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Blockchain in Consumer-Centric Electricity Markets: An Overview

Pedro Peters*, Ettore P. L. B. Aquino*, Diogo Barros Pinto*, Tiago Soares**, Bruno Dias*
*Federal University of Juiz de Fora, Juiz de Fora, 36036-900 Brazil
e-mail: {pedro.peters, ettore.aquino, diogo.barros}@engenharia.ufjf.br, bruno.dias@ufjf.edu.br
**INESC Technology and Science, (INESC TEC), 4200-465 Porto, Portugal - e-mail: tiago.a.soares@inesctec.pt

***Abstract*—The power and energy sector transition into decentralized and distributed models brings a set of challenges that need to be overcome. Among them is consumer empowerment, which requires secure economic transactions and reliable system operation. Thus, new technologies and procedures such as blockchain have gained prominence, due to their reliability and privacy-preserving capabilities. These characteristics are essential for the proliferation of energy community markets. Therefore, this paper provides an overview of blockchain technology applicability to consumer-centric electricity markets, highlighting existing projects and initiatives. Additionally, key enablers and barriers to blockchain deployment in local electricity markets are discussed, followed by a roadmap for the comprehensive adoption of such technology.**

***Index Terms*—Blockchain, Consumer Centric, Electricity Markets.**

I. Introduction

In light of the growing popularity of renewable energy resources (RES) and the expansion of energy markets to small consumers, many technological advancements have been made to further develop the electricity sector. Along these lines, measures such as the adoption of smart meters, and distributed generation control are extensively explored in the literature.

Among the many possible decisions to adjust the electricity sector to current trends, blockchain technology is seen as a possible solution to several problems. More precisely, it enables a greater degree of customization and interaction among energy producers and consumers, while ensuring the privacy of its members without jeopardizing the grid operation [1].

For the electricity markets, discussions in the area arise due to the growing penetration of RES and electricity consumer empowerment. That said, the remodelling of current electricity networks in a distributed fashion also instigates changes to the current energy market models. Due to the recent shifts in the power scales of electricity markets and the changes to the infrastructure that interconnects its players, consumer-centric market models that adopt a distributed organization tend to be favoured.

Having said that, many works in literature focus on the variations of blockchain technology [2], on the pros and cons associated to their implementation to the financial market [3] or simply on using blockchain as a solution to problems in the energy sector [4]. However, a thorough overview of all these aspects is seldom found among the papers. One of such thorough works offers a review on the three aforementioned topics along with an extensive list of existing projects which employ blockchain technology in the electricity sector [5].

Therefore, this paper offers a concise and well-founded analysis of the use of digital ledgers in consumer-centric markets, as well as the struggles related to their integration into the grid. To do so, the papers and projects reviewed are categorized according to their area of work and influence.

The approach used consists of an investigation based on a layered abstraction of each addressed system. These layers can be mainly defined as: *(i)* the *physical layer*, which is related to the actual grid responsible for the transmission and distribution of electricity, *(ii)* the *organizational layer*, which is responsible for the market designs and organization structures related to energy transactions among the system's participants, and *(iii)* the *informational layer*, which sustains the other layers with information on the whole system, contains data on the existing contracts and enables the creation of new contracts among the market players [6], [7].

The main contributions of this work towards consumer-centric energy markets and blockchain are as follows: (i) An overview of their combination focusing on the aspects that bridge the two concepts together and why a digital ledger approach is one of the technological candidates to support the digitization of power grids; (ii) A review of the main initiatives adopting distributed ledger technologies; (iii) A description and discussion about some of the current strengths and weaknesses related to the implementation of the combined technologies.

Regarding the structure of the article, Section II summarises the concept of blockchain technology. After that, Section III describes the design principles and the existing projects related to consumer-centric markets and blockchain. Section IV discusses about the some of the enablers and barriers commonly found on projects related to this topic. Furthermore, the section also highlights some of the inconsistencies and particularities related to the theme, as well as surveying some of the measures in order to adopt a consumer-centric market combined to a blockchain technology. Finally, Section V gathers the most important conclusions of this work.

II. Blockchain Technology

Created after a series of works published in the area of cryptography since the 1970s [2], blockchains are a form of distributed database that registers data related to transactions between two or more parties [3]. Distributed systems, such as blockchain, are part of a broader concept of systems design, where nodes interact with each other to achieve their objectives. Figure 1 illustrates the connections between parties under different system designs, namely, centralized, decentralized and distributed. The absence of centralization entities in the distributed system should be highlighted.

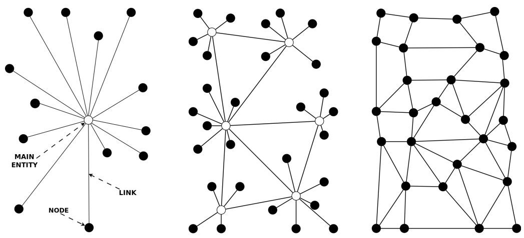

Figure 1. From left to right: centralized, decentralized, distributed system. Adapted from [3].

To ensure the safety and reliability of the process, the information blocks are linked to each other and are protected by cryptography. The linking of the blocks of data in a chain is shown in Figure 2. That aside, each blockchain architecture may possess its own: (i) *access policy* that determines the accessibility of the information contained within it; (ii) *control policy* that determines the prerequisites for the evolution of the blockchain and the annexation of new blocks; and (iii) *consensus policy* that is responsible for validating the blockchain state and solving disputes that may arise [2].

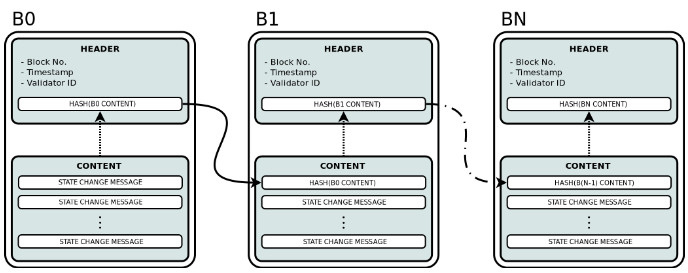

Figure 2. Diagram of chained data in a blockchain. Adapted from [4].

Therefore, blockchain can serve the purpose of increasing the rate of digitalization of distributed systems where transactions take place, such as in electricity markets. Trades among producers and consumers are ensured not only by the contracts, but also by the system's limitations, whether they are natural or agreed restrictions between peers.

III. Consumer-Centric Markets with Blockchains

The consumer-centric electricity market models can be classified into different organizations, along with relevant pros and cons [8], as well as integrated with network constraints [9] and coordination [10] where they are located.

A distributed consumer-centric organization, which focuses on the local electricity producers and consumers, needs to provide its members/peers with a system capable of regulating the energy market. This system translates the peer's production and consumption of electricity into offers and demands for energy while also offering them a mean of conducting transactions among themselves. Consequently, this system strengthens the concept of local electricity markets (LEMs), since peers commonly seek to exchange energy with those nearby and tend to organize themselves in clusters when sharing the same interests.

Due to these circumstances, the use of digital ledgers, such as blockchain, stands as a viable solution to the consumer-centric organizations. A large number of publications already address the use of blockchain in the electricity sector [5], however, there is still a lack of abstraction models that can expose details of how this technology impacts the grid as a whole. Nevertheless, some publications tackle this issue and propose frameworks that are capable of evaluating the impact of blockchain solutions on the electrical grid domain [6], [11].

Xu et. al. used the *Smart Grid Architecture Model* (SGAM) proposed by [12] as a proxy to evaluate innovative cases of business models in different domains of a smart grid [7]. The paper proposes that blockchain technology allows a new business model, called *Blockchain Marketplace*. Blockchain Marketplace is a fully distributed market model where an market operator is not necessary. For example, market participant 1 can directly match its needs with the resources of market participant 2, while the financial value from participant 1 is directed to participant 2 as form of compensation for shared resources, this whole process takes place without a mediator.

As argued by Xu et. al., a blockchain marketplace theoretically ensures that there is no outflow in the direct value creation, meaning that a larger benefit is shared among market participants. Due to the nature of blockchain technology, it is expected that a large volume of distributed transactions will become automated, which in turn reduces costs, enables direct value creation and improves overall market efficiency [7].

A. Design Principles

Based on the premise that all participants are allowed to commercialize energy among themselves, the consumer-centric model enables peers to determine the price and the amount they desire to trade. This freedom to negotiate requires an adequate apparel to keep record of who negotiated energy, as well as when the transactions took place and how much was traded [13].

When proposing distributed market designs that use blockchain, many of the works in the literature address the coupling aspects of the three layers described at the end of Section I, but only a few address specific aspects of blockchain implementation and design. The authors of [14] focus on the Informational Layer, highlighting digital monitoring and the necessary computational improvements, to implement a distributed energy market. In contrast, the authors in [15] show some of the electricity market designs to which the blockchain needs to be adjusted. Complementary, [16] investigates incentive-based mechanisms to ensure and improve the performance of the system as a whole.

Regarding blockchain implementation aspects, Yinan et. al. [13] proposed a design for a distributed energy system incorporating RES and blockchain. In this design, every participant is identified in a private network by a Decentralized Identifier (DID). All the transaction records are safely stored on a blockchain where evaluations are endorsed by digital signatures so that any suspicious act can be easily traced back to the speculators.

B. Existing Projects

Some projects are being conducted with the goal of closing the gap between real world challenges and theoretical studies. In Brooklyn, LO3 Energy runs the Brooklyn Microgrid (BMG) project which comprehends participants from the distribution grids of Borough Hall, Park Slope and Bay Ridge [17]. In addition to the smart meters, the physical infrastructure is composed of an electrical grid built in addition to the existing grid. Every 15 minutes the market platform based on a private blockchain executes a double auction, leaving the consumers whose bids are below the clearing price to be supplied by the local retailer.

In Madeira Island, Portugal, the authors of [18] developed an energy trading system called Power Share. In the first pilot, 9 households were equipped with smart meters to collect energy consumption and generation data. An app allowed the users to simulate transactions with each other and payments were performed via cryptocurrency. The second pilot successfully implemented a blockchain based on the Hyperledger Fabric framework, which enabled transactions via smart contracts while also mitigating problems found in the first version of the project, such as low transaction speed and high energy consumption.

A project called Quartierstrom supported by the Swiss Federal Office of Energy took place in Walenstadt, Switzerland [19], [20]. It consisted of 10 consumers and 27 prosumers with PV plants, 7 of which had battery energy storage systems. Similar to the market mechanism implemented in the BMG project, an automatic process generates bids composed of price preferences set by the users via a web app and energy data measured by the smart meters. The market is cleared every 15 minutes through a decentralized double auction mechanism integrated with the developed blockchain platform. Additionally, this project proposed a dynamic grid tariff that promotes voltage stability. For example, in times of high energy production, this tariff rewards flexible loads and battery energy storage systems for consuming power.

There are also companies such as Electron and Power Ledger which provide services for many other projects worldwide. Their initiatives are best described in [21] and [22], and are mainly focused on providing innovative solutions for energy trading in emerging markets.

As real world projects in this context are resource-intensive and still face regulatory challenges to be implemented, some works focus on paving the way for future implementations combining theoretical propositions with real data [23], [24]. Vieira et. al. [23] used real data to propose and validate two frameworks of autonomous auction mechanisms using blockchain, matching supply and demand and executing transactions via smart contracts. The data used was acquired from the Pecan Street website and relate to houses located mostly in Austin, Texas.

Data from an industrial site in Milford Haven, Wales, was used in [24] to validate a blockchain framework leveraged by smart contracts. Scalability was put to the test using Peersim simulator. This framework meets some requirements of the General Data and Privacy Regulation (GDPR), partially addressing a major issue when it comes to blockchain applications which is complying with current regulation. Similar to projects mentioned previously, Hahn et. al. [25] uses energy production data from a PV plant located at Washington State University to simulate energy transactions. The authors implemented a Vickrey second-price auction mechanism executing transactions based on smart contracts using the PV data collected.

Another path to explore and evaluate the impact of new ideas and techniques involving blockchain applied to LEMs is through strictly theoretical propositions. Siano et. al. proposed an innovative consensus protocol for P2P energy trading in LEMs named Proof of Energy [26]. Similar to Proof of Stake, it provides the benefit of not being energy demanding as other alternatives such as PoW, and it also stimulates energy efficiency between prosumers and contributes to reducing power losses in the distribution grid. This work also proposes a novel transactive controller for energy storage systems applied to energy trading in LEMs.

In view of the National Institute of Standards and Technology's smart grid conceptual model, the authors in [27] provide an analysis to serve as a reference for future blockchain-based applications in smart grids. The authors elaborate the analysis based on three main blockchain features: decentralization, trust and incentive. In traditional blockchain models, storage capacity and highly complex calculations may be an obstacle for scalability. To overcome this issue, Wang et al. proposed a blockchain model based on the Directed Acyclic Graph method, and formulated an optimal scheduling of microgrids using the Unscented Transform for modelling uncertainties [28]. In [29], the authors provide a step-by-step implementation of a blockchain-based energy trading system using the Multichain platform.

The information about the project names associated with each corresponding work in the literature is shown in Table I.

Table I
BLOCKCHAIN-BASED ENERGY TRADING APPLICATIONS.

Practical Applications	Theoretical Applications with Real Data	Purely Theoretical Applications
Brooklyn Microgrid [17]	Pecan Street [23]	Proof of Energy [26]
Power Share [18]	Milford Haven [24]	NIST [27]
Quartierstrom [19] [20]	Washington State [25]	DAG [28]
Power Ledger [21]		Multichain [29]
Electron [22]		

IV. FURTHER DISCUSSIONS

Regardless of the projects or implementations of blockchain technology along with local energy markets, whether in real circumstances or purely theoretical, many aspects must be taken into account. The current electricity network infrastructure, market organization and policies are some of the main aspects that affect the feasibility and performance of such initiatives [14]. Aside from those, it is also fundamental for the success of such initiatives to ensure that the LEM players or peers show some degree of commitment to the projects being proposed.

There are also a variety of design decisions about blockchain that can be made to adjust it to better fit the system's and user's needs [30]. Decisions regarding the degree of transparency, accessibility, controlability, security and flexibility of the blockchain are some of the main parameters that define the design, which matches the system preferences.

Given the freedom related to the wide range of possible combinations between blockchain technologies and the electricity market designs, it becomes difficult to pinpoint specific concerns related to each architecture. However, it is possible to discuss issues that affect most of them. Concerns related to the privacy and cybersecurity of platforms are one of the discussions that involve nearly all projects [31]. Although this topic is generally viewed in a bad light by those unconvinced of the benefits of the combination between blockchain technologies and the energy markets, some works strive to present beneficial implications and repercussions of this combination [11].

A. Enablers and Barriers

Considering the projects analysed, it can be said that their propositions yield a collaborative dimension to the process of energy generation. This can be stated since the project participants are allowed to receive financial income based on their business interactions with each other. In addition, in a LEM context where the players interact with those nearby, the projects can also contribute to the creation of social interests or strengthening of community bonds.

Aside from that, since the market organization can confer to its members the freedom to choose their business partners, the combination with blockchain can confer a degree of transparency and competitiveness to the system. By means of adopting blockchain platforms and experimenting, the projects enable the monitoring and diagnosis of energy consumption and generation in the electricity network [14]. This provides the opportunity for the market player to improve their energy management procedures.

Additionally, the use of blockchain in LEM also enables energy certification due to improved observability of the system. This translates into an improved system of verification of the types and sources of energy available, which increases the reliability and insurance that can be made during transactions.

Due to the observability and controlability provided by blockchains to the grid, it is also expected that the service will improve the operation of the system as a whole. After all, the exchange of real-time information enables the system operators to locate and interconnect resources to the demand, further improving the decision-making process and energy management abilities.

However, there are also weaknesses that must be considered when evaluating each proposition. A major inconsistency arises when analysing the combination of blockchain and the energy market. Although blockchains can be recommended as a trustless mechanism for decentralized and consumer-centric markets, its benefits would be countered if the energy market organization chooses to imply great control power into a single entity, *e.g.* the community manager in the community-based energy market [32]. In such a configuration the community managers/aggregators could theoretically pose a threat to the fairness of the system.

In addition to the influence of the market operator, another weakness of the widespread use of blockchain platforms in consumer-centric markets is the power that the platform creators and builders possess. Given that some blockchain structures can restrict important decision-making to certain nodes, one needs to ensure that the system would be tamper-proof so as to not allow energy market manipulation by its own creators.

Further concerns related to blockchain technologies in the energy market mention that despite its efficiency, the processes of verification, validation and cryptography remain energy expensive. That along with the exponential increase to the amount of data processing needed for the electricity sector are problems yet to be solved.

Last, the lack of actual legislation on the topic poses a threat to the successful deployment of blockchain in consumer-centric energy market projects. That combined with misinformation among the general public prevents these projects from gaining momentum associated with public support.

The relevant enablers and barriers as well as factors that can be interpreted as either one, are summarised in Figure 3.

B. Roadmap to Broad Adoption

As a common procedure adopted by many of the existing projects, a starting point is usually the research on the blockchain platform and energy market organization that best fit the existing network features. Once these possibilities have been listed, a consensus must be reached among the market players to define which type of structure will rule the system.

Considering that it gains public support, a next step for a successful initiative would be to start the implementation of the theoretical principles into the actual grid with willing test subjects. In that regard, the opportunity to conduct experiments in laboratory systems and gather data and experience in sandbox electricity networks is seen as invaluable. It is usually through such experiments that works show how issues related to trust, security, transparency and coordination can be addressed in a system based on blockchain and smart contracts [4]. Additionally, some authors advocate that slowly integrating blockchain technology into legacy systems and Internet of Things (IoT) is one of the best approaches towards its implementation in the electricity network [7].

After the critical issues related to each system have been properly solved, the step of reporting the findings along with the gathered data to policy makers begins. Such findings must be reported in a clear and detailed fashion to the responsible entities regulating the activities in the electricity sector. One of these technical reports, made by the Joint Research Centre (JRC) of the European Commission's science and knowledge service, provides evidence-based scientific support to the policy-making

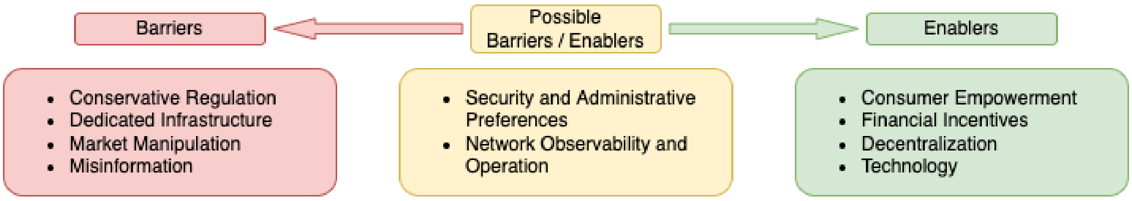

Figure 3. Enablers and barriers to the implementation of blockchain in the energy sector.

process [33]. In the report, the authors explore the use of the distributed ledger paradigm to encourage the participation of citizens in a truly free, open and interoperable energy market.

Finally, following the formulation and approval of new regulations comes the investment by the interested parties in a widespread implementation of these projects. Depending on the project's intentions and the pre-existing network, investments can be made to adjust the layers of each electrical system or the creation of new systems according to the project's specifications.

The roadmap approach to ensure the broad adoption of blockchain technologies in LEM is shown in Figure 4. The process starts with selecting viable or desirable frameworks, followed by simulation and implementation on sandbox structures. Once implemented, Steps III through VII cover the fine-tuning that needs to be made to the system during its test phase. Finally, Step VIII presents the project framework as a final product ready for adoption and implementation by the public.

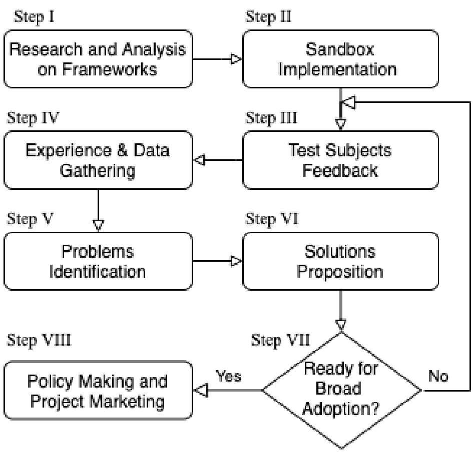

Figure 4. Roadmap procedure for implementation of blockchain in the electricity network.

V. Conclusion

The adoption of a fully distributed technology such as blockchain completely disrupts the current power sector business models. Although blockchain presents itself as a very promising solution, capable of providing a powerful platform for distributed business models, the technology alone cannot solve or address all of the issues and complexities of the energy system.

In this review, the current trend in peer-reviewed publications addresses the use of blockchain in at least one of the layers described in Section I. However, there is a lack of practical implementations that were carefully evaluated and reviewed. One can conclude that this disparity between theoretical and practical works is mainly due to three reasons. The first reason consists mostly of the lack of legislation allowing such business models to exist. To put into perspective, the very definition of *consumer* and *supplier* becomes unclear, bringing legal uncertainties that need to be addressed by proper legislation. The second reason consists of market trade secrets. Since many projects have been developed by companies, specific aspects of their approach remain as publicly undisclosed information. Finally the third reason is due to the complexity of the initiative. Considering that the business models adopted affect the entire energy infrastructure, so far there is no single framework capable of testing everything at once.

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