Energy Communities, among others) can transact selling and buying of energy in order to

clear locally its energy supply and demand [20]. Hence, this multidimensional and massive process brings with it some challenges to be overcome.

Some of the most important challenges are as follows: mitigating uncertainty of renewables generation, reduction of high and fluctuating energy prices for end-users [16], managing in real-time supply and demand energy gaps [21], avoiding grid instability and low power quality scenarios [22], alleviating distribution grid needs with profits from new players in energy markets, amongst others.

Blockchain technology offers a new alternative to overcome these DER challenges for several reasons: It provides a trusted environment for different stakeholders to interact peer-to-peer with enhanced security for energy, data, and financial transactions. Blockchain technology can also provide faster and smoother decentralized system operation. Moreover, it is inherently a decentralized mechanism that works in conjunction with other energy-related technologies and paradigms such as Smart Grids (SGs) [23], [24], peer-to-peer energy trading [25]–[28], virtual power plants [29]–[32], IoT [33], [34], among others, looking to enhance their features wherever a coordinated integration (technical, market, and financial) of these resources is sought, in order to participate in energy markets, providing value and empowerment to consumers and offering different grid services due to their security, reliability, and efficiency in DER-integrated power systems.

### A. KEY CONTRIBUTIONS

It is important to mention that several studies have been conducted on the influence of blockchain technology on distributed energy resources (DER) and their applications. However, these studies have been oriented to specific and limited scientific contexts (i.e., reduced location, pilot projects) or have not addressed other initiatives around this topic due to its complexity and novelty.

This expresses the need for a study that comprehensively shows the efforts made for the blockchain technology use in DER management and integration by the different stakeholders (i.e. scientific community, business initiatives, among others), as well as analyzing the challenges that still persist for this approach. Table 1 summarizes important survey articles related to the application of blockchain technology in different areas related with DER management and integration. The terms high, moderate and low are the levels of coverage and complexity in each presented area.

The review articles presented in this table show the previously mentioned, the big interest in showing different blockchain applications for DER management and integration as well as their current barriers and future challenges according to the time where they have been published, many of them related with exploratory analyses of a mostly technical nature and focused on development pilots. However, it is also evident that these studies have not focused on showing business efforts or applications in this same line (e.g. crowdfunding), or a further study in the key issues at

**TABLE 1. Summary of important surveys on blockchain for DER management and integration.**

Reference	Blockchain Integration for DER	Coverage of blockchain applications	Business Initiatives	Technical Aspects	Multi-dimensional Issues	Future Challenges	Remarks
[35]	High	High	High	Low	Moderate	High	It comprehensively covers blockchain-based applications of different DERs, as well as related future challenges.
[36]	Moderate	Moderate	Low	High	High	High	It specifies the future direction and challenges of blockchain application in SG thought towards the security of integrating DER.
[37]	High	Moderate	Low	Moderate	Moderate	Low	Concise details of blockchain applications related with DER management are provided.
[38]	Moderate	Moderate	Low	Low	Moderate	Moderate	It specifically details the multidimensional challenges of blockchain applied to the energy sector.
[39]	Moderate	Moderate	Low	Moderate	Low	High	The development of blockchain in the energy internet paradigm is reviewed and analyzed (challenges, issues and features).
[40]	Moderate	Moderate	Low	Moderate	Moderate	Moderate	Specifies the use and future issues and challenges of blockchain technology in the energy internet paradigm.
[41]	Moderate	Moderate	Low	Moderate	Low	Low	Details various applications of blockchain technology used on different types of DER.
[42]	High	Moderate	Moderate	Moderate	High	High	Describes the applicability of blockchains specifically on SGs. Clearly specifies current limitations and future development trends.
[43]	High	High	Low	High	High	Moderate	Different DER integration approaches and their respective considerations (limitations, formulations, among others) are analyzed.
[44]	Moderate	High	Low	Moderate	Low	Moderate	Blockchain-based applications for different types of DER are specified, as well as evaluating different architectures to consider other potential uses.
[45]	Moderate	High	High	Moderate	High	Moderate	The challenges faced by current solutions are identified, and the frameworks and techniques used to integrate blockchain are highlighted.
[46]	Moderate	High	Moderate	Moderate	High	High	The limitations of blockchain and its impact on energy systems are analyzed in depth. They also show an overview of different blockchain-based applications.

other dimensions for the Blockchain development for these tasks.

Therefore, this review paper offers insights on up-to-date activities of rapidly growing blockchain applications focused on DER integration and management from different perspectives (technical, regulatory, economic, among others), highlighting recent challenges and opportunities. Furthermore, this paper also presents some applications in different areas where blockchain technology has a great influence on DER management and integration tasks. The key contributions of this paper are summarized as follows:

- A description of blockchain technology strategies (e.g., categories, consensus mechanisms, smart contracts, etc.) related with DER integration and management.
- The current research scope of blockchain related technologies defined by DER management and integration applications including entrepreneurial efforts.
- A review of different issues and development opportunities related to blockchain implementation for DER.

This paper is organized as follows: Section II provides some theoretical background of blockchain technology as

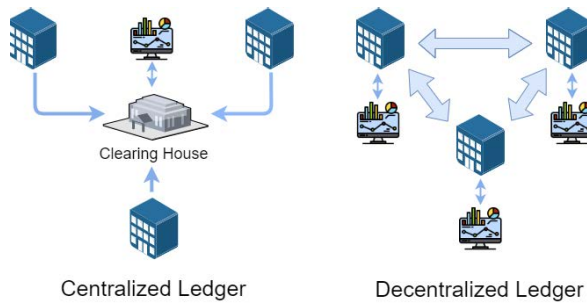
it relates to DER integration and management. Section III presents different paradigms of DER management and integration where Blockchain has contributed significantly, as well as the role of ICT in this process. Section IV addresses the different areas and applications of blockchain technology for DER. Section V highlights the challenges and opportunities that blockchain technology presents in DER management and integration. Section VI discusses the effects of blockchain technology implementation on DER applications. Finally, concluding remarks are provided in Section VII.

## II. BLOCKCHAIN TECHNOLOGY

This section presents the blockchain technology as a support for DER integration and management. Three topics are included: distributed ledger technology, blockchain and smart contracts, and the consensus mechanisms.

### A. DISTRIBUTED LEDGER TECHNOLOGY (DLT)

Like a database, the electronic distributed ledger technology is defined for recording information that is not executed by a single entity (i.e., a centralized ledger). These DLTs allow



**FIGURE 1.** Comparison between centralized and distributed ledger technologies.

data storage and use in a decentralized fashion with peers and distributed (connected and therefore can communicate) in a private or public way, as shown in Figure 1. Any modification made in the DLTs is shared and validated by all the nodes (consensus or agreement) within seconds or minutes in order to offer security, transparency and reliability [36], [47], [48]. Blockchain is a type of DLT which has the capability to empower different parties take on an active role in energy transactions by eliminating third-party involvement, so that consumers, prosumers and producers can interact directly [49].

## B. BLOCKCHAIN AND SMART CONTRACTS

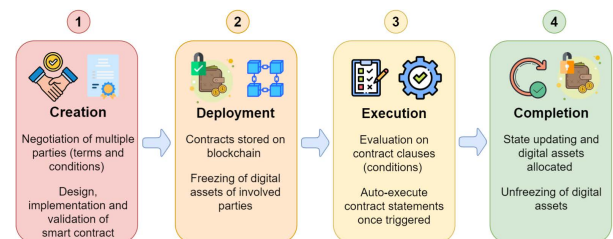
A *blockchain* is defined as a distributed registration system that promotes decentralization (actors or blocks are connected), transparency (does not require intermediaries) and data integrity (verified by all nodes in the network). Authors in [35], [47], [50]–[54] define it more specifically as a secure (immutable, append-only) digital data structure that runs on digital networks that contain an information database with different transactions, records, or files in chronological order, where many peers can participate. Also, other authors in [36], [55], [56] add that it is a collection of information “blocks” (e.g., hashes, scripts, timestamps, transactions, amongst others) distributed in chains (especially by cryptography), which when created, are distributed to all nodes that they share.

Based on information accessibility, blockchain systems can be categorized into *private* (partially decentralized systems with high-efficiency, where some selected and trusted users are permitted to read, validate and participate in publishing new blocks to the system [36], [57], [58]), *public* (fully decentralized systems with lower efficiency compared to private ones, require mandatory consensus mechanisms for security and data integrity, allow open participation by providing a copy of the blockchain to all its members, and it is almost impossible to tamper [59]) and *consortium* blockchains (a special type of blockchain because it is semi-decentralized, where predefined groups of nodes that can validate transactions through consensus mechanism in order to make transactions faster [60]). All of these blockchain topologies can be used to integrate and manage DER depending on the context and task involved.

The *Smart Contracts*, on the other hand, are essential for current blockchain ecosystems since they are scripts written

with programming languages that can self-execute actions in an immutable, transparent and completely safe way according to a series of parameters already established (in most cases solidity). Other authors such as [61]–[63] define it more precisely as an auto-executable and immutable script that verifies specific actions like contractual clauses in a regular contract. When certain conditions are fulfilled corresponding actions will be executed.

As with DLT, smart contracts can help eliminate the brokerage part in various use cases, reducing transaction costs and allowing for low-value transactions. A smart contract is a piece of code stored and deployed in a blockchain without a control entity in the blockchain framework. Instead of legal terms, these contracts store the conditions and events such as a value or a deadline date or simply transaction information [36], [64]. In this way, other authors [65] agree that smart contracts are most efficient for contracts that can be reduced to simple “if-then” statements, as their terms are easy to convert to computer code and can be executed automatically. Based on [66], Figure 2 shows the life cycle of a smart contract.



**FIGURE 2.** Life cycle of a smart contract.

## C. CONSENSUS MECHANISMS

The consensus mechanisms or algorithms are key components for the proper blockchain operation, since they are responsible for determining the correct record state after making a transaction between nodes. However, these mechanisms are not universal for all blockchain due to their performance and privacy features. Based on [67], Figure 3 shows, how any blockchain works with a consensus mechanism. Next, some of the most popular consensus mechanisms applied in DER management and integration are explained.

### 1) PROOF OF WORK (PoW)

The Proof-of-Work is the most common consensus algorithm that ensures a record (i.e., the name used for the set of blocks that store all operations) is immutable (too expensive to convince the 51% of blockchain nodes to recalculate). Also, authors in [36], [68]–[70] extend this meaning by including the main objective of PoW when creating a new block, is to solve a computationally costly cryptographic puzzle with computing power which is challenging to solve but easy to verify (*mining*). After this process, the first node to solve this puzzle receives a reward (*fee*) as compensation. Once mined and paid for, the solution is attached to the new block and transmitted over the network.



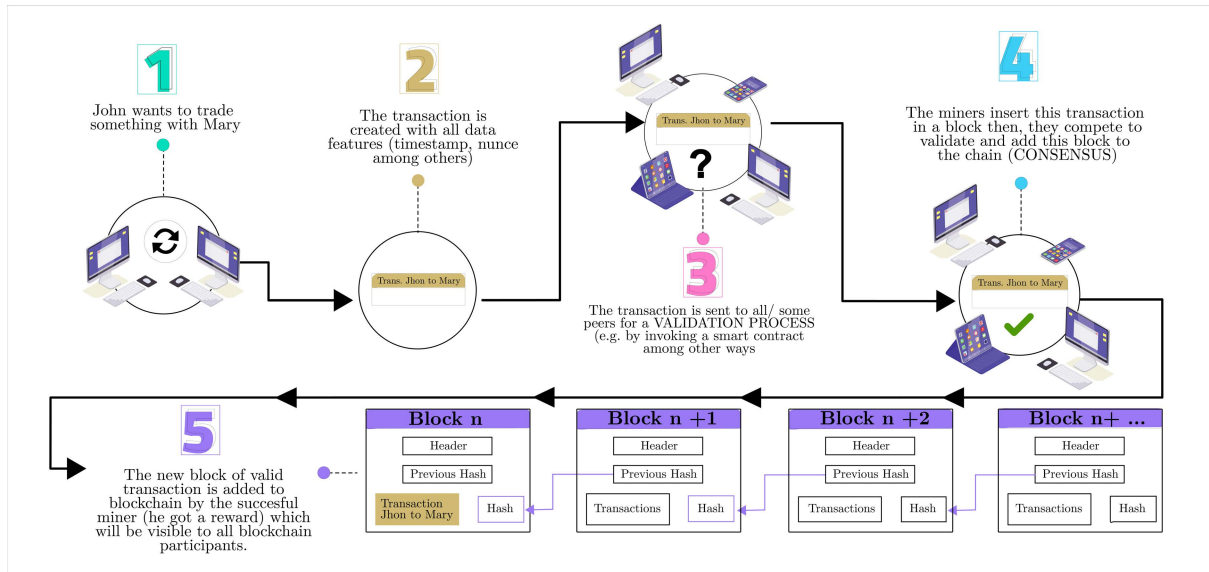


FIGURE 3. How the blockchain with validation and consensus mechanism works.

2) PROOF OF STAKE (PoS)

The Proof-of-Stake is the most popular consensus mechanism or algorithm alternative to PoW. This method is oriented to solve PoW issues related to scalability and security. The algorithm randomly selects the nodes that will validate the creation of new blocks. The probability of a node being chosen is proportional to the assets balance (or longevity) that the node has. Other authors [36], [64], [69]–[73] indicate that the algorithm requires far fewer CPU computations and energy for mining instead of running a high computational puzzle-solving effort that PoW involves.

3) DELEGATED PROOF OF STAKE (DPoS)

This is a PoS consensus mechanism variant, which is designed for a highly scalable blockchain. The implementation of this protocol offers Byzantine Fault Tolerance (BFT). It provides high levels of security in public blockchains (that is highly desirable in decentralized energy systems). The mechanism of DPoS is based on all the network peers vote for some “delegates” nodes, which rotate amongst themselves so that each one can produce a block and collect a reward for it [72], [74], [75]. It provides the network with lower power consumption, faster transaction creation and validation, and high tolerance to tampering attempts [76].

4) PROOF OF AUTHORITY (PoA)

The Proof-of-Authority is another BFT-based consensus algorithm that is designed as a practical and efficient solution (lower energy consumption compared to PoW and PoS) [23], especially aimed at private and permissioned blockchains (i.e., limited participation, and restricted rights to validate transactions with fault tolerance). PoA takes advantage of real identities to allow validation within a blockchain system. That means, the authenticators (called *authorities* in this algorithm) put their real identity and reputation as transparency

guarantee in order to distribute the responsibility of creating new blocks [77].

5) PRACTICAL BYZANTINE FAULT TOLERANCE (PBFT)

The Practical Byzantine Fault tolerance is a consensus mechanism dedicated to replicating state machines that tolerate the presence of blockchain malicious nodes (i.e., independent node failures or attacker nodes in the network sending out misleading information). Essentially, these nodes communicate with each other with ordering, where all honest nodes (at least two-thirds or 66% or  $3f + 1$  nodes, where  $f$  is the number of faulty nodes or data) in the network agreed (voting-based) on the blockchain status (creation and reception of blocks) [40], [69], [78].

6) PROOF OF CAPACITY (PoC)

The PoC algorithm (also known as Proof-of-Space) is a particular consensus mechanism since it allows miners to use available hard disk space instead of computational power (PoW) or coins number (PoS), for the transaction deployment (divided in two phases: hard disk plotting with Shabal instead of SHA-256 as encryption algorithm, and mining) [79], [80]. Thus, this consensus mechanism emerged as an alternative to the high energy consumption of PoW as well as the PoS crypto-assets maintenance.

In order to display similarities and differences between these algorithms and show some examples of DER management and integration applications or projects that implement them, a comparison of the above discussed consensus algorithms - based on [81] - is presented in Table 2.

7) IMPACT OF CONSENSUS MECHANISMS ON DER INTEGRATION AND MANAGEMENT

Driven by advances in blockchain technology and the widespread use of DER, different development teams of

**TABLE 2. Consensus algorithms in DER management and integration.**

FEATURE	PoW	PoS	DPoS	PoA	PBFT	PoC
Type of blockchain	Permissionless	Both	Both	Both	Permissioned	Both
Energy consumption	High	Moderate	Low	Low	Moderate	Moderate
Scalability	Strong	Strong	Strong	Strong	Weak	Strong
Reward	Yes	Yes	Yes	Yes	No	Yes
Hardware dependency	Yes	No	No	No	No	Yes
Computational cost	High	Moderate	Low	Moderate	High	Moderate
Transaction fees	Yes	Yes	Yes	Yes	No	Yes
Block creation speed	Low	High	High	High	High	Moderate
Decentralization Level	High	Medium	Medium	Low	High	Moderate
DER management and integration applications/projects	Power Ledger [82]–[85] Evertly [35], [94] Grid+ [96], [109], [110]	SolarCoin [86] Energolabs [95], [96] NRGCoin [111]–[113]	EnLedger [87] Sun Exchange [97]–[100]	GridSingularity [88], [89] Slock.it [101]–[103] Share&Charge [114]–[116]	SunChain [90] LO3 Energy [104]–[106] Tennet & Sonnen [117], [118]	Pylon Network [91]–[93] Chia Network [107], [108]

stakeholders (e.g., utility companies, project pilots, among others) have explored the feasibility of using blockchain technology to manage and integrate these resources from different perspectives [119]–[121]. In this sense, it has been possible to demonstrate the great impact of consensus mechanisms for these tasks.

Firstly, consensus mechanisms with a higher degree of maturity such as PoW and PoS (which are highly scalable, flexible and with low latency) have great influence in digitization and decentralization of DER-associated energy, since they are used in a wide range of applications (e.g., decentralized energy trading, policy or contract terms execution, EV management, among others). These are especially true in the use of devices and enabling technologies for local DER integration and management such as AMI and IoT. However, these mechanisms (especially PoW) present a substantial energy consumption that goes against the objective of sustainability that DERs pursue. Nevertheless, the associated benefits often outweigh the detriments caused by this side effect.

Therefore, other consensus mechanisms (i.e. BFT-based, PoA, PoC, among others) have appeared as an alternative to more specific approaches related to DER management and integration (for enterprise environment, higher security and limited access, lower energy consumption, and task-oriented). However, it also means that in the short-term, there is no unified criteria for the operation of these DER blockchain-based systems, which may negatively impact their coordinated large-scale implementation.

Thus, the consensus mechanisms choice is highly correlated with the use case that has different requirements for performance, latency, security, scalability, environment, privacy, etc. [23], and likewise this indicates the leverage that this will have on the overall performance of the DER-centric system where it is applied.

### III. DER INTEGRATION AND MANAGEMENT THROUGH BLOCKCHAIN

Considering the decentralization trend that energy systems currently show due to DER joining and advances in related

areas (i.e., market, technical, policies, among others), activities such as the integration and management of these resources have acquired more importance. This situation has led to the development of different approaches that could perform these tasks, according to the current system topology features (voltage levels, leveraging the current infrastructure), the number of potential users and the coordination that could exist between them. Therefore, this section presents under which DER management and integration paradigms, blockchain technology has contributed significantly. On the other hand, the role of ICT in the development of these paradigms is also emphasized.

#### A. ICT ROLE

As a result of the different advances associated with various cross-cutting trends related to the widespread use of DER (i.e., the 3Ds: decarbonization, digitalization and decentralization trends) coupled with ongoing efforts in different areas (e.g., new devices, systems, and approaches), there has been a deep and seamless integration between energy technology and ICTs, where the latter led by blockchain (or energy blockchain) have delivered features for the proper functioning of decentralized systems that have been developed: privacy, security, transparency, reliability, interoperability, and flexibility. Thus, advanced metering infrastructures as the main exponent of energy-focused ICTs, and due to their capabilities such as enabling real-time communication between consumers and producers, measuring and storing electricity-related data with high resolution, easy combination with other ICT-based solutions (including blockchain), remote management of available energy resources, among others, have become the most important component of this energy-ICT integration [122]. Therefore, the adoption of these ICT-based solutions has led to a significant positive impact on the power systems operation, mainly a more efficient management and control of the available energy resources [123], [124] considering the inclusion of DER as generation assets in energy markets, which highlights the role of these technologies in energy systems road map in the near future [125].

## B. DER INTEGRATION AND MANAGEMENT PARADIGMS

As a result of the breadth of the potential benefits of DERs in power systems (i.e., reducing the cost of electricity and grid dependence, providing ancillary services, grid operation upgrading, among others) as well as negative impacts to mitigate (uncertainty, variability, frequency instability scenarios, among others), different paradigms have been developed to integrate and manage them properly. Based on the classification presented in [43], these paradigms fall into three main groups: *individual, coordinated, and decentralized paradigms*.

### 1) INDIVIDUAL PARADIGMS

The individual paradigms group automated single energy management systems that aim to minimize their cost through the proper management of their resources (i.e., distributed generation, energy storage, demand response) without considering the grid or their neighbors in order to be grouped or coordinated. Examples include mainly home energy management systems (HEMS) and their variations, where service constraints are usually considered.

In this sense, blockchain has mainly contributed as a secure, private and brokerless way of linking these systems to the other paradigms mentioned above, where individual energy management has been combined with different market mechanisms and interaction with other users [19], [126]–[128], in order to mitigate different drawbacks related (e.g., privacy, security, high consumption costs, communication, maximizing self-consumption, among others). Therefore, this technology for this paradigm has not yet had as much relevance compared to the others presented in this paper.

### 2) COORDINATED PARADIGMS

The coordinated paradigms, on the other hand, present a more cooperative scope, since they have the potential to orchestrate through an intermediary planning entity (i.e., community manager or aggregator) the operation of the DERs of several users for their joint benefit. This joint DER operation is allowed by changes in generation and consumption patterns usually driven by price changes, usually under an optimization problem context. Likewise, this management and integration paradigm is very appealing, due to the different economic incentives offering. Some of the most important representatives of this paradigm are the virtual power plants (VPP), and the different OPF-based aggregation schemes (e.g. local energy communities, microgrids, multi-energy systems, among others).

For this case and unlike the individual paradigm, Blockchain technology has had a greater relevance in this field. This is due to the high compatibility between the topology of this type of network and an interconnected energy scheme. Therefore, the range of areas and applications that have been developed under this paradigm are more extensive: transactive energy (or coordinated and bi-directional

energy trading between nodes or users) [129], [130], energy management and scheduling [119], [131]–[133], EV integration [134]–[136], among several others.

### 3) DECENTRALIZED PARADIGMS

This decentralization paradigm is not directly associated with operating in a coordinated (or aggregated) or individual basis. Actually, it aims to take better advantage of DERs and their most important features through the establishment of decentralized energy markets. Thus, this type of market is oriented on the peer-to-peer (P2P) approach. Here, users or nodes can adopt the role of buyers or sellers according to their situation in an energy market, in order to trade surplus electricity between them directly through a multi-layer structure (i.e. bi-directional energy flows, information and economic transactions in separate operational layers working at the same time).

On the other hand, it is important to highlight that this decentralization paradigm can also work in an aggregated or coordinated way. In fact, these synergies have created hybrid approaches such as the presented in [137] (i.e., community-based P2P and hybrid P2P energy markets), in order to leverage the operational (compatibility with existing infrastructure, scalability), economic and social benefits that these systems bring. Some studies such as those presented in [30], [138]–[140], provide evidence of these relationships.

Hence, for this paradigm, blockchain technology has had the greatest influence among those presented. This is especially due to the existence of greater compatibility according to the required structure and blockchain operation (i.e., peer-to-peer). Like in the coordinated paradigm, the areas and developments in this case have been diverse: energy trading [141]–[143], energy crowdsourcing [144], demand side management [145]–[147], among others.

### a: SUMMARY

In this section, we have presented a DER Integration and management paradigms where blockchain can contribute meaningfully. Here it can be evidenced that the approaches where the blockchain technology can have the most significant and diverse impact, coincide directly with the aggregation approaches paradigm (i.e. where a common benefit is prioritized, whether centralized or decentralized), where ICT plays a fundamental role since it is the basis for the features that allow the development, evolution and efficient operation of these infrastructures, in particular, the advanced metering equipment required for its expansion.

## IV. BLOCKCHAIN APPLICATION IN DISTRIBUTED ENERGY RESOURCES INTEGRATION AND MANAGEMENT

In this section, we will emphasize the blockchain technology contributions for DER integration and management by presenting several recent applications and perspectives.

### A. ADVANCED METERING INFRASTRUCTURE

With the Advanced Metering Infrastructure (AMI), the utility companies, consumers, prosumers, and producers can

interact through the two-way communication supported by smart meters. In comparison with traditional energy meters, they can collect energy information from their owners. All this data is used for billing, control, troubleshooting, and monitoring purposes. Moreover, all this data is stored in centralized storage systems or clouds. The use of these centralized points involves potential risks of information tampering and privacy issues (i.e., identities, contact info, energy use, consumption patterns, among others), in addition to scalability and response time issues. Thus, generators and consumers still find it challenging to rely on these infrastructures. In this subsection, we summarize some of the most critical blockchain studies to address these AMI issues.

The works in [148]–[152] develop feasible applications and studies related with AMI for DER management and integration. Specifically, the authors in [148] propose a flexible, efficient, secure, and trustworthy blockchain-based access control scheme with Ethereum smart contracts (as a broker) in order to manage permissions in a distributed and reliable way. The architecture was designed in Ropsten, an official Ethereum test network, where the results confirmed that this mechanism increases the security, flexibility, efficiency, and at low cost, developing a promising solution to mitigate cyber-attacks in smart grids. This provides an interesting contribution, considering that DER are connected to these systems.

In [149] a model is introduced to explore the blockchain with smart contracts for smart grids resiliency and security. The contracts act as a broker between consumers and prosumers in order to reduce procedure costs. Once the smart meters (AMI) are connected to the blockchain system, they send a record to create a new block with a timestamp for later validation. The consumer will be charged based on the information registered in the ledger system. However, the lack of discussion in technical terms of the subject has limited the progress of this work.

Plaza et al [150], has presented a system where a smart metering infrastructure is leveraged as a secure entity for energy data trading and community governance. In addition, a blockchain-based approach is proposed for energy exchange between local energy community (LEC) members with PV power generation.

On the other hand, in [151], a model of demand-side management is introduced to decentralize smart grids. The blockchain is used to create a secure, automated and decentralized energy grid where all these nodes work independently, without the need for centralized supervision or system operator control. Additionally, it is used to store energy consumption information obtained from the smart meters integrated into the system. On the other hand, intelligent contracts offer control to validate agreements, calculate incentives or fines, and apply the rules associated with the supply and demand balance.

Meanwhile, [152] introduces a secure and reliable energy scheduling model called PPES (Privacy-Preserving Energy Scheduling) for energy service companies (ESCOs). Through

blockchain and smart contracts, they address the growing privacy concerns of centralized ESCOs, which can encompass financial and behavioral information that would cause privacy issues (data security from AMI and trading) for the distributed energy market. They used a distributed optimization method to decompose the model into several individual problems to be solved with consensus algorithms and smart contracts, and probed in several case studies based on multiple energy buses.

In addition to the presented studies and projects, blockchain technology has impacted on other AMI issues, being crucial in DER management and integration tasks. Some of these fields are: IoT and blockchain deployment, privacy and security issues, AMI as an energy trading interface, smart metering and management, and artificial intelligence (AI) as well as smart city applications.

## B. ELECTRIC VEHICLES

Electric vehicles (EVs) are considered as one of the main pillars of the recent energy sector development [153]. They can act as energy storage devices as well as trade energy with the power grid, charging stations and other neighboring EVs on a P2P basis [36]. Nonetheless, frequent two-way power and data communications within three possible interaction scenarios (i.e., Vehicle to Vehicle, Vehicle to Grid, and Grid to Vehicle), the short communications range, and mobility can introduce some security and privacy issues [154]. Thus, it is crucial to develop decentralized and transparent EV management and integration mechanisms. To develop such mechanisms, some of the most important contributions of intellectual production are as follows.

In this area, references [155]–[159] present possible studies related to electric vehicles fitting to blockchain environments. In [155], the authors focused on the smart contracts development empowered in permissioned blockchain systems in order to implement an EV charging framework with RES on smart grids. To deploy these contracts, an innovative energy distribution algorithm was used. Such contracts are made between energy aggregators and EVs so that they are allowed to choose the energy consumption source according to each user preference while maximizing profits. On the other hand, the energy distribution method was introduced to locate the limited energies of RES (solar PV) in EVs. However, the consensus method employed does not yet clarify the responsibility for validating transactions or incentives.

In [156], the work proposed how to store and validate EV charging-related data in blockchain and how to process EV charging payment transactions in a blockchain-based information system. Within the ongoing research activity, they evaluated some blockchain technologies regarding their applicability for this scenario. Further, they implemented a decentralized app (dApp) design and its smart contracts as a proof-of-concept for the technical feasibility of the solution, considering factors such as interoperability, data storage, trust and scalability, showing good results on simulation scenarios.

Moreover, [157] introduces a method of conserving privacy in a transparent and self-contained manner that allows



EVs to find the cheapest and most viable charging stations based on energy prices and distances. This method uses blockchain when a request for supply is made for a specific energy level, where the identity of the vehicle (geographic location) is preserved and verification of the requests is increased, in order to ensuring transparency. In addition, the charging stations as an integration and management entity are also connected to the blockchain where they keep their offer records according to the requests. This method does not yet discuss the scalability of the proposal or the payment method through blockchain.

Furthermore, the authors in [158] presented a blockchain-based model for EV charging. This model incorporates smart contracts to implement the registration, scheduling, authentication and charging phases of a vehicle at a charging station. A security analysis is presented where the results show that the model meets the established objectives.

Another development under this trend is the one presented in [160], where the focus is on the infrastructure needed to charge electric vehicles, specifically the private charging piles and their corresponding operational issues. A blockchain-based framework is proposed to facilitate secure energy sharing services with cryptocurrency from a technical perspective based on the consensus mechanism performance. All operative scenarios were evaluated through game-theory approaches (joint coalition-matching game), where it was determined that this approach improves the efficiency of these charging piles. A similar approach is presented in the development presented in [161], where a novel energy blockchain system with license was realized to implement secure energy supply services for electric vehicles and charging stations, including the consensus mechanism and incentive scheme for their operation (i.e., charging and discharging tasks). The results evidenced that the proposed scheme can efficiently allocate produced energy resources to various zones with different electric loads through the movement of electric vehicles.

In addition to the presented studies and projects, blockchain technology has generated great impact on other areas of EV development, being crucial in DER management and integration. Some of these fields are: Smart charging and EV battery management, privacy and security issues, EV in VPP and crypto-currency paradigms, EV as energy trading asset, and AI as well as smart city applications.

### C. ENERGY TRADING AND MARKETS

The bi-directional energy and data flows feature allow consumers to act as producers and vice versa depending on the situation (i.e., prices, energy surplus, balancing supply and demand). DER integration and management are expected to organize an increasing number of consumers, producers, and prosumers (producer + consumer roles) with different types of DER into distributed energy trading scenarios in order to get some benefits as load peak shaving, power loss decrease, lower electricity prices, amongst others.

Therefore, it is necessary to perform energy trading integration along with its necessary formalities that can offer supply management, negotiation and the execution of contracts between the participants of a blockchain system. Thus, consumers and producers will be able to trade energy among themselves directly [36]. However, in traditional methods, the participants can only participate in these commercial formalities with each other indirectly through numerous third parties who experience some issues and challenges (e.g., introduction of operational costs transferred to end-users, appearance of non-competitive markets, lack of transparency and equity). In order to design a more decentralized open market and trading, the blockchain and smart contracts technology are used as discussed below.

The blockchain use for energy trading and market applications was first reported in 2014, where authors in [111], [112] introduced a virtual currency to appraise DER according to real-time metering information on production and consumption. However, existing literature does not present a comprehensive approach but focuses on specific features of blockchain-based energy markets, such as cryptocurrencies [162], [163], privacy and security [34], funding [164], optimization models [32], among others divisions. Some of the most important contributions of intellectual production are presented next.

Authors in [165] proposed a blockchain-based energy trading for EVs as an energy asset in smart parking lots. The platform architecture consists of two layers (physical and digital) that represent all the components of the system (charging stations, EVs, transformers, electric feeders, IoT devices). These components allow and support the operation of selling/buying energy among EVs (taking advantage of their dual roles of storage and consumption) in order to facilitate auditability and traceability of energy transactions. The proposed platform was implemented in Hyperledger Fabric, JavaScript and configured in Ubuntu OS. The platform provides profits for all participants and also balances energy using the electricity tariff provided by the DSO and local loads.

In [166], the authors provided a clear landscape, as well as details and technical procedures for the implementation of a pilot platform for blockchain-based P2P energy trading, considering each system node would be integrated with DER. They developed a platform connected to mobile apps as well as to different computer equipment (computers, smart meters), to execute smart contracts in Ethereum-based (tobalaba) networks, using tools such as NodeRed, Ionic, among other open-source technologies.

Under the same decentralization paradigm, some authors [137] have proposed designs for markets supporting multiple transactions between peers. In particular, the design of a full peer-to-peer market represents a challenge given the diversity and quantity of energy and services. The authors in [167] have developed a full design for a peer-to-peer market based on a multi-bilateral economic dispatch. A general formulation is presented in Eq. 1, based on [137]. This formulation expresses generation dispatch considering bilateral

transactions between peers. It is important to highlight that blockchain as an enabling technology does not include any special conditions in formulation, but it is highly correlated to the P2P paradigm.

$$\begin{aligned}
 & \min_D \sum_{n \in \Omega} C_n \cdot \left( \sum_{m \in \omega_n} P_{nm} \right) \\
 & \text{s.t. } P_n \leq \sum_{m \in \omega_n} P_{nm} \leq P_n \quad \forall n \in \Omega \\
 & \quad P_{nm} + P_{mn} = 0 \quad \forall (n, m) \in (\Omega, \omega_n) \\
 & \quad P_{mn} \geq 0 \quad \forall (n, m) \in (\Omega_p, \omega_n) \\
 & \quad P_{mn} \geq 0 \quad \forall (n, m) \in (\Omega_c, \omega_n)
 \end{aligned} \quad (1)$$

where, the function  $C_n$  corresponds to the production cost and  $P_{nm}$  corresponds to the transaction either sale or purchase between peers  $n$  and  $m$ . The set  $\omega_n$  corresponds to all transactions done between peers. On the other hand, the sets  $\Omega_c$  and  $\Omega_p$  represent the consumer and producer nodes respectively. The power transactions  $P_{nm}$  and  $P_{mn}$  are equal but with opposite signs. The mathematical techniques to solve this problem includes decentralized or distributed optimization techniques such as developed in [168] and [169]. Therefore, the blockchain integrated into markets based on transactions between peers or agents represents a potential for full deployment of DER integration and management related tasks (e.g., planning, scheduling, among others).

On the other hand, inspired by energy transition trends, in [170] a breakthrough P2P energy trading scheme was proposed under the Virtual Power Plant approach using smart contracts on the blockchain Ethereum platform. P2P energy trading is a recent trend with several test projects among the power and energy societies; it facilitates the RES generation and trading in a distributed way within the local community. This scheme is based on public blockchain systems and the auctions are operated by smart contracts addressing both safety and cost issues. The implementation and execution of the smart contract in a VPP framework, including the bidding, withdrawal and development of control modules are the main features of this work.

#### D. ENERGY CROWDFUNDING

Since the scaling up of small and medium sized renewables, there have been big issues in reducing the capital cost of investment that end-users must bear to access DER-related devices. This is because the capital expenditures of renewable technologies are higher than conventional generation assets, even if there are no associated fuel costs. This high capital cost also carries the penalty of higher financing costs, which makes the cost of capital more critical to the economic competitiveness of renewables and their widespread adoption. On the other hand, the number of brokers and requirements for accessing possible funding sources to acquire these devices, make it difficult for many end-users to become interested in acquiring DERs.

These situations has led to the development of different studies and initiatives based on blockchain, using concepts

such as decentralized finance (DeFi) to facilitate DER access and management to end-users collectively through methods such as crowdfunding. Below are some relevant studies related to this section.

References [164], [171]–[173] developed feasible applications and studies related with crowdfunding for DER integration and management. Authors in [171] propose and evaluate a blockchain-enabled crowdfunding financing option for investments in residential PV assets to further decrease LCOE values, in order to make solar PV more competitive in terms of economic viability. the findings of this study evidence that blockchain, have a positive impact in terms of reducing the financial costs and also the LCOE values of residential solar projects, which may represent a greater adoption of this resource on a small scale.

In [172], the levelized cost of residential-scale lithium-ion battery storage using blockchain-based crowdfunding is evaluated and compared to conventional financing. As a result, a tool is developed that allows multiple smaller stakeholders to offer loans with longer terms and lower interest rates, which will enable partial digital ownership of such investments and provide additional incentives for the rapid deployment and effective management of energy storage solutions.

On the other hand, entrepreneurial efforts such as those presented in [164], [173]–[175] have developed disruptive financing models that use a tool for crowd-funding small and medium-scale solar PV energy projects, eliminating the layers of intermediaries between financing and energy consumption. This tool is especially geared towards individuals who wish to use their resources to promote community development and renewable energy projects.

#### E. DECENTRALIZED ENERGY MANAGEMENT

The massive incursion of DER has a significantly disruptive and transforming impact on the centralized power system with unidirectional power flow that is currently in place. It is widely accepted by academia and the energy sector that a shift to a decentralized power system with bi-directional power flow is necessary for the integration of these resources [30], [54].

Due to this transformation scenario, it has become important to develop tools, frameworks, and methodologies for the proper management of DERs given their uncertainty, variability, and operational characteristics, in addition to the transitional environment facing the sector mentioned above. This management aims to facilitate a rich set of transactional energy activities between residential users with renewable energy, energy storage and flexible loads. It is also intended to guarantee reliability and efficiency, as is the case in the centralized energy approach.

Therefore, this section shows some developments in DER energy management, especially with a decentralized approach. It is important to mention that a large number of contributions have addressed how to manage DER for various objectives (e.g., energy trading, security, aggregation).

Authors in [119] developed a reliable decentralized management system for DERs using blockchain technology and smart contracts in order to integrate them to aggregators. For this purpose, several DERs were modeled and formulated a cost minimization problem for them in order to optimize their energy trading, scheduling and demand response.

Moreover, [176] proposed an integrated energy management and aggregation platform based on blockchain and smart contracts that optimizes energy flows (i.e. OPF) in a microgrid with different DERs while implementing a bilateral trading mechanism. The results evidence an increase in power grid independence by reducing imported power.

Overall, many of the developments in this field are oriented towards coordinated approaches (i.e. to proper management of DERs for the joint benefit of the end-users and the aggregator or DSO), in particular blockchain-based virtual power plants (VPPs) and smart grids (SGs) [177]. Therefore, some VPP-based developments such as those presented in [30], [178]–[182] and smart grid-based developments as [151], [183]–[185] show a high degree of adoption of both approaches in the proper management of DER from different levels (operational, financial, security, among other fields), due to these approaches are aimed at contributing to the process of decentralization of the electricity grids through interaction with the existing infrastructure, always prioritizing the economic and social benefits represented by DERs.

#### *b: SUMMARY*

In this section, we have presented a number of recent blockchain pilots, developments and entrepreneurial efforts for DER integration and management. This section has been divided into five subsections according to the different purposes that blockchain has been used for: Energy management, Electric vehicles, Advanced metering, Energy crowdfunding, and Energy markets and Trading, where it has become evident that efforts have been directed to this last area from different and unique perspectives, in order to provide an economically and technically efficient management of these resources. However, the main drawback in all these blockchain-based developments regardless of its purpose is scalability, since many of them are based on consensus mechanisms that present well-known transaction throughput issues such as PoW-based consensus mechanisms.

Besides the areas presented in this section, a comparison summary of some of the most important blockchain-based projects, pilots and applications related to DER management and integration are presented in Table 3. Considering the positive impact of business initiatives based on enabling technologies and approaches such as IoT through its concrete approach called IoE. and VPP, they have been included as divisions in this table.

## **V. OPPORTUNITIES AND CHALLENGES OF BLOCKCHAIN IN DER INTEGRATION AND MANAGEMENT**

Blockchain presents many promising opportunities and challenges for the DER integration and management. All

blockchain technology (i.e., smart contracts, consensus mechanism, among others) has made possible for different assets to communicate without the support or regulation of a broker or intermediary.

Nonetheless, blockchain-based systems depend heavily on predetermined rules during operation time, even though no such intermediary exists, so it is necessary to ensure that this system is reliable, secure, and accurate. On the other hand, blockchain technology is still in a growth phase, where it faces several disadvantages, threats, risk and limitations such as scalability, adoption of this technology by different actors, transactions speed, among others related to its implementation and some electricity sector features in particular. In this section, we present some of the challenges and the opportunities that this technology offers for these tasks.

### **A. CENTRALIZATION**

Currently, blockchain applications for the energy sector are in general still in the gestation stage, so it is still prone to attack from energy conglomerates that could exploit it for financial advantages [228]. Another reason for the existence of centralization is due to the architecture in the energy sector that is not yet adapted to the decentralized structure that a blockchain-based system requires [229]. This situation implies that a large investment is needed in multiple fields (e.g., technology, data flow, financial, among others) to migrate to an environment that allows interacting with this technology properly and avoid risky situations with reliable production, energy management, bad practices related to transactions, among others [40], [230].

Therefore, strict supervision must be applied under government laws as described in V-C, especially during the early stages, to ensure security and transparency in all areas. On the other hand, this situation also represents a great opportunity to create decentralized platforms additional to the financial infrastructure, where all the peers participating in the network share their computing capacity and thus avoid centralization and its issues. This development will allow an efficient operation and control of mechanisms that integrate and manage DER in power systems as well as providing other possibilities for the management of these type of systems [231].

### **B. TECHNICAL COMPLEXITY**

Currently, the implementation of blockchain-based designs presents great challenges due to different technical issues. The processes carried out with blockchain technology involve excessive energy and computational consumption to perform the validation and security processes required for transactions in these architectures [39], [232].

This situation can lead to scalability issues, as well as being against the energy sustainability principles that they promote. On the other hand, current early-stage blockchain designs are extremely difficult to develop, deploy and maintain. For the novice user (like most potential users interested in incorporating and managing DER), performing a blockchain transaction can become an obstacle, as it requires technical knowledge

**TABLE 3. Comparative summary of blockchain start-ups, applications and trials in DER integration and management in different areas: 1. Energy Crowdfunding, 2. Electric vehicles and storage, 3. Decentralized energy management, 4. Energy trading and markets, 5. IoT, 6. VPP.**

Blockchain App or project	References	Description	Area					
			1	2	3	4	5	6
ChargCoin	[153], [186]	Multi-layered digital ecosystem focused on EVs and charging stations using internet of energy (IoE), in order to manage and support energy and cryptocurrency trading.		✓		✓	✓	
CUBi	[187], [188]	Blockchain-based energy management platform that includes IoT (smart meter for DER integration) and AI in order to indicate enhancement opportunities.			✓		✓	
Dexentralize	[189]	Energy trading platform focused on self-consumption as well as massive micro-grid implementation in connected and off-grid areas.				✓		
Efforce	[190]–[192]	Blockchain-based energy management and saving trading platform in order to bring together clients and investors for the development of energy efficiency projects in buildings and remuneration in tokens.			✓	✓		
ElectronConnect (Electron)	[193]–[195]	Platform focused on decentralized markets development where different agents and energy assets trade across P2P.			✓	✓		
Enexis	[54], [196]	Prototyping IOTA-based cryptocurrency transactions for EV charging (currently with IBM consulting)		✓				
Energy Web Chain (EWC)	[197], [198]	Public and enterprise-grade blockchain-based platform designed for enabling any energy asset owned by any customer to participate in any energy market. Also includes a Cryptoasset (energy web token)				✓		
Enosi	[199]–[201]	Blockchain platform focused on smart metering and tracing for energy management and energy community services as well as decentralized markets.			✓	✓		
ETHome	[61], [202]	Open-source blockchain-based community energy proof of concept focused in the local power sharing control and interactions, especially with ESS.			✓	✓	✓	
FlexiDAO	[203], [204]	Blockchain-based platform specialized in the management and integration of DER assets at any scale as well as decision making, currently implemented in Iberdirola.			✓			
FOHAT	[187], [205]	Brazilian blockchain-based platform which integrates DERs and manages over-the-counter P2P energy trading and virtual power plants.			✓	✓	✓	✓
Greeneum	[110], [206]	Decentralized and multi-layer platform that use blockchain with machine learning algorithms in order to improve solar energy trading interactions.			✓	✓		
Grid+	[96], [109], [110]	Decentralized peer to peer energy trading platform focused on energy cutting and management.			✓	✓		
Lition	[207], [208]	Proprietary ethereum-based blockchain solution (in partnership with SAP) focused on P2P energy transactions between consumers and producers directly, avoiding all third-parties.			✓	✓		
LO3 Energy	[104]–[106]	Blockchain-based platform that operates the Brooklyn Microgrid, letting people to generate, store, buy and sell clean energy at local level. Since 2019, LO3 has been working with Kyocera to develop blockchain-based VPPs to enhance its services.		✓	✓		✓	✓
ME SOLShare	[209]–[211]	Blockchain-based power sharing platform focused in “swarm electrification” through AMI and the high availability of distributed generation in Bangladesh.			✓	✓	✓	
MyBit	[195], [212]	Blockchain-based crowdfunding platform that distributes the small-scale PV system ownership among owners. several owners	✓					
NRGCoin	[111]–[113]	Decentralized virtual currency and multi-layered digital ecosystem pilot focused on energy trading between prosumers				✓		
PowerLedger	[82], [84], [85]	Multi-layer blockchain-based platform focused on new energy markets enabling energy trading and flexibility services for communities.			✓	✓		✓
Power2Peer	[213]	Multi-layer and blockchain-based platform for P2P energy trading using local PV in order to bring local resilience to the grid.			✓	✓	✓	
Pylon Network	[91]–[93]	Energy blockchain platform where all energy transactions are stored in order to play the role of ICT and trading.		✓	✓			
Share & Charge (MotionWerk)	[114]–[116]	Blockchain-based platform for electric vehicle charging/discharging management and coordination for a better experience in Europe		✓			✓	
Solara	[214], [215]	Blockchain-based platform for secure solar energy data management in order to enable new financial models.			✓		✓	
SolarChange (SolarCoin)	[216]–[218]	Blockchain-based app suite that includes cryptocurrencies as an incentive for solar energy production and crowdfunding, as well as energy management features.	✓		✓			
Slock.it	[101]–[103]	Blockchain and IoT based platform focused on peer-to-peer sharing of IoT DER assets in cooperation with Energy Web Foundation.				✓	✓	
Synergy (Electrify Asia)	[219]–[221]	P2P energy trading platform using blockchain, connecting energy producers (or prosumers) and consumers directly across main grids.				✓		
Sun Exchange	[97]–[100]	Blockchain-based crowdfunding platform to fund PV installation which supply energy to public benefit buildings in South Africa (e.g hospitals, schools, among others).	✓					
Transactive Energy Initiative (Colombia)	[222]–[224]	Blockchain-based platform of DER transactive energy under pilot development focused on P2P trading and markets for energy communities in Medellín, developed by EIA together with UCL and ERCO.			✓	✓		
Unergy.io	[175]	Blockchain-based collaborative economy platform that enables secure crowdfunding to invest in or finance solar energy projects at any scale.	✓					
Verv VLUX	[201], [225]	Developing platform for p2p (private blockchain) energy trading at grid edge. Its focus is on local energy communities.				✓	✓	
WePower	[226], [227]	Blockchain-based green local energy trading (collaborative economy) platform through energy tokenization.	✓		✓			



and several sophisticated steps. This added to the standardization problem mentioned in section V-E, making the ICT systems too complex for the end-users who then avoid using them.

Therefore, it is necessary that the development of future blockchain-based applications adopt plug-and-play infrastructures that are more simpler and user-friendly to make a transaction (financial, data flows, etc.) more common among end-users. Likewise, in relation to the high computational and energy consumption of these systems, there is a long way to go in the development of specific and lighter consensus mechanisms for the unique dynamics of DER management aimed at lower energy consumption, while maintaining the privacy, security and decentralization standards required for these systems, and developing compatibility with enabling technologies such as IoT [233], VPP, among others.

On the other hand, it is crucial to move towards a more interconnected and technology-enabled smart grid. Currently, many companies in the energy sector are forced to manufacture their own smart meters, making it a gradual process that requires a sustained effort to install all the necessary devices (meters, poles, cables, among others) to facilitate inter-connectivity.

### C. POLICY SUPPORT

Energy applications for blockchain-based DER integration and management in many countries still suffer from several gray areas, which result in institutional [38], [234] and socioeconomic [235] consequences. There is a lack of information on potential distributed energy consumer markets as well as implementing restrictive energy markets, which would be valuable for the formation of an appropriate institutional and regulatory framework.

This situation has prompted regulators to support the active participation of users in energy markets, the creation of institutions, and well-defined laws that support DER integration and management. However, when it comes to substantial changes in the main power grid and the core business, these same entities do not yet support key issues for DER integration, such as direct energy trading and management between consumers or prosumers.

Therefore, precise legal definitions as well as well-defined regulatory and institutional frameworks are needed to mitigate the level of uncertainty associated with blockchain in this task. Thus, new types of agreements, market mechanisms, institutions, and policies must be introduced, in order to support DER integration and management including all stakeholders [236], which are currently heavily restricted due to the high risks that this technology can still represent [237]. In this way, although blockchain technology has shown great value in managing and integrating DER into the network (i.e., microgrids, electric vehicle management, among others) there is still great resistance to the adoption at regulatory level of this type of technology on a large scale.

### D. DEVELOPMENT COSTS

Blockchain technology development for DER integration and management requires high costs in order to restructure the current grid, upgrading the meters for the transactions with smart contracts. Investing in information and communication technologies is required for advanced metering interfaces in order to interact with these resources of conventional power grids in a hybrid way. All these costs keep the grid operators from investing in the blockchain deployment, opting instead for alternatives with a higher maturity degree and lower costs (e.g., telemetry).

However, the blockchain technology has passed several proof-of-concept phases that show its feasibility. For this reason, it must compete with more mature proposals in relation to its profitability and scalability. There is the possibility of reducing the cost of storage (one of the highest deployment costs for this technology) by storing the actual data in side chains (as a subsidiary blockchain) and operating the main blockchain as a control layer instead of a storage layer [41]. It is important to mention that it is necessary to focus on a lighter overall development of these systems (e.g., aggregators [30], IoT-based systems, among others), in order to reduce both transaction costs and physical device specifications needed to carry them out.

### E. STANDARDIZATION

A series of mechanisms, protocols and technological solutions are being developed for the power grid based on blockchain. However, the main challenge faced by these systems for integrating and managing DER is that it lacks widely-accepted standards due to the lack of maturity of this technology.

Ultimately, this situation prevents the integration of different devices as smart meters, IoT devices, electric cyber-physical systems, electric vehicles, and other entities related to the power grid [238], [239] as well as new issues related to utility operators and electricity markets [240]. However, this issue also represent a great opportunity for the development of standards/rules related to success cases that reflect good results (e.g., demand supply balance, forecasting grid requirements, self-adjusting power consumption, among others) and thus establish a road map for new developments in this area.

Thus, this development should be oriented towards creation of a safe, open and easily applicable framework, which together with other technologies and standards of quality (e.g. IEEE, IEC, among others) [241], [242] will give rise to holistic and applicable guidelines related to the DER integration and management considering all features that this process entails.

### c: SUMMARY

In this section the main challenges and opportunities related to the management and integration of DER through blockchain technology have been presented. It can be seen that great efforts must still be made in multiple fields in

a coordinated way, since few properly regulated sandboxes or pilots have been found that allow testing these developments in order to address these issues. Therefore, public policy in different countries should promote an expansion in blockchain-based developments in a fair way, with a joint objective and duly regulated along with technical development (i.e. to make the centralization of the energy sector more flexible from the regulatory and technological perspectives), where alternatives can be generated to reduce development costs, as well as the known problems of standardization and scalability according to the context of each place, so that these developments become viable both for business initiatives and new business models and for the communities that appropriate the DER from a decentralized approach.

## VI. DISCUSSION

An explanation of blockchain technology applied to DER integration and management is carried out in the previous sections. Based on the insights provided in Sections II, IV and V, it is evident that the blockchain contribution to the future development of DER integration and management could be very significant.

This is evidenced by the exponential increase and inclusion in recent years of different DER in small-scale distribution grids, as well as the growing number of projects and start-ups in the energy sector that are involved in projects with this technology as shown in Table 3. On the other hand, based on its own nature, blockchain technology in conjunction with other enabling technologies such as AI, IoT, VPP, among others, can improve the performance, efficiency and stability of the grid, considering DER variability, uncertainty and decentralization.

However, it is important to highlight that the transition cost to decentralization with special focus on power systems operation and markets, and corresponding blockchain implementation can be very high (due to the multi-layered nature of this process), but the benefits are numerous and will ultimately reduce electricity costs. By migrating to a decentralized, blockchain-based system, the following benefits could be available to the current electricity sector:

- Advanced support for DER integration and local energy management (metering and efficiency services).
- Flexible, sustainable, and secure energy trading without brokers.
- Real-time statistics on energy consumption patterns, generation prices, time-of-use pricing and suggestions on improving energy efficiency.
- Peak load shaving based on flexible and convenient hours of operation, as well as rewards (e.g., crypto-assets, energy credits or tokens) both locally and on a large scale.
- Extended support to ancillary energy infrastructures and services (e.g., city surveillance systems, street lighting, DR programs, EV charging stations, among others).

In addition to the aforementioned benefits, with the advancement in the energy sector digitization, DER management and integration processes have also improved with respect to reliability, availability, resilience, stability, security, and privacy [243]–[245]. The following paragraphs analyze the blockchain contribution in the enhancement of these features.

Availability, reliability and stability are the most critical features of the management of the grid and its resources (whether distributed or centralized). This is due to their increasing complexity in the modern energy sector, meeting the objectives of these features becomes more difficult. In this sense, blockchain technology in conjunction with tools such as smart grids, could provide a more complete control and monitoring of DER in power grids in order to solve the problems related to aggravated grid congestion, and DER uncertainty and variability [14], [246], [247].

The issues associated with security, privacy and resilience, derive from the P2P energy trading on the grid as an alternative for managing and integrating DER, even under unexpected disruptive events. The trust and transparency features of blockchain ensure that the data flow (i.e., financial and data flows) between peers is always secure and occurs through specific channels based on the agreement defined in mechanisms such as smart contracts contributing to an orderly management of available resources in order to provide data integrity and confidentiality.

Overall, the blockchain research revealed a greater scope in DER integration and management processes when it has been accompanied with other paradigms linked to coordinated and community-based aggregation schemes such as IoT, VPP, among others, in order to improve its features and effectiveness. Likewise, the fundamental role of ICT in the development of blockchain is evident, since it supports the operability, evolution, and future path of its development, where scalability, standardization of mechanisms, support at the policy level, and development costs are the main issues, where a joint effort at the level of regulation and technological progress is needed.

## VII. CONCLUSION

Blockchain technology in DER management and integration is a new and emerging area that has attracted attention due to its effects on power generation resilience. In this paper, a comprehensive review of the current blockchain landscape for DER management and integration is presented. First, the theoretical background of blockchain technology is presented. Next, some recent blockchain success cases (pilots, trials, and start-ups) in DER management and integration tasks are summarized. Finally, the opportunities and challenges of DER integration as well as blockchain features in order to understand the reasons for using it in these tasks are examined. This development together with other technologies has great applicability in DER mainstreaming and therefore in the energy transition process that the world needs to carry out.

According to the literature review performed, the following conclusions are presented in order to contribute to the blockchain development for the management and integration of DER:

- Blockchain technology is very promising for DER management and integration considering the different applications geared to this task. However, it is noted that blockchain technology is still at an early stage of development. This implies that deep changes are needed in a comprehensive way in relation to the infrastructure and technology of centralized power grids. Currently, there is no clear and standardized scheme within regulatory market and institutional frameworks to guide its deployment.
- Blockchain technology relies on the joint use of other technologies (e.g. IoT, AMI, AI, among others) and approaches such as VPP, smart grids, local energy communities, amongst others, to take full advantage of the utilities it can offer. However, there is no unified approach on how to implement these technologies in a coordinated fashion; currently this is occurring based on the environment of the DER-based application or system where it is deployed.
- One of the key research objectives for developing blockchain-based applications for DER management and integration is to incorporate flexibility in multiple fields (economic, operational and market) within the energy sector. Therefore, the future direction of research should focus on multidisciplinary efforts (regulatory, scientific, economic, market, among others) so that its contribution may be comprehensive, which may represent better results in the short to medium term.

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