Blockchain Applications In Smart-Grids: A Review

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ABSTRACT

With the advent of Blockchain (BC) technology, there is significant momentum to leverage the benefits of decentralization offered by BC and apply it in various disciplines, including medical, financial, identity authentication, asset management, etc. The application of BC in electrical energy grids is receiving considerable attention. Nonetheless, the rush to prioritize BC applications in energy trading (ET) aspects is masking its vast genuine potential. While the latter leaves many other fronts untapped, it provides new opportunities for BC applications in electrical energy systems that require further exploration. This paper reviews BC applications in four main smart grid (SG) areas, including Peer-to-Peer Energy Trading (P2P-ET). The limitations of the BC technology, hindering its immediate adoption in SG operations, are also discussed.

Keywords: Blockchain, Smart grids, Suitability-Evaluation-Framework.

1 Introduction

The technological and industrial revolution have led to an ever-increasing demand for electricity worldwide. However, the depleting/costly/unreliable (due to the political state of affairs) fossil fuel reserves were naturally pushing power companies to look for alternatives. Their thirst has been well-quenched by renewable energy sources (RES) in the last few decades. The advancement in Power Electronics helped in the smooth integration of RES with the grid and changed the unidirectional power flow of the traditional grid to bidirectional. Owing to the distributed and renewable generation, the consequent proliferation of Distributed Energy Resources (DER) has made the measurement and control structure of the conventional grid more complex. The advancements in information and communication technologies outpaced the challenges posed by this paradigm shift of the grid and gave rise to the concept of the Smart Grid. This idea was perceived to enhance the performance of traditional power grids in terms of reliability, scalability, resilience, cost efficiency, resource utilization, etc. From the generation through the transmission to the distribution level, extensive communications (control, measurement, trade etc.) are required between grid entities to realize the SG concept. Thus, the importance of a reliable communication infrastructure needs no justification. Single point of failure and higher cost of communication will be the main concern for the system if the aforementioned medium remains centralized. Therefore, a decentralized, immutable, transparent, secure, and efficient communication infrastructure can competently do the task.

With all those adjectives inherently embedded in its structure, the Blockchain comes into the picture. The idea, which was originally proposed in the early 90s and initially applied in digital currencies, looks promising for different aspects of SG. The boom of digital currencies in the last decade has unfortunately caged many researchers to exploit BC only in finance-related applications (such as energy trading), while there were many areas of SG that could have been linked with this technology. As such, in this paper, we have tried to review the applications of Blockchain in four different areas of SG without emphasizing any single one.

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Structurally, this paper has been divided into seven sections where sections II and III go with the brief introductions of smart grids and blockchains, respectively. Section IV concisely reviews the BC application in four main areas of SG. The challenges present in the immediate adoption of BC for SG have been emphasized in section V. The concluding remarks and relevant references are presented in sections VI and VIII, respectively.

2 Smart Grids

Leveraging the advancements in information and communication technologies for optimally utilizing DER in the grid, applying advanced protection and control strategies, enhancing the grid's resilience, allowing network reconfiguration, and automating the mutual payment settlements are the main ideas behind the smart grids [1]. In simpler words, we can argue that the smart grid is the upgrade of the traditional grid in terms of resilience, service quality, sophisticated control, resource utilization, and mutual trading by virtue of modern-day technologies. This upgrade makes unorthodox concepts like P2P-ET, grid automation, Electric vehicle charging/discharging, and cyber-security (for control and measurement signals) look feasible. The applications of BC in these unconventional attributes of SG will be discussed in section IV of this paper.

3 Blockchain

Blockchain is a digital distributed public ledger which can store transaction information. It has an Append-only link-list type structure where each new block has the address of the previous block. All the information in the single block is Hashed (a one-way encryption process) through some hashing algorithm, so a mutation in the older blocks becomes nearly impossible. Any new piece of information or block can be added to the BC once it has passed through some consensus mechanism involving participating nodes. Thus, that information can easily be trusted after becoming part of the chain.

3.1 Types of Blockchains

Depending upon the accessibility framework, BCs are classified into Public, Private, and Consortium blockchains. In the Public or permission-less BC, any public user can join, create, and validate the blocks in the network and update the ledger status by making transactions with other network entities [2]. It requires a PoW or Proof-of-Stakes (PoS) type consensus mechanism for reaching an agreement on the state of the BC. Contrarily, a centralized architecture in the Private or permissioned BC controls the transactional activities in that chain. That authority can control common nodes' joining capabilities and accessibility to the information, and their ability to make transactions [3]. Somewhere between two extremes, the Consortium BC lies, where the group of organizations maintains a distributed ledger instead of a single authority. The ledger-keeping authorities can control the Read/Write rights of the participants. Usually, it is suitable for scenarios where the group of companies forms a consortium for some common interest [4].

3.2 Suitability Evaluation Framework

With the dawn of BC technology, the question of applicability popped up naturally. There is a need to have some criteria for deciding whether BC applies to some specific application or not, depending upon the specific needs of that application. If yes, the next question is which type of BC would serve the purpose more efficiently. Researchers in Ref [5-9] tried to efficiently formulate the BC suitability frameworks to evaluate the justification of its usage. Ref [10] refined the previous frameworks by pointing out the areas where even the BC solutions are unavailable. After confronting some common questions posed by them, the authors of this paper have developed a refined version of the suitability evaluation framework, as depicted in Figure 1.

4 Blockchain in Smart Grids

The BC applications in the smart grids were broadly categorized in Power Generation, Transmission & Distribution, and Consumption domains by Ref [11]. However, that discussion lacks specificity from the application's perspective. Thus, the actual BC application can fall either entirely into a single domain or the overlapping of multiple domains. In this section, we will discuss the actual applications of BC in four specific areas of SG.

4.1 Grid Control and Operation

Smart or microgrid entities (i.e.) Dispatchers, Aggregators, and Prosumers must be managed efficiently for that grid's proper and profitable functioning. Mutual communication between these entities is an integral part of this management. Conventionally, one central authority (trusted by all the stakeholders) manages all the SG activities. Since BC provides the opportunity to establish a decentralized and trustable medium of communication, thus, researchers felt tempted to deploy BC in grid management, making this process autonomous.

The flexible nature of SG (in terms of network configuration, DGs availability, load demands, etc.) requires Flexible regulation for proper operation [12]. A consortium-BC-based Signcryption algorithm analyzes the multi-dimensional data and formulates the relevant control policies for different SG entities conveyed

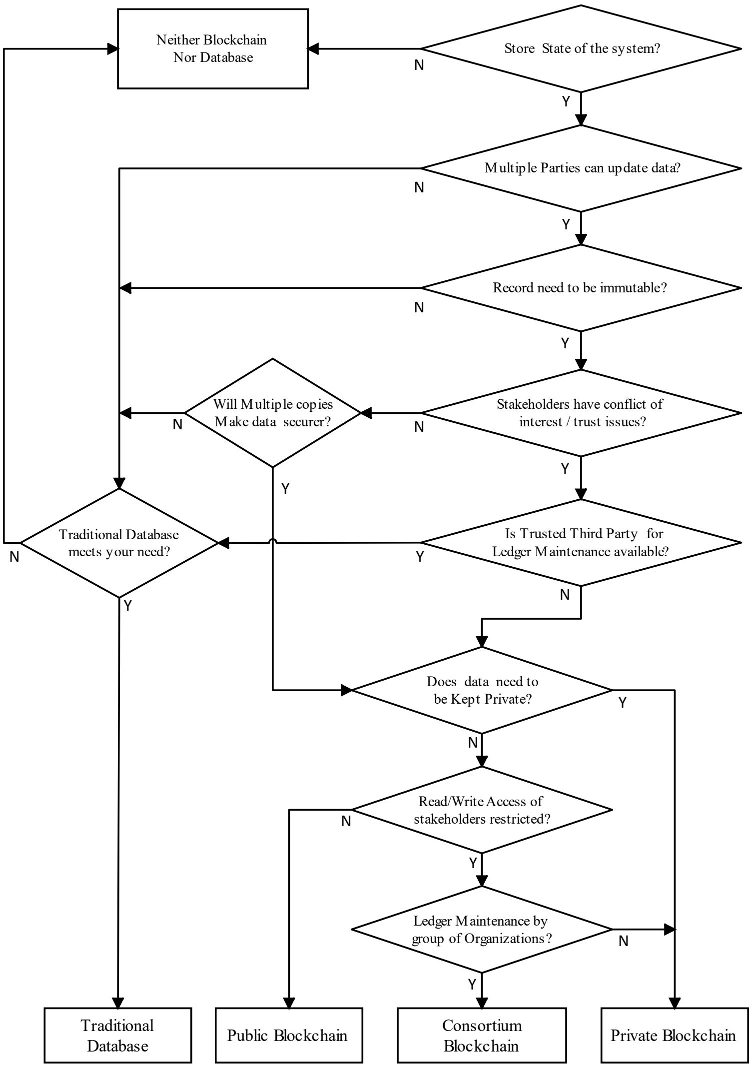

Figure 1: *BC Suitability Evaluation Framework*

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through smart contracts. With its vulnerabilities, SG usually operates in adversarial settings and is regulated based on estimated system states. The authors of Ref [13] have proposed a BC-based dynamic state estimation mechanism for wide-area SGs (composed of geographically separated subregions supervised by a local control center). All regional centres coordinate to perform trustable state estimation in a decentralized manner.

The employment of BC for solving Economic Dispatch (ED) problems for DGs was investigated in Ref [14]. A distributed algorithm for solving the ED problem was developed, which uses an Alternating Direction Method of Multipliers (ADMM) - based decomposition.

Ref [15] proposed a BC-based virtual-power-plant control system and adopted the distributed edge calculation to improve the calculation efficiency. A theory-based game technique can perform the demand–response management in P2P-ET, involving the active energy suppliers (modelled through two non-cooperative games) [16]. The purported strategy significantly reduces the net peak load, especially with the off-chain processing mode. Smart devices (like smart meters, grid protection devices, etc.) play a crucial role in the safe operation of SG. A consortium-BC-based equipment analysis method can realize the decentralized, trustable, secure, and efficient maintenance of such devices [17].

4.2 Energy Trading

One way to deal with the excess renewable energy generation is to sell it back to the utility grid through Net metering. With decentralization, prosumers can transact such energy to individual customers without utility intervention, termed P2P-ET. As such, a BC-based transactive platform for energy exchange is presented in [18], whose ET algorithm incentivizes prosumers and achieves the socially optimal solution by lowering the operational cost of every participant. Mutual trading preferences of peers in the local energy market are an important aspect and can be determined through two approaches (i.e.) the demand-supply gap of the participants and the mutual distance between them in the network [19]. Synergy Chain, a BC-assisted adaptive model, can improve the scalability and decentralization of the prosumer grouping process as Ref [20] purported that the coalition of multiple energy prosumers outperforms the individual prosumer's participation in the energy market. The Credit management system (which penalizes users with bad credit) in the BC environment can minimize the users' default behaviours during the trading mechanism [21]. Furthermore, Ref [22] talks about Energy Sharing, which differs from energy trading as it involves the energy exchange among the prosumers and consumers in return for future benefits.

A sensitivity analysis-based methodology can check for the instances of electrical network constraint violations (i.e.) voltage and capacity, and allow only those transactions that fall within the allowed limits [23]. DeepCoin is a deep learning and BC-based ET framework for preventing SG attacks [24]. This intrusion detection system (IDS) can detect network attacks and deceptive transactions by employing Recurrent Neural Networks.

4.3 Electric Vehicle (EV) Charging

Integrating Electric Vehicles (Dynamic or Static) into the utility grid (from the perspective of charging/discharging) is a bit of concern for the researchers as it poses a significant impact on the electrical network in terms of congestion, smooth operation, and resilience (to name a few). The simultaneous charging of multiple EVs will lead to the overloading of the utility network, while the stress on the grid can be reduced by discharging stationary EVs. The critical aspects of the efficient charging/discharging mechanism are the proper scheduling and coordination among the EVs and charging stations. The researchers felt persuaded to leverage BC's decentralized and privacy-protected attributes to address these issues.

Ref [25] proposed a model in which Charging stations (CS) broadcast their slot availability through Road-Side-Units (RSUs). EVs select the suitable CS (by solving a decision optimization problem) and locks the final agreement through Smart Contracts. A charging-station-to-vehicle (CS2V) and vehicle-to-vehicle (V2V) ET scheme can use a BC-based payment system while preserving EV drivers' privacy [26]. The Sybil attacks-resistant scheme could avoid powerful attacks, such as Denial of Service and threatening service availability. The record maintenance of all energy transactions happening between EVs, Charging Stations (CS), and utility centers (UC) in the Vehicle-To-Grid (V2G) network can be done by employing BC [27]. A Private Charging Pile (PCP) sharing framework in an energy BC environment can enhance the EV charging process efficiency [28]. By leveraging edge computing, and a reputation-based PoW consensus mechanism, the operational cost of establishing a BC among resource-limited EVs and PCPs can be reduced. A prioritization ranking algorithm for EV drivers (based on driving and charging behaviors) and a BC-based incentive system can reduce the overall burden on the utility grid and maximize RES utilization [29].

To address the limited driving range of electric vehicles (EVs) and promote EVs' penetration, vehicular energy networks (VENs) have emerged and opened the possibility of charging EVs in motion via dynamic wireless power transfer technology (DWPT) [30]. Ref [31] proposed the dynamic EV charging strategy in which the information sharing between the Charging Service providers (CSP) and EV is kept secured while the final payment settlement is done through Banking channels, contrary to the main idea of BC. Besides using the Proof of Reputation (PoR) consensus protocol in the energy BC, Ref [32] took DWPT to a new level by introducing an incentive model (based on a pricing mechanism) to stimulate EVs to cooperatively deliver RE to various areas with different electricity loads, maximizing EVs' utilities. Thus, CS with excess amount can transfer RE to the RE deficient CS by using EVs going through that way.

4.4 Cyber-Physical Systems

In Cyber-Physical Systems (CPS), devices (meant for performing technically useful tasks) interact with computing devices for the bidirectional exchange of operational, measurement, and directional information through sensors and actuators [33]. Computing nodes are meant to process the data from the sensing devices, while physical devices are supposed to act according to the directions received from the computing nodes. It is a closed-loop control structure that has a vast range of applications. BC (with the ability to decentralize such information flow) has room for application in CPS.

In the context of CPS, Trust is interpreted as the firm belief in the reliability and truth of data produced by those CPS devices. Ref [34] proposed to use BC as the trust enabling system component for Cyber-Physical Trust Systems (CPTS). The suggested approach can perform device identification, authentication, integrity, and non-repudiation and protects against prevalent attacks, such as replay and spoofing.

The inclusion of the IoT in the modern CPS (like autonomous driving) requires analyzing a considerable volume of data while maintaining accuracy and low latency. For efficiently analyzing such data, DeepBlockIoTNet applies the Deep Learning (DL) operation in a delocalized format via BC in the edge layer to get higher accuracy and lower latency than the other approaches [35].

Since CPSs produce substantial amounts of heterogeneous data from various sensing devices and networks, thus, they are naturally prone to cyber-attacks. Ref [36] comprehensively reviewed and classified techniques that make CPS and their data cyber-attacks resistant. Their employment and working principles were elaborated, including perturbation, authentication, machine learning (ML), cryptography, and BC.

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5 Challenges of BC Adoption in SG Operations

Technical aspects of the BC platform (like scalability, programming language, data storage limit, etc.) must be analyzed thoroughly prior to its utilization in a particular area. For instance, the BC platform with the fastest converging consensus algorithm should have been preferred for the time-sensitive application. As most of the available BC platforms are either specific for digital currencies or financial applications, the difference between them and SG applications should be well-considered before employing them to SG. The SG operations, like optimal load flow, network reconfiguration, protection, etc., require lengthy, rigorous, and time-sensitive calculations. Thus, any BC platform with slow scalability will be unfit for serving the purpose. Especially in the field of protection, where the corrective actions need to be done in micro or milliseconds, BC has yet to offer any viable solution. In some other SG operations, like grid dispatch, there is a trade-off between transparency and the system's security while applying BC. Transparency requires revealing the system's overall picture to all the generating nodes, which will make the security of the SG quite vulnerable. Contrarily, transparency issues will pop up if the SG's data is hidden from generating nodes.

The programming languages for creating smart contracts in BCs are specific and have limitations that create serious impediments in the mathematical operations and length of the code. Such as, Solidity is the only language allowed for programming Ethereum Smart Contracts, and it does not allow the use of fractional numbers. Contrarily, any load flow or optimal power flow calculation would involve fractional numbers. This architecture is understandable as Ethereum is meant for financial dealings, and the smallest transaction unit is GWEI which is equal to 10^{18} the part of Eth (Ethereum's digital currency). Thus, with this small transaction unit, they do not require fractional numbers. However, that is not the case with SG calculations. Then, the next challenge for creating any SG-related smart contract is the length of the code allowed per block of BC, owing to the Gas limit. The optimization codes are usually lengthy and exceed the block's gas limit, thus need to be segregated into different blocks. The communication between different sub-parts of the code can become worrisome, especially when such sub-parts are larger in numbers.

Lastly, utilizing digital currencies for the valuation of SG services or payment settlements will become problematic as the market values of cryptocurrencies are volatile. Therefore, the smart contracts governing those transactions must be updated regularly based on the actual and current market value. Moreover, using the already established BC networks for SG applications requires spending digital currencies per transaction. For the calculation-extensive applications, this solution may not remain financially viable. Thus, the customized BC architecture (for SG applications) with lower transaction costs will be better able to address all the stated issues.

6 Conclusion

Blockchain technology (BC) is a versatile tool that can provide flexible and distributed services in many disciplines. In particular, the immutable, decentralized, intermediary-less, secure, and stable inherent architecture of BC makes it suitable for trust less environments. After the successful demonstration of strength in the field of finance with Bitcoin, many possible applications of BC in medical, digital verification, energy trading, IoT, and many other fields were proposed in the literature. However, BC integration in SG was initially overshadowed by the P2P-ET aspect. This paper extensively described the potential implementation of BC into various new aspects of the smart grid (SG), including the propositions of BC applications in SG operations, cyber-physical security, EV charging, and Demand Response management. Furthermore, the challenges with the presently available BC architectures, from an SG perspective, that may complicate their smooth adoption in the proposed applications were highlighted.

7 Declarations

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7.2 Competing Interests

There is no conflict of interest.

7.3 Publisher's Note

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